

Agroforestry for natural resource management



Ian Nuberg • Brendan George • Rowan Reid
(Editors)

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Contributors

Ed Barrett-Lennard: Principal Research Officer, Department of Agriculture, Western Australia.

John Bartle: Principal Research Scientist, Revegetation Systems Unit, Department of Environment and Conservation, Western Australia.

Mike Bennell: Principal Researcher, Department of Water, Land and Biodiversity Conservation, South Australia.

Paul Brennan: Manager, Sustainable Landscapes, Forest Products Commission, Western Australia.

Peter Bulman: Consultancy 'Farm Tree Systems' and Executive Officer Mt Lofty Ranges Private Forestry, South Australia.

Margaret Byrne: Principal Research Scientist, Department of Environment and Conservation, Western Australia.

Andrew Callister: R&D Manager, ITC Forestry Ltd, Albany, Western Australia.

Tim Ellis: Research Scientist, Water Quality and Environmental Flows. CSIRO Land & Water, Canberra.

David Freudenberger: Principal Research Scientist, CSIRO Sustainable Ecosystems, Canberra.

Brendan George: Industry Leader for Private Forestry and Bioenergy, Department of Primary Industries, New South Wales.

Richard Harper: Principal Research Scientist, Forest Products Commission, Western Australia.

Ted Lefroy: Professor and Director, Center for Environment, University of Tasmania.

Nico Marcar: Principal Research Scientist, CSIRO Forest Biosciences.

John McGrath: Manager, Science and Resources, Forest Products Commission, Western Australia.

Melissa Millar: Research Scientist, Department of Environment and Conservation, Western Australia.

Hayley Norman: Research Scientist, CSIRO Livestock Industries, Perth, Western Australia.

Ian Nuberg: Senior Lecturer in Agriculture and Animal Science, School of Agriculture, Food and Wine, University of Adelaide.

David Pannell: Professor, School of Agricultural and Resource Economics, University of Western Australia. ARC Federation Fellow.

Digby Race: Principal Researcher, Institute of Land, Water and Society, Charles Sturt University, Albury, New South Wales.

Rowan Reid: Senior Lecturer in Farm Trees and Agroforestry, Department of Forest and Ecosystem Science, University of Melbourne.

Grant Revell: Senior Lecturer in Landscape Architecture and Associate Dean, Faculty of Architecture, Landscape and Visual Arts, University of Western Australia.

Daryll Richardson: Director of Agave Education, Education Manager for Future Farm Industries Cooperative Research Centre.

David Salt : Consultant science communicator.

Keith Smettem : Professor and Research Director, Centre for Ecohydrology. Head, School of Environmental Systems Engineering, University of Western Australia.

Lynley Stone: Research Scientist, Department of Environment and Conservation, Western Australia.

David Thompson: Resource Economist and Principal, Centre for Agricultural and Regional Economics Pty Ltd (CARE), Armidale, New South Wales.

Albert van Dijk: Research Scientist and Leader, Terrestrial Remote Sensing and Ecohydrology Research Team, CSIRO Land & Water, Canberra.

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Agroforestry as integrated natural resource management

Ian Nuberg, Rowan Reid and Brendan George

Integrated NRM: a time of great change for the better

‘It’s a great time to be involved in the management of agricultural lands and forests in Australia.’ If we wrote that sentence 100 years ago, we would have probably substituted the word ‘management’ with ‘opening up’ and ‘exploitation’. We might have added that this was essential to secure Australia’s place as one of the leading economies and nations of the modern world. While the focus of the task is very different, the scale and urgency of the many issues facing land management in Australia today has not diminished.

As we continue to develop the economic productivity of our land we are confronted with the question of how to sustain this development. Agriculture and forestry both impact, and are impacted upon by, soil and water resources, native and feral plants and animals, and by atmosphere and climate. The people who manage the land are responsive to community perceptions of appropriate land management, either by legislative coercion or by gradual changes in their own environmental awareness. The agriculture and forestry sectors share much in their response to the future, and for those involved there is a great opportunity to contribute to the development of truly sustainable and economically viable rural landscapes that are uniquely Australian.

The challenge of the early 20th century was to remove the forests and woodlands to make room

for agriculture; the challenge for the future is understanding the interactions between forests and farming and designing new agricultural landscapes that integrate them for conservation and profit. Agroforestry, a marriage of forest and agricultural science, is a pivotal discipline in the practical implementation of this change.

This chapter lays the foundation for appreciating the urgency and nature of this change. We begin with a robust and pragmatic definition of agroforestry. Then follows an explanation of how agroforestry emerged in the efforts to secure sustainable agriculture and forestry in Australia. We mount our argument for agroforestry as a key strategy for on-ground action that integrates many natural resource management issues.

Moving from theory to practice, we describe the design and planning processes by which farmers integrate their individual vision and resources with real and meaningful changes on the ground.

We then introduce the rest of this book by summarising and linking each of its chapters.

What is agroforestry?

The terms agroforestry and farm forestry are used interchangeably in Australia with respect to the establishment and/or management of trees on farms for productive purposes. We have chosen the term agroforestry for this book because it reduces the emphasis on timber production, thus acknowledging the equally important role of non-timber

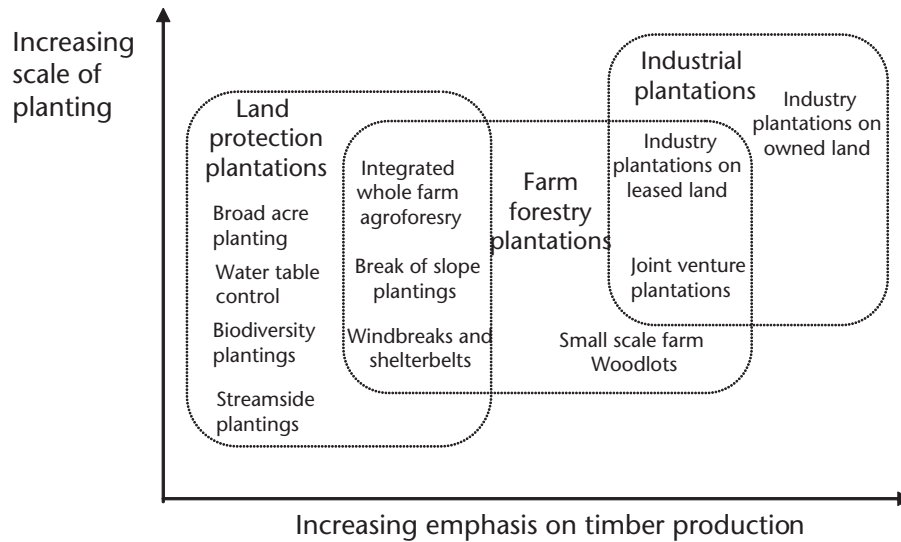


Figure 1.1: Farm forestry distinguished from industrial forestry and land protection plantings on the basis of scale and emphasis on timber production (Prosser 1995).

products. It also particularly recognises the use of trees and shrubs on farms to support agricultural production, protect soil and water resources, enhance biodiversity, sequester carbon, and improve landscape values. At its simplest, agroforestry, in our view, is a useful all-encompassing term for the deliberate management of trees and shrubs on farms.

Nonetheless, specific or comprehensive definitions are important. Shared definitions improve understanding, particularly with respect to new land management practices. Definitions are also important for policy-makers and funding bodies. For example, the increasing government support for farm forestry in Australia during the 1990s generated a great deal of debate over whether farm forestry was different from forestry on farm land. Alexandra and Hall (1998) highlighted the importance of a clear distinction because ‘the lumping of all forestry together tends to blur the issues which are important to farm forestry’. Detailed definitions of plantation types, they argued, ‘are required, not for pedantic reasons but because, by accurately recognising the differences, policies and programs can be targeted accurately’.

The National Policy Director for Australian Forest Growers, Alan Cummine (1999), acknowledged that political forces were instrumental in driving sector and government support for particular definitions during the 1990s. He suggested

that the industrial sector, while initially keen to discredit farm forestry, were nonetheless seeking to promote the concept of a seamless continuum between industrial forestry and farm forestry when funding for the National Farm Forestry Program was increased in 1995. This is evident in the model for defining forestry-related land management practices produced by Prosser (1995), representing the National Association of Forest Industries (Figure 1.1). His model was later adopted by many agencies including government departments responsible for administering farm forestry research and development (Donaldson and Gorrie 1996).

Within a few years, social research commissioned by government in response to community and environmental concerns over the rapid expansion of corporate or industrial plantations on formerly family-owned farms rekindled debate on terminology and definitions. Pearson *et al.* (2000) argued that ‘language is important and acceptance of farm forestry is made more difficult when it is confused with social, stakeholder and environmental issues which relate to plantation or industrial forestry’. Schirmer (2000) agreed, confirming that among those in the rural communities where industrial forestry is seen as a threat, farm forestry or the ‘development of plantations on agricultural land owned by farmers’ is seen as very different from

Table 1.1: Ecological interactions in agroforestry systems, showing positive (+), negative (-) and neutral (0) impacts on the tree and other components in the system (i.e. crop, animal, pest)

Interaction	Between (tree, non-tree)	Examples
Competition	(-, -)	Competition between plants for light, water, nutrients and space.
	(0, -)	Allelopathic interference
Predation	(-, +)	Predation of insects pests by birds
		Herbivory by pests and livestock
		Parasitism of productive and pest species
Mutualism	(+, +)	Mycorrhizal associations
		Nitrogen-fixing associations
Commensalism	(0, +)	The effect of shelter provided by trees on the growth and development of plants and animals
		Cycling of nutrients of one species via surface litter, organic matter and soil fauna to be available to another species

Source: Modified from Anderson and Sinclair (1993)

industrial plantation forestry even if it involves the same species grown in a similar manner.

The discussion of plantations on agricultural land continued through the 1990s, but there was also a growing interest in non-timber species (for example for fodder, shelter, groundwater management and non-timber products) recognised as a form of agroforestry without dispute (RIRDC 1992; Bird *et al.* 1994; JVAP 2002).

A definition for every purpose

Internationally, the definition adopted as the basis for an international scientific journal (*Agroforestry Systems Journal*) and the International Council for Research into Agroforestry (now the World Agroforestry Centre) in the early 1980s attempted to provide a scientific basis for agroforestry research and acknowledge the wide diversity of existing land use practices that might be included:

Agroforestry is a collective name for land use systems and technologies where woody perennials are deliberately used on the same land unit as agricultural crops and/or animals, either in some form of spatial arrangement or temporal sequence. In agroforestry systems there are both economical and ecological interactions between the different components (Lundgren 1982).

This definition is cumbersome but does contain some important elements, especially in defining how agroforestry science might be distinguished from other formal disciplines. First, the term

‘woody perennials’ includes not only trees but shrubs, palms and bamboos;. Some of these are important elements of integrated farming systems. Second, the definition emphasises the integration of the woody perennials with agricultural species (crops, pastures, animals) and acknowledges that this may occur at a number of scales, from paddock to farm or even landscape scale. It may also occur over time. Phase farming systems are an example of temporal integration where productive trees may be used to draw down a watertable, then clear-felled, and thereby make the ground suitable for an agricultural phase (see Chapter 3).

A third and most critical point is that in agroforestry systems there is an interaction – physical, environmental or economic – between the agricultural and tree or shrub components. This interaction can be positive or negative. The science of agroforestry focuses on understanding these interactions so that land managers can better design and manage systems that minimise the negative and maximise the positive interactions in a way that best satisfies those involved.

The ecological interactions between these components (Table 1.1) underpin the economic interactions. Even without any ecological interactions the inclusion of trees into a farming system might complement agricultural production by diversifying income or better utilising farm labour or equipment. These economic interactions can be just as significant as the environmental or agricultural benefits that drive most agroforestry projects.

One of the difficulties of assessing the net result of the many interactions is that some of the benefits of growing trees may not accrue for many years. Similarly, if the trees are being grown to minimise the impact of a possible environmental or agricultural risk, such as soil erosion, drought, bad weather or failing markets, it may be difficult to quantify the impact of the trees. There may be no way of telling when the trees will be required. Agroforestry design and management is very much more complex than simply selecting a planting configuration or mixture of trees and farming that appears to be more productive or sustainable than farming alone.

Although the International Council for Research into Agroforestry definition provided a useful basis for physical research for the development of a new scientific discipline, it was not appropriate for those outside science. With an eye on the political realities of government funding and public promotion, there has been a tendency to include the anticipated benefits of agroforestry and farm forestry in definitions. For example, when ICRAF was renamed as the World Agroforestry Centre in 2001 it redefined agroforestry as:

A dynamic, ecologically based, natural resource management system that, through the integration of trees on farms and in the agricultural landscape, diversifies and sustains production for increased social, economic and environmental benefits for land users at all levels (FAO 2008).

The Australian Joint Venture Agroforestry Program (JVAP) provides and manages funds for research on agroforestry and farm forestry, and facilitates delivery of that R&D to industries, communities and government. Its definition of agroforestry and farm forestry presumes the intention of the land manager: 'Agroforestry or farm forestry is the incorporation of trees into farming systems, for commercial and natural resource management benefits' (JVAP 2006).

Reid and Stephen (2001) argue that it is not appropriate to define farm forestry as a predefined set of land use practices or to distinguish it from other forms of revegetation on the basis of scale or intention. Nor is it proper to embellish the definitions with attractive outcomes that suggest agroforestry or farm forestry is more profitable or

sustainable than alternative land uses. They suggest that what clearly distinguishes a farm forest or an agroforest from a corporate, industrial or government forest is ownership. Not just ownership of the land or the trees, but ownership of the decision to do it and how it is done. Reid and Stephen argue that farm forestry and agroforestry are terms that relate not to the outcome but to the process by which these forests are established and managed, and that it is this process of farmer decision-making that should guide the research and development of agroforestry. They offer the following definition:

Farm forestry (or agroforestry) is the commitment of resources by farmers, alone or in partnerships, towards the establishment or management of forests on their land.

Just as there is little need to define agriculture or forestry, other than what is done by those who see themselves as agriculturalists or foresters, there is no need to define agroforestry on the basis of what it looks like. As Reid and Stephen (2001, p. 7) say:

Farmers may establish and manage their forests for any mix of the benefits they might provide. They may place an emphasis on a single outcome, such as timber production or biodiversity, or they may seek to balance a range of benefits in a multipurpose planting. Their priorities may vary over the farm and change over time. A forest initially established or managed for wildlife or land protection might later be harvested for timber or valued for its beauty (amenity value). Forests on farms may increase agricultural production or simply displace it. They might be sustainable, even improve economic, social and environmental capital, or they may deplete these assets. The farmer, or their partners, may profit from farm forestry or come to regret their involvement. Making a commitment to forestry is not necessarily a good decision – it is simply a decision.

The goal of this book is that: knowledge and experience can improve decision-making, thus helping all land managers, and those working with them, to design and maintain landscapes that better meet their economic, environmental and social aspirations. If that involves the establishment and management of trees on farms, then it might be called agroforestry.

For those involved in the plant and animal sciences of agroforestry, the World Agroforestry definition which emphasises the interaction between the tree and agricultural components of the system provides a clear basis for research. For those more interested in policy, definitions of agroforestry or farm forestry that focus on the ownership of the land may be more appropriate. Our interest, for this book, is the role that trees and forests can play in supporting and sustaining farming systems in Australia. It may not be important whether the trees are integrated with agricultural crops or stock. Neither may it be critical who owns the trees or the purpose for which they are being grown. For us, agroforestry is about the deliberate establishment and/or management of trees in the agricultural landscape of Australia.

Agroforestry in Australia

How and where agroforestry develops in Australia will reflect the interests and motivations of the farmers involved, and the preparedness of various interest groups to reward those who are able to provide the products and services the community value. Some will be consumers of particular products, such as timber or water. They will look to agroforestry as a means of improving the supply and quality of the particular products they are seeking at a price that they are willing to pay. Others will be more interested in the potential for agroforestry to support farmers by improving agricultural productivity, ameliorating land degradation and improving farming incomes or viability through diversification of income. A third group of stakeholders is concerned about broader environmental and social issues such as biodiversity, climate change, social stability and regional development. All the expectations and views of the respective groups are valid, but the link between the groups can be tenuous. Generally, large-scale change is underpinned by tangible markets that provide an income from agroforestry activities.

Much has been made of the great potential for agroforestry to become a valuable contributor to the economic and environmental well-being of rural Australia (Reid and Wilson 1985; Alexandra and Hall 1998). Agroforestry, in its different forms, represents a significant proportion of Australia's

native forest estate and if the trend towards increased plantation establishment continues then farm forestry could become an important component of planted forests. In comparison, in North America more than 10 million non-industrial private forest owners collectively manage approximately half the national forest estate and surpass the combined timber production from industrial and government forests (Biles 2001). However, despite a dramatic increase in the number of farmers taking an active interest in agroforestry and the rise in the financial and political support from government, industry and community groups in Australia, it remains difficult to ascertain if this potential will be realised in the short term.

In this book we review the potential of agroforestry to produce various wood products. We introduce the issues and opportunities facing those establishing and managing agroforestry systems for non-wood products of commercial value. If these forests can also address some of the opportunities for enhancing and sustaining agricultural production, for example by reducing soil erosion or offering protection for livestock, their attraction for farmers is obvious.

Agroforestry can help meet some larger social and environmental objectives, such as catchment-based biodiversity goals. The key issue for landholders whose actions provide these community benefits is the lack of tangible rewards. The relationship between the on-farm and off-farm impacts of agroforestry is therefore critical. Agroforestry systems designed and managed to enhance the viability of the farm may also provide catchment and community benefits. For example, a well-established and maintained windbreak can lead to reduced soil erosion or an improvement in the livestock survival rates from key operations such as lambing. These outcomes will be at a local or farm level and may directly (e.g. increased lambing) or indirectly (e.g. reduced erosion) assist with the sustainability of the agricultural production systems. They will also reduce the off-farm impact of soil erosion, including dust storms.

The most difficult component of valuing the non-wood returns from agroforestry relate to larger sustainability issues and concerns such as biodiversity. There is clear evidence that planting of native trees, especially in mixed species stands, can

dramatically improve the biodiversity habitat of many species (Kavanagh *et al.* 2005). But how do we establish a system where land managers can do this and gain some economic return? The lack of markets does not detract from the importance or the biophysical need to consider increased mixed species planting to meet these non-wood opportunities. However, the lack of economic certainty limits the capacity of land managers to invest. To increase the appeal of agroforestry we need to understand not only the markets and wood and non-wood values, but also the key social and biophysical drivers.

Timber production as a driver for agroforestry development

For large-scale development of any industry it is important that there is a sound economic base and a capacity to operate in domestic and international markets. Due to our large land area and efficiency of production, the majority of Australian agricultural commodities are exported (approximately two-thirds). This varies across the sectors but is expected to increase. Most of the trade now occurs with countries within the Asian sector. In 2005–06 the value of Australian forestry exports was estimated at \$2.1 billion, predominantly to countries in the Pacific region including Japan, New Zealand and China. By value, the major export commodities were woodchips (\$839 million), paper and paper products (\$593 million), panel products (\$151 million) and sawn timber (\$118 million) (Commonwealth of Australia 2007). In the same period Australia imported approximately \$4.0 billion in wood products. The majority of the imports were value-added forest products, predominantly paper, paper manufactures and paperboard (\$2.6 billion), miscellaneous forest products, such as furniture (\$528 million) and sawn wood (\$419 million). The large trade deficit of approximately \$1.9 billion acts as an incentive to develop the forest industries that can take low-value products, such as woodchips, and convert them to high-value products, such as paper products. Further, there is a significant opportunity to develop high-value sawn timber. This is of particular interest to agroforestry managers in valuing a long-term product (the sawlog) while managing the system to deliver on agricultural products and environmental services.

The sector needs to yield a competitive return on the investment, however, to be favourably considered. And the investors need to understand some of the risk associated with their investment activities. Agroforestry systems can help address both aspects of financial gain and, with consideration, larger economic gain for the community. Appropriate government policy and initiatives are critical to meeting these targets.

Much of the policy developments in Australia over the last 15 years have been driven by the National Forestry Policy statement (NFPS) delivered in 1992 (DAFF 1995). The goals offer a strategic direction for private native forests and plantations. For native forests, the NFPS goal is:

Ensure that private native forests are maintained and managed in an ecologically sustainable manner, as part of the permanent native forest estate, as a resource in their own right, and to complement the commercial and nature conservation values of public native forests (p. 4).

The NFPS clearly recognises the importance of private native forests. Their capacity to contribute to the total value of native forests wood products has increased significantly since the introduction of the Regional Forest Agreements in the mid 1990s.

The NFPS goals for plantations are:

Expand Australia's commercial plantations of softwoods and hardwoods so as to provide an additional, economically viable, reliable and high-quality wood resource for industry. Other goals are to increase plantings to rehabilitate cleared agricultural land, to improve water quality, and to meet other environmental, economic or aesthetic objectives.

The scale of plantations has increased in Australia since the end of the 20th century. This activity is underpinned by *Plantations for Australia: The 2020 Vision* (Plantations 2020 2003). This strategy aims to guide the sustainable expansion of the plantation forest estate, including significant private sector investment. By 2020, the expanded plantation forest estate will provide Australia's plantation-based processing industries with the capacity to:

- operate in the global marketplace;
- be internationally competitive;

- be commercially oriented – market-driven and market-focused in all their operations (Plantations 2020 2003, p. 5).

Thus the development of plantations is intended to increase the production of wood and wood products, especially from private investment and generally based on cleared agricultural land. Importantly, the 2020 Vision states that ‘returning trees to the landscape as a profitable crop can also significantly benefit rural and regional communities and the environment’ (Plantations 2020 2003, p. 5). However, this objective leads to conflict in some areas over production-scale forestry replacing cleared agricultural land operations.

Carbon markets and other drivers for agroforestry development

Not only is the potential value of wood products changing in a dynamic international market, but so are the expectations of delivering non-wood products and values from government and privately controlled land. This recognition is being followed, albeit slowly, by developing markets such as carbon trading.

Nicholas Stern, when reviewing the potential economic impact on climate due to changing greenhouse gas concentrations, described it as the greatest market failure the world has seen (Stern 2007). The potential impacts from climate change on life, human lifestyles and the economy in Australia are highly significant and calling for urgent action (Garnaut 2008). The potential mechanisms for international carbon markets are described in Yamin (2005) and Australia has responded with its Carbon Pollution Reduction Scheme (Australian Government 2008).

While agroforestry will have a role in addressing some of the market drivers (e.g. sequestration of carbon within an emissions trading scheme), the opportunity and influence on agroforestry activity should be viewed within the context of other non-wood products and issues. The relative importance of the drivers may change (for example, the introduction of the Carbon Pollution Reduction Scheme in Australia will lead to the development of a price for carbon and forestry activities benefit from early participation). But the development of robust agroforestry activity needs to account for multiple out-

comes for large-scale implementation. Some of these considerations, from an economic perspective, are outlined by Thompson and George in Chapter 18.

Not only will agroforestry be able to meet opportunities through mitigation of climate change, but there will need to be further consideration of adaptation for the long-term survival and productive capacity from the systems. Climate change will potentially lead to altered conditions for species as temperatures increase, rainfall patterns shift and the general climatic patterns become more variable. These issues are beyond the scope of our work but should be considered in the planning and management of future agroforestry systems, especially where species may already be at the limit of their natural ecophysiological range.

Other social or environmental drivers of land use and management change include the development of peri-urban activities, where small-scale farms are being managed by people with off-farm income. There is significant opportunity for agroforestry systems to meet some of these non-wood values, but planning is required. There will always be an opportunity to balance the wood and non-wood values from agroforestry systems, but for large-scale uptake there must be markets that will allow land managers to remain economically viable. The value of wood products is important to regional areas and Australia; we now consider some of the scale of the forestry output.

Production value of agriculture and forestry in Australia

Australia is the most urbanised country in the world, with approximately 84% of its (now) 21 million people living in the major cities around the coast (Hamnett and Freestone 1999). Though now predominantly urbanised, Australia has historically relied upon significant primary production, especially for international markets. Following the fundamentals of economic development, primary production has retreated from that dominance as other sectors of the economy advance. Today, primary production directly contributes only about 3% to the Gross Domestic Product. Nevertheless, in 2005–06 the value of Australian agriculture was estimated at \$38.5 billion while the gross value of logs removed from forests (value at the mill door) estimated at \$1.7 billion (DAFF 2007). An important

Table 1.2: Land use in Australia

Land use	Area (Mha)	% of total land area
Plantations	1.8	0.2
Agriculture		
Agricultural and horticultural crops	26.7	3.5
Grazing	442.4	57.5
Total	469.1	61.0
Native forests and woodlands		
Public native forest where timber production is permitted	11.4	1.5
Forests in nature conservation reserves	21.5	2.8
Other categories	129.8	16.9
Total	162.7	21.2
Total land area	766.0	100.0

Source: Parsons *et al.* (2007)

aspect of the forest industry is the value-adding along the supply chain. Wood and paper products, for example, support the manufacturing and construction sectors of the economy.

There are about 155 000 farm enterprises in Australia (ABS 2008) and forestry is the second-largest manufacturing industry, with 83 000 jobs (DAFF 2007). Agriculture and forestry are critical for employment and local economies for the estimated 16% of the population living in rural areas. Apart from the economic links between country and city inhabitants, agriculture and forestry together are highly significant in their impact on the ecological services provided by natural resources that all Australians rely on. Schirmer *et al.* (2005) estimated that, in the south-west slopes of New South Wales, for each dollar invested in plantation forestry approximately \$1.63–1.81 was generated within the local economy. Of this, some \$0.31–0.49 was spent in local wages. This has significant implications in areas where farm returns have declined over long periods and the capacity to increase local employment exists, especially through processing of wood products.

The size of the Australian agricultural sector is dependent on market conditions (including the Australian dollar and commodity prices) and on local environmental constraints such as drought. For example, in the summer of 2007 around 60% of broadacre farmers indicated their properties

were drought-affected. This is the same proportion that was drought-affected in 2002 (ABARE 2007). The effect of drought is expected to worsen with climate change impacts – the capacity to adapt and mitigate the problem is critical.

Land use and agroforestry

Agricultural and public production forestry utilise significant areas in Australia to support the production of primary industries goods and services to the economy (Table 1.2). There are approximately 163 Mha of forests in Australia covering about 21% of the land area and comprising just over 4% of the world's forests. About 13% of the forest estate is formally protected in nature conservation reserves (BRS 2007a). The majority (approximately 70%) of Australia's native forests are controlled through private management, via leasehold or outright ownership. Thus private forestry has a significant role not only in meeting wood and wood products demand but also in managing forests to achieve better environmental outcomes through maintaining or enhancing biodiversity, water quality and carbon sequestration. However, the lack of transparent markets in these non-wood values limits some of the opportunities for the land managers. These managers carry significant costs, reducing production capacity to meet environmental policy (Productivity Commission 2004).

Table 1.3: Estimated areas of plantations located on farms across Australia, 2005–06

State	Total plantation area	Hardwood	Softwood	Unknown plantation	Estimated area 'farm forestry'	% forestry on farms
WA	377 598	270 813	104 480	2305	65 702	17.4
NSW	331 623	55 196	273 606	2821	27 856	8.4
Vic.	384 599	164 724	218 412	1463	25 384	6.6
Tas.	227 200	155 500	71 600	100	21 357	9.4
Qld	225 637	37 496	186 033	2108	4738	2.1
NT	16 329	14 090	2239	0	425	2.6
SA	166 962	42 341	124 164	457	14 359	8.6
ACT	9500	0	9500	0	0	0
Total	1 739 448	807 437	990 034	9254	159 820	9.2

Source: BRS (2007a)

The 2007 National Plantation Inventory Update (BRS 2007b) indicates that in Australia there are about 1.82 Mha of plantations. Some 807 500 ha are hardwoods, almost 1 M ha are softwoods and 9254 ha are unidentified (Table 1.3). Between 1997 and 2007 most of the increase in plantations was for hardwood investment. For example, in 2006 there were 67 200 ha hardwood established compared to 11 100 ha of softwoods. Most of the plantation development is carried out by companies linked with managed investment schemes.

The National Farm Forestry Inventory (NFFI) indicates that over the last thirty years there has been a significant increase in the area of small grower plantations (Stephens 2001). Table 1.3 shows that only about 9% of plantations are located on farms.

While the penetration of forestry into the agricultural sector is good for correcting the trade imbalance for wood products and rehabilitation of degraded agricultural land, a balance must be found between changing land uses. Only 0.2% of the land resource is under plantation forestry, but there is a common perception of conflict with 'traditional' agricultural land use. As agricultural landscapes change with tree plantations, there is considerable concern about the social, economic and environmental impacts of large-scale monoculture eucalypt and pine plantations (Spencer *et al.* 1989; Schirmer 2000; Hopton *et al.* 2001; Schirmer *et al.* 2005). In this context, the way that agroforestry is implemented becomes important in balancing the needs of production and scale with local

community perceptions and aesthetic values. This leads us to consider the people in these communities who will implement these changes to land use and production.

Human capital and agroforestry

As a group, farmers are getting older. The average age of farmers in 2006 was estimated to be 52, and it is increasing (ABS 2008). The next generation has less interest in managing the family farm. There are significant demographic changes in rural Australia, which mean there will be new attitudes to planting trees on farms. Many of the younger farmers who take control of existing family farms (and sometimes significant debt) need to maintain profit and cash flow. They will not be interested in broad-scale agroforestry unless it is a commercially competitive option. As detailed in Chapter 17, they will assess an agroforestry investment with a high discount rate. Other landholders, especially those near large regional towns or cities, are more inclined to focus on lifestyle over production or look at lower input systems (Barr and Wilkinson 2005). The 'tree-changers' who move from urban to rural areas for lifestyle reasons may view agroforestry with a low discount rate, i.e. environmental and aesthetic values dominate over future financial return. Age, attitude and financial means influence the individual likelihood and capacity to adopt agroforestry. Efforts to enhance the adoption of agroforestry to increase natural resource management outcomes will need to consider the heterogeneity of the audience and their

goals. The extension strategies used to support agroforestry are detailed in Chapter 19. We need to accept that provision of information alone will not necessarily increase the adoption of agroforestry (Pannell *et al.* 2006). The mechanisms of government policy for enhancing adoption are discussed in Chapter 18.

Agroforestry for integrated NRM

Agriculture and forestry are conventionally considered as separate sectors of the natural resource economy with traditionally different physical resource bases, geographic distribution and ownership and investment structures. Agroforestry straddles the two sectors, as the traditional boundaries are being blurred. The case has been made that drivers in the forestry sector will ensure that farm-grown trees will be an important component of that sector; the essential driver in the forestry sector is economic opportunity in a world market increasingly requiring more wood products. Earlier sections outlined changes in the resource base and social structure in the agricultural sector that underpin the increasing role of trees in agriculture. We could argue that the essential driver for agroforestry in the agriculture sector is the need for sustainable and profitable management of the natural resource base.

While agriculture is still a significant contributor to Australia's export income it has declined in relative importance to other sectors in the national economy. This decline has been shadowed by changes in the demography of rural populations and their political influence. Agricultural research has evolved from a focus on increasing productivity to considering the sustainability of agricultural systems, particularly in relationship with larger landscape processes. All this change has occurred across one or two generations of farmers – farmers who will be caring for the land in 2020 will have a very different environment from their predecessors. In aggregate, they will be wealthier and manage larger, more technologically and commercially sophisticated operations which will be more closely and efficiently linked into global commodity supply chains (Barr 2003).

These farmers will be widely recognised for their role in managing the landscape to sustain its ecological services, particularly water, carbon and

biodiversity. Agricultural systems will have to be more closely adapted to Australia's fragile soils, highly variable seasons and increasingly changing climate. Some agricultural systems may, to some degree, mimic natural ecosystems in structure and/or function (see Chapter 2). We may see a proliferation of new income streams as farmers are paid for non-wood values such as the carbon they store, the biodiversity they maintain and the extent to which they manage water, increase catchment water yield and reduce catchment salinity (Williams and Saunders 2002). Innovative thinking is leading discussion on the value of forest management for environmental outcomes and the concepts of stewardship payments to land managers (Southern Cross Group 2006). Already we are seeing concerted efforts to establish new tree-based industries for pulp and energy production in agricultural areas (Chapter 16).

The role of non-horticultural trees in rural landscapes has traditionally been secondary to the field crops and pastures that provide the marketable commodities. Trees and shrubs have had a role in protecting crops and soils (Chapter 5) and livestock (Chapter 13), and in providing fodder (Chapter 14) and landscape amenity (Chapter 8). However, over the last two decades there is general acknowledgement of the importance of farm trees in maintaining the hydrological balance (Chapters 3 and 4) and biodiversity of rural landscapes (Chapter 6). Direct income from farm trees is now a possibility for many landholders (Chapters 10–12), not just the enthusiastic few. There has also been growing awareness of the multi-functionality of rural landscapes beyond providing just grain and meat.

Agroforestry is finding a niche in 'amenity farming landscapes'. Generally, this is the classic rolling green hills where urban escapees retire or seek a tree-change in lifestyle. Similarly, peri-urban landscapes offer an opportunity for small-scale tree planting. The price of land in these landscapes is usually beyond the means of viable farm business investment and the main income of landholders is from off-farm sources. Agricultural income may be niche horticulture or small-scale grazing of beef or sheep, not without attendant problems. The beef industry is increasingly geared to paddock-to-plate quality control procedures beyond the means of small producers. Running sheep in more densely

populated landscapes with non-farm dogs also has problems. Finally, weed and pest management can be a significant problem for time-poor or indifferent landholders (Barr 2003). In this context, small-scale tree planting for a long-term investment, perhaps to be realised as part of a local farm-forestry cooperative, offers an aesthetically and ethically satisfying alternative land use.

The Decade of Landcare (officially 1990–2000) was largely responsible for the huge expansion of farm tree planting in areas of broadacre agriculture and grazing (Walker 2000). Plantings were mostly for soil conservation, stock shelter and fodder, groundwater control and wildlife habitat. They were the sign of an awakening and cultural change, especially among younger farmers. Landcare relied on committed individual and community efforts, from people who could see beyond the bottom line of annual gross margins. It remains to be seen how firmly embedded the tree-planting ethos is as farm sizes increase, their business structures become more strongly coupled to global markets and the rural population continues to decline. For agroforestry to flourish in this context we will need new tree-based industries for low-rainfall areas. These are likely to be multi-product industries (e.g. fibre and energy) that are supported by incentives from other natural resource sectors, such as energy and water supply. Woody–perennial fodder systems may cover even larger areas of this landscape as they will be more easily integrated into existing agricultural systems. The search for these, as well as herbaceous–perennial farming systems, is central to the activity of the Cooperative Research Centre for Future Farm Industries (2008–2014).

Natural resource management is planned and implemented in Australia through 56 regional bodies or catchment management organisations with various structure and functional arrangements (Pannell *et al.* 2007). The funding of resources has been devolved to the local (catchment) level. This allows for better identification and recognition of, and relationship to, specific issues. For agroforestry opportunities and issues, placing responsibility and action at the local level delivers improved understanding and better on-ground outcomes.

NRM bodies share the task of integrated management of a broad range of natural resource assets,

one of which is perennial vegetation. Agroforestry is a land use option that integrates income generation for landholders with, most notably, ground and surface water management, soil conservation and biodiversity management. It can also be a consideration in the regional management of pests, weeds and fire. Planning and management around these issues relies on a good understanding of the nature and options of agroforestry and a recognition of the dual role of production (e.g. wood) and sustainability from the managed system.

Whoever is considering agroforestry, whether at the level of an individual property or as an option that may that may be promoted across a region, will need an understanding of the design and planning processes in agroforestry (discussed below). Identifying the key objectives, and applying suitable species and styles to attain those objectives, is critical in developing a robust agroforestry system capable of delivering a successful outcome.

Design and planning processes in agroforestry

There are essentially two approaches to agroforestry design: the ‘best bet’ and the ‘diagnosis and design’ approaches.

‘Best bet’ approach

The ‘best bet’ approach is where a landholder simply copies the species, establishment techniques, planting arrangement and management used or advocated by others. The design and practices being adopted may have been proven effective by industry, researchers or other landholders. This approach can be effective but overlooks the potential, and the possibly the need, to adapt the design and management of agroforestry systems to better reflect the objectives, resources, attitudes and opportunities facing each particular landholder.

If agroforestry design were as simple as selecting off-the-shelf packages or recipes there would be little need for a book like this. All that would be needed is a collection of best bets or design options developed by researchers and practitioners for every region. Landholders would simply pick the one that seems to suit. They might prefer options developed by people like them or those used in their region on similar soil types, or they could just

choose options that appear affordable and appeal to their sense of aesthetics. It would be a bit like going to a used-car yard – you look at all the models on offer and pick the one that seems the best, fits your budget and matches your self-image.

It is easy to assume that every tree-grower faces the same constraints (e.g. limited land, time or money) and measures success in the same way (e.g. discounted returns per hectare). In our experience this is not always the case (see Chapter 17). As every farm family and every farm is different, it follows that the most appropriate agroforestry design for each will be unique. People have different attitudes to investment risk, measure profit in different ways and have diverse views about the likely future value of different products and services. And these attitudes may change over time. The situation is even more complex where landholders are seeking a mix of commercial and non-commercial benefits from their trees.

Diagnosis and design

As Andrew Campbell wrote when he was the National Landcare Coordinator, ‘the complexities inherent in sustainability and the primacy of farmers in making land management decisions mean that a recipe approach to land management recommendations won’t work’ (Campbell 1994, p. 200). Fortunately the alternative is not only practical, it is less risky, more affordable and likely to be much more rewarding. It involves a diagnosis of the concerns, opportunities and aspirations of the landholders, a review of the role that trees and forests might play, the design of possible agroforestry systems and evaluation on the basis of the rewards, costs and risks associated with each.

The importance of this book lies in the fact that a landholder with clear objectives and some basic knowledge can design and manage an agroforestry system that best matches their own circumstances, acknowledges their particular exposure to risk and maximises the suite of rewards that are most important to them. The diagnosis and design approach provides a guide to developing unique agroforestry designs for each situation. The key difference is the starting-point: rather than having a particular species, layout or management plan in mind, it starts with a review of the landholder’s particular circumstances and

the role that agroforestry might play in addressing them. Then, based on the landholder’s individual constraints and goals, possible designs are developed and tested. Their advantages and disadvantages are highlighted in a way that informs landholder decision-making.

An important advantage of this approach is that it acknowledges that forests planted for a particular purpose can be designed and managed to deliver a range of benefits over time. For example, the need for land degradation control or stock shade and shelter may define where trees must be established on a particular property and the role they must play to be effective in the short term. Then, if the landholder has an interest in producing timber, they may consider how to adapt their design to incorporate commercial species and forest management options that keep alive the possibility of harvesting a commercial product in the future (see Figure 1.2).

Much of this book is dedicated to providing an understanding of the processes underlying common land management problems and opportunities facing landholders across Australia. Chapters 2–8 describe the underlying processes and role of growing and managing trees on farms in meeting these needs. Chapters 9–16 go further by reviewing the growth and development of trees and exploring the management options available to landholders interested in producing commercial tree products and services. It is this type of knowledge, coupled with the aspirations and experience of landholders themselves, which is required to design and manage successful appropriate and adaptable agroforestry systems.

Planning tools for agroforestry

There are a number of planning tools and techniques that can be used during the diagnosis and design process. Some are systematic or step-wise techniques for planning the most appropriate location of trees on a farm; others are conceptual tools for exploring the structural design and management options that may be feasible.

Data overlay method

Many landholders are now familiar with using an aerial photograph and a series of plastic overlays as a planning tool to determine the location of fences,

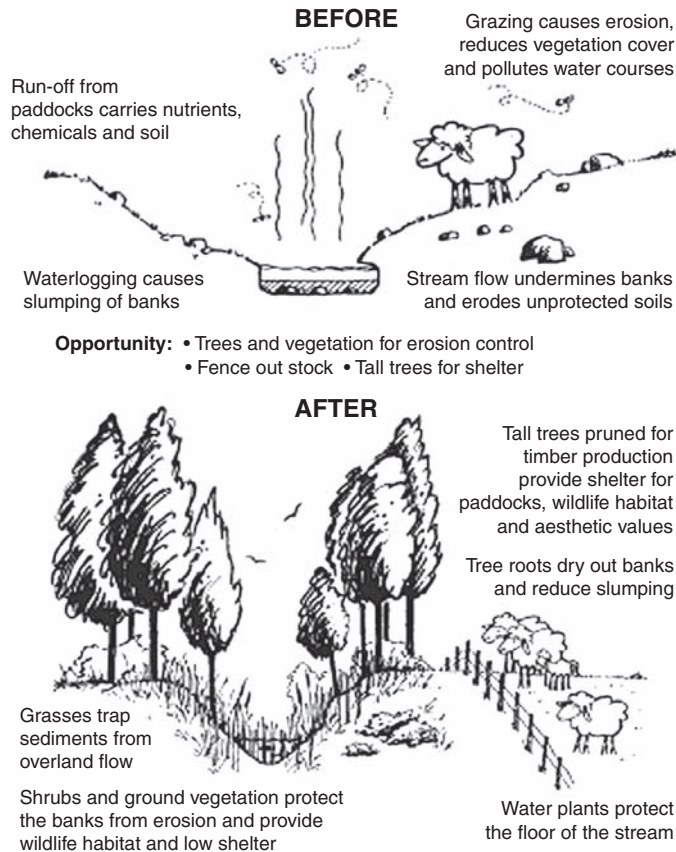


Figure 1.2: Appropriate agroforestry design for multiple outcomes begins with an understanding of the problems and opportunities. This example of a multi-purpose riparian buffer seeks to achieve a range of commercial and non-commercial outcomes while maintaining management flexibility (Abel *et al.* 1997).

roads, stock laneways and revegetation projects. Information not shown on the aerial photograph, such as soil types, contour lines, vegetation types, threats, fence lines and recent improvements, can be added to a base overlay sheet, thereby providing more information when exploring possible fencing and planting locations.

The increasing availability of physical and production data and software means that the overlay method can be extended to incorporate annual crop-yield data, real-time soil moisture measurements and other information that can improve farm management decision-making. The value for agroforestry design lies in highlighting opportunities for fitting tree-growing into the farming landscape, complementing other farming activities and improving economic and environmental landscape function.

Analogue systems (mimicking natural systems)

The term ‘analogue forestry’ was first used to describe an approach to system design and evaluation that promotes options which closely mimic the structure and function of natural forests (Senanayake and Jack 1998). The underlying assumption is that we can learn a lot about the productive and ecological potential of a site by looking at the structure and function of the native vegetation. An example is the use of nitrogen-fixing tree species in eucalypt plantations that mimic the natural species mix common in native eucalypt forests found in the area. In some cases the emphasis might be on the aesthetics rather than functionality. For example, the aim might be to recreate the open woodland or parkland appearance thought to have been induced by Aboriginal fire-stick farming, but using sheep, improved pastures and wide-spaced



Figure 1.3: A good property plan allows farm foresters to integrate their tree plantings with agricultural activities for optimum performance (photo by R. Reid).

commercial timber trees instead of kangaroos, native pasture and old twisted red gums.

Flow diagrams

Many natural and production systems that occur on farms can be broken down into a number of distinct steps or stages and presented in a flow diagram. Displaying the annual production cycle associated with the production of farm stock or crops as a flow diagram can highlight opportunities for trees to enhance productivity or reduce risk. The stages involved in establishing, managing and harvesting tree products can also be presented in a flow diagram. This may be useful in highlighting when and how much labour is required for particular management activities, planning harvesting operations or identifying when the landholder needs to begin learning new skills or negotiating with buyers.

Cause and effect relationships

In this book we review the theoretical and scientific knowledge of the processes underlying common natural resource management problems on Australian farms. When coupled with landholders' experience, observations and on-farm research, this information can help build understanding of the processes that link a particular action (e.g. tree planting) with an outcome (e.g. lowering watertables or reducing wind speeds). However, tree planting can result in unintended consequences. Good design requires broad-based thinking about the possible impacts of a proposed agroforestry system on all aspects of the farming system, before the trees are planted.

Good agroforestry design allows for change

Designing a new tree planting project is a little like designing a house to suit a particular family – a review of the family's needs and aspirations now and in the future is essential. However, the process of managing a forest is never completed. Forests are dynamic and landholders must continually adapt their management in response to changing circumstances. Good agroforestry design involves exploring opportunities and planning for uncertainty so that the decisions made now provide the greatest prospect of success in the future.

Summary and invitation to this book

There are many good texts that lay the foundations for an understanding of natural resource management (Aplin 1998; Yencken and Wilkinson 2000; Dovers and Wild River 2003). There are some fine books describing and prescribing the practice of agroforestry in Australia (Abel *et al.* 1997; Reid and Stephen 2001). *Agroforestry for Natural Resource Management* presents a multi-disciplinary perspective of how agroforestry is being used as a strategy for sustainable management of Australia's natural resources. The authors come from a wide range of disciplines – agronomy, forestry, community and molecular ecologies, agricultural economics, soil science, hydrology, landscape architecture and rural sociology. They are writing for students and professional practitioners of natural resource management as defined earlier in this chapter.

The scope of agroforestry in this book is the planting of trees and shrubs on rural property largely, but not exclusively, with an intention to manage dryland salinity. This will include plantings in high- (>700 mm) and low-rainfall zones in southern Australia. The trees may be grown for timber and other commercial outcomes or for environmental outcomes only.

The book is divided into three sections, each with a different focus.

Part I: Environmental function of trees in the landscape

This section examines the main environmental functions of trees in the landscape.

It opens with Ted Lefroy's discussion, 'Agroforestry for functional mimicry of natural ecosystems'.

The powerful concept that our agricultural systems should mimic the structure and function of the natural ecosystem has encouraged scientists to look for productive land management systems that are in tune with the landscape, that do not deplete resources and degrade the land. As most natural land ecosystems are dominated by woody perennial species, agroforestry is an obvious way to re-invent our agricultural landscape. Lefroy provides challenging answers to important questions. Is it necessary to mimic structure to achieve functional goals? Does perennality inevitably imply a trade-off in productivity? Can competition be managed in synthetic polycultures of trees and crops? How can complex farming systems be successfully managed to ensure a return to the farmer?

An important function of agroforestry in some landscapes is to control groundwater and thereby mitigate dryland salinity. Land managers have to integrate a lot of difficult science to develop and implement revegetation strategies. It is equally important to know when revegetation is not the answer, when other strategies, such as drains, are more appropriate. In Chapter 3, 'Using trees to manage local and regional water balances', Keith Smettem and Richard Harper provide the fundamentals for understanding the hydrological and physiological processes behind the use of perennial vegetation for mitigating salinity. They offer advice for the strategic placement and configuration of tree planting in the landscape.

That chapter is complemented by the next, 'Agroforestry for the management of water, salt and agricultural diffuse source pollutants', by Tim Ellis and Albert van Dijk. Where Chapter 3 focuses on groundwater and salinity, Chapter 4 discusses the management of surface water and the pollutants it carries, including sediment and nutrients responsible for eutrophication as well as salt. It describes the hillslope scale processes by which tree plantings may capture water and pollutants and their effects on stream flow and dryland salinity at catchment scales. It provides an insight into the type of experimental and modelling work undertaken to understand these linked stream-groundwater systems. Guidelines on the design and placement of agroforestry plantings are provided specifically for the purposes of surface water and pollutant management.

The scale of revegetation required to restore the pre-agriculture hydrological balance is vast. Most

of this landscape is under broadacre crops and pastures. We cannot afford to blanket the landscape with trees at the expense of agriculture. The shelter provided by trees is often touted as a commercial justification for integrating tree-planting with broadacre agriculture. In Chapter 5, 'Trees protecting dryland crops and soil', Ian Nuberg and Mike Bennell examine this concept in the light of international and recent Australian research. They show that trees can provide considerable shelter to dryland crops and are particularly important during extreme wind events in dry years. We are fooling ourselves if we believe that windbreaks will elevate net crop yields over large areas of Australia, but they can insure against storm damage to crops and soil as well as enhance livestock production.

Protecting and enhancing biodiversity is another compelling reason for promoting agroforestry. Agroforestry plantings cannot substitute for native vegetation communities but they can provide some of the resources necessary for some regional wildlife and native plants. David Salt and David Freudenberger, in 'Biodiversity and habitat enhancement' (Chapter 6), help us understand biodiversity and how agroforestry can enhance it in agricultural landscapes. They provide very practical guidelines to follow in planning and managing an agroforestry enterprise for biodiversity. The chapter includes case studies where these principles have been applied.

The simple act of planting trees does not necessarily improve biodiversity. Indeed, as Chapter 5 explains, a poorly designed plantation can be an environmental liability. Not only can it have little positive value for local flora and fauna, it can have a serious negative impact. Most people relate this to exotic tree species, such as pines, and consider any Australian native species a more benign alternative. However, in Chapter 7, 'Environmental risk in agroforestry', Margaret Byrne, Lynley Stone and Melissa Millar describe the weed and genetic risks associated with the use of native species for large-scale revegetation for agroforestry, even within their natural range. This is not a call to limit agroforestry to protect biodiversity, but to employ risk management frameworks in the implementation of revegetation programs.

The final chapter on the environmental functions of agroforestry is Chapter 8, 'Landscape aesthetics and agroforestry', by Grant Revell. Revell

uses the word ‘landscape’ in a very specific way. The landscape is the way we sense the environment, filtered through our values and belief systems. Our perceptions about whether a landscape is being well or poorly managed are grounded in our culture. While land managers may think that they are managing biophysical resources for the private and public good, Revell shows how they are also the creative managers of cultural symbols. How do we make environmental features important for biological reasons and economic values important for landscape aesthetic reasons? Revell discusses different paradigms of landscape assessment according to their resource management priorities. The chapter offers design guidelines and case studies that illustrate the meaningful and multiple benefits of agroforestry planning from this understanding of landscape.

Part II: Productive function of trees in the landscape

Chapters 9–16 provide a comprehensive discussion of how trees and shrubs can be used for productive purposes in southern Australia.

The primary productive function of a tree is its wood, and the section begins with Rowan Reid’s ‘Wood as a farm product’. Land managers dealing with tree planting do not have to be foresters, but they do need to understand wood as a product for the trees to reach a market and for the landholder to receive a worthwhile return. Reid describes tree and wood growth and how we can manage inter-tree competition in a plantation to achieve the optimum yield and quality of marketable wood. With an explanation of log prices and harvesting costs, Reid outlines management principles that will achieve the best trees for different target products. Reid follows this in the next chapter, ‘Growing high-quality sawlogs’, in which he describes in greater detail the silviculture, value-adding and marketing of farm-grown sawlogs.

Sawlogs are by no means the only wood product available from farms: firewood and pulp are two very important alternatives. Sawlog production has traditionally been restricted to higher-rainfall environments (>700 mm) and great advances are being made in extending its range into the lower rainfall zone (>400 mm). In Chapter 11, ‘Farm firewood production’, Peter Bulman and Ian Nuberg show how the relative value of firewood

versus sawlog production is strongly determined by the costs of production, changes in the value of the products and the value given to an early harvested product. Depending on the physical and economic context, firewood production can sometimes compete with sawlog production even under relatively high rainfall situations.

In Chapter 12, ‘Pulpwood production’, Richard Harper, John McGrath, Keith Smettem, Rowan Reid and Andrew Callister describe the history and extent of this very important industry. Covering an area of approximately 500 000 ha in 2006, Tasmanian blue gum production for pulpwood is the largest form of farm forestry attracting significant private investment from urban sources. The chapter outlines the process of site selection and yield prediction, crucial elements of the planning process for blue gum establishment. It discusses the environmental, legal and marketing issues associated with blue gum production – understanding these is very important for farm foresters and land use planners, to ensure that the plantations are in the right place for the right reason. The chapter also includes an outline of the essential steps in the growing of blue gums.

There are more than 400 million ha of grazing land in Australia, where trees can most readily be integrated with the agricultural system. In Chapter 13, ‘Trees in grazing systems’, Rowan Reid reviews our understanding of the impact of trees on pasture and animal production. Trees will compete with pasture just as they do with crops but the relative net effect on pastures is less severe. When the marked benefits of shade and shelter on animal production are included, along with the opportunity for wood production in higher-rainfall areas, trees can be easily justified on a farm financial basis. Reid illustrates this with a case study of integrating multi-purpose trees and grazing on a property in Victoria.

About 1 million ha of Australia’s are in low-rainfall (300–450 mm) saline landscapes and may not be suitable for the trees and systems that Reid describes. Naturally occurring saltbush (*Atriplex* spp.) has long been the basis of the pastoral industry in the southern pastoral zone, as these plants have high levels of salt tolerance. Ed Barrett-Lennard and Hayley Norman describe the use of saltbush in Chapter 14, ‘Saltbush for fodder production on Saltland’. They describe the types of saltbush

that can be used for plantations as drought reserve or fodder on saline lands. When matching sites to pastures that include saltbush, it is important to understand the relationships between saltbush production and salinity, waterlogging and inundation. The chapter explains what can be expected from animal production and water use on saltbush pastures, and the key to their establishment.

Fodder is not the only productive land use on saline lands and Nico Marcar explores this issue further in Chapter 15, 'Productive use and rehabilitation of saline land using trees'. Salinity is one of the major forms of land degradation affecting agricultural lands, so Marcar outlines the problem's extent and nature before explaining the range of native timber species' genotypic response to salinity. This needs to be understood so that farm foresters can minimise the risks to growth when planting trees in saline landscapes. Marcar describes the main tree planting configurations being followed and how the economic opportunities in timber and non-wood products from these trees depend on growth rates, product quality and market considerations. He shares his thoughts on the prospects for the rehabilitation of saline lands with productive trees.

This section on the integration of productive woody perennials into farming systems is capped off with a case study of mallee in the wheatbelt of Western Australia. John Bartle's chapter, 'Integrated production systems', reviews the development of a short harvest cycle, mallee coppice system which produces oil, bioenergy and industrial wood and carbon products at the same time as controlling groundwater responsible for dryland salinity. It is a heroic task which, at the time of publication, is still not completed. The chapter shows the complexity and long development time involved in developing a new industry based on woody perennials.

Part III: Implementation of agroforestry

This last section (Chapters 17–19) of the book discusses the essential points of implementing agroforestry: how to evaluate agroforestry, how government policy can facilitate agroforestry, and the adoption of agroforestry by landholders.

David Thompson and Brendan George's chapter, 'Financial and economic evaluation of agroforestry', outlines the essential principles and techniques of evaluating the financial feasibility of agroforestry systems as a farm business, and the

economic impact at the catchment level. It outlines a study of an agroforestry system, detailing the essential criteria and comparing farming options.

This systematic financial and economic approach is useful for landholders to make decisions about investing in agroforestry. It is also essential for resource managers to be able to make economic measures of the environmental benefits from agroforestry. However, other criteria are of equal importance, including farmer intentions and capacity to operate. Some issues and opportunities are poorly addressed through economic considerations and market mechanisms do not always reflect where community and environmental benefits can be realised, allowing the government to intervene. David Pannell's chapter, 'Enhancing the environmental benefits of agroforestry through government policy mechanisms', discusses the circumstances in which government intervention to enhance environmental outcomes from agroforestry is appropriate. He weighs the pros and cons of a wide variety of policy approaches and mechanisms, and concludes with the difficult question of who should pay for the public environmental benefits generated on private land.

In the final chapter of this book, Digby Race discusses the adoption of agroforestry in Australia. He presents a historical and policy context determining adoption of agroforestry, with a focus on medium- to low-rainfall areas or the wheat-sheep zone, then outlines various extension strategies for enhancing adoption of agroforestry.

The DVD

The DVD that accompanies this book offers the following material to complement and enhance the knowledge presented in the text. This material includes tools and instructions as well as inspirational stories.

Videos	Tree measurement for farm forestry
	Yan Yan Gurt Farm
	Harvesting sawlogs at Bambra farm
Regional resources	Qld/NSW South Australia Tasmania Victoria Western Australia
Master Tree Growers	Design principles for agroforestry The Farmers Forest

Greening Australia	Multiple benefits of farm forestry
Treesmart	Database of agroforestry species
Farm Forestry and Agroforestry Reference Library	Database of references to publications, non-published reports and research projects on farm forestry and agroforestry in Australia
Farm Forestry Toolbox	Collection of programs for assisting managers of shelterbelts, plantations or native forests

References

- ABARE (2007) *Australian Farm Survey Results 2004–05 to 2006–07*. Australian Bureau of Agricultural and Research Economics. Commonwealth of Australia.
- Abel N, Baxter J, Campbell A, Cleugh H, Fargher J, Lambeck R, Prinsley R, Prosser M, Reid R, Revell G, Schmidt C, Stirzaker R and Thornburn P (1997) 'Design principles for agroforestry: a guide to assist farmers to decide where to place trees and farm plantations on farms'. RIRDC/LWRRDC/FEPRDC Joint Venture Agroforestry Program, Canberra.
- ABS (2008) *Yearbook of Australia, 2008*. Catalogue no. 1301.0. Australian Bureau of Statistics, Commonwealth of Australia.
- Alexandra J and Hall M (1998) 'Creating a viable farm forestry industry in Australia: what will it take?' Rural Industries Research and Development Corporation, Canberra. RIRDC Publication no. 98/74.
- Anderson LS and Sinclair FL (1993) Ecological interactions in agroforestry systems. *Agroforestry Abstracts* 6(2), 57–91.
- Aplin GJ (1998) *Australians and Their Environment: An Introduction to Environmental Studies*. Oxford University Press, Melbourne.
- Australian Government (2008) Carbon pollution reduction scheme: Australia's low pollution future. Accessed 13 January 2009. <<http://www.climatechange.gov.au/whitepaper/report/index.html>>
- Barr N (2000) Structural changes in Australian agriculture: implications for natural resource management. Department of Natural Resources and Environment, Victoria. Accessed 18 January 2008. <<http://www.anra.gov.au/topics/people/pubs/national/theme6-3-4-2.pdf>>.
- Barr N (2003) Future agricultural landscapes. *Australian Planner* 40, 123–127.
- Barr N and Wilkinson R (2005) Social persistence of plant-based management of dryland salinity. *Australian Journal of Experimental Agriculture* 45, 1495–1501.
- Biles L (2001) What America's federal and state governments want from private forests: their preparedness to fund programs related to government being a stakeholder in private forestry. Paper presented at the *IUFRO Working Party (S6.06–03) Symposium on Forestry Extension: Assisting Forest Owner, Farmer and Stakeholder Decision-making*. 29 Oct–2 Nov, Lorne, Australia. <<http://www.anu.edu.au/forestry/IUFROFE2001/index.html>>.
- Bird PR, Kearney GA and Jowett DW (1994) 'Trees and shrubs for south west Victoria'. Department of Agriculture, Pastoral and Veterinary Institute, Hamilton, Vic. Technical Report Series no. 205, February 2004.
- BRS (2007a) *Australia's Forests at a Glance*. National Forest Inventory, Bureau of Rural Sciences. Commonwealth of Australia.
- BRS (2007b) *Australia's Plantations 2007: Inventory Update*. Bureau of Rural Sciences. Commonwealth of Australia.
- Campbell A (1994) *Landcare: Communities Shaping the Land and the Future*. Allen & Unwin, Sydney.
- Cummine A (1999) Farm forestry: how is it different? Paper presented at the *Institute of Foresters of Australia National Conference*, Hobart.
- DAFF (1995) National Forestry Policy Statement: a new focus for Australia's forests. December 1992, 2nd edn 1995. Department of Agriculture, Fisheries and Forestry, Commonwealth of Australia. Accessed 4 March 2008. <<http://www.daff.gov.au/forestry/policies/statement>>.
- DAFF (2007) *Australian Agriculture, Fisheries and Forestry at a Glance 2007*. Department of Agriculture, Fisheries and Forestry, Commonwealth of Australia.
- Donaldson J and Gorrie G (1996) Farm forestry policy. In *Proceedings of Australian Forest Growers Conference: Farm Forestry and Plantations*

- *Investing in Future Wood Supply*. 9–12 September, Mt Gambier, SA. p.7.
- Dovers S & Wild River S (Eds) (2003) *Managing Australia's Environment*. Federation Press, Sydney.
- FAO (2008) Agroforestry systems. Accessed 14 April 2008. <<http://www.fao.org/forestry/site/33356/en/>>.
- Garnaut R (2008) 'The Garnaut climate change review'. Cambridge University Press, Cambridge.
- Hamnett S and Freestone R (eds) (1999) *The Australian Metropolis: A Planning History*. E & FN Spon, New York.
- Hopton H, Schmidt L, Stadter F and Dunkley C (2001) Forestry, land use change and water management: a green triangle perspective. In *Proceedings of a National Workshop: Plantations, Farm Forestry and Water*. 20–21 July 2000, Melbourne. (Eds EKS Nambier and AG Brown). RIRDC Publication no. 01/20.
- JVAP (2002) 'Emerging products and services from trees in lower rainfall areas'. Joint Venture Agroforestry Program Research Update Series no. 2. Rural Industries Research and Development Corporation, Canberra.
- JVAP (2006) The Joint Venture Agroforestry Program: a partnership between Rural Industries Research & Development Corporation, Land and Water Australia, Forest and Wood Products Research & Development Corporation. <<http://www.rirdc.gov.au/programs/JVAP-Brochure-2006.pdf>>.
- Kavanagh R, Law B, Lemckert F, Stanton M, Chidel M, Brassil T, Towerton A and Herring M (2005) 'Biodiversity in eucalypt plantings established to reduce salinity'. Canberra. RIRDC Publication no. 05/165.
- Lundgren BO (1982) What is agroforestry? *Agroforestry Systems* 1(1), 7–12.
- NAFI (2006) Key statistics 2006: Australia's forests, forest products, consumption trade and employment. National Association of Forest Industries. Accessed 14 February 2007. <http://www.nafi.com.au/Forest_Statistics2006.pdf>.
- Pannell D, Marshall G, Barr N, Curtis A, Vanclay F and Wilkinson R (2006) Understanding and promoting adoption of conservation practices by rural landholders. *Australian Journal of Experimental Agriculture* 46(11), 1407–1424.
- Pannell DJ, Ridley A, Seymour E, Regan P and Gale G (2007) 'Regional natural resource management arrangements for Australian states: structures, legislation and relationships to government agencies (April 2007)'. CRC for Plant-based Management of Dryland Salinity, Perth. SIF3 Working Paper 0701.
- Parsons M, Frakes I and Gerrand A (2007) *Plantations and Water Use*. Bureau of Rural Sciences, Canberra.
- Pearson C, Coakes S and Aslin H (2000) Social research to support successful farm forestry. In 'Socio-economic research to support successful farm forestry'. Rural Industries Research and Development Corporation, Canberra. RIRDC Publication no. 01/13.
- Plantations 2020 (2003) Plantations for Australia: the 2020 vision. An industry/government initiative for plantation forestry in Australia. 2002 rev. edn. Accessed 4 March 2008. <<http://www.plantations2020.com.au/vision/index.html>>.
- Productivity Commission (2004) 'Impacts of native vegetation and biodiversity regulations'. Melbourne. Report no. 29.
- Prosser M (1995) An industry perspective on farm forestry. Paper presented to the Graduate Certificate in Forest Science (Farm Forestry), University of Melbourne, Melbourne.
- Reid R and Stephen P (2001) The farmer's forest: multipurpose forestry for Australian farmers. Rural Industries Research and Development Corporation, Canberra. RIRDC Publication no. R01/33.
- Reid R and Wilson G (1985) *Agroforestry in Australia and New Zealand*. Goddard & Dobson, Melbourne.
- RIRDC (1992) *Proceedings of a Workshop on Low Rainfall Agroforestry*. 30–31 August Yanchep, WA. Rural Industries Research and Development Corporation, Canberra.
- Schirmer J (2000) It's not easy being green: perceptions of the 2020 Vision for plantation forestry in Australia. In *Socio-economic Research to Support Successful Farm Forestry. Selected Papers and Abstracts from the ANU Forestry Colloquium*. 28 February 2000, Canberra. (Ed. D Race) pp. 22–39.

- Schirmer J, Parsons M, Charalambou C and Gavran M (2005) 'Socio-economic impacts of plantation forestry in the south west slopes of NSW, 1991 to 2004'. Report produced for FWPRDC Project PN04.4007. Forest and Wood Products Research and Development Corporation, Melbourne. <<http://www.affashop.gov.au/product.asp?prodid=13295>>.
- Senanayake R and Jack J (1998) *Analogue Forestry: An Introduction*. Department of Geography and Environmental Science, Monash Publications in Geography, no. 49. Monash University Press, Melbourne.
- Southern Cross Group (2006) A proposal for stewardship support to private native forests in NSW. <<http://www.privateforestry.org.au/SCG.pdf>>.
- Spencer R, Bigsby H, Campbell A, Hoare J, Jellinek L, Reid R and Senanayake R (1989) 'Consultant's report to State Plantation Impact Study, May 1989'. Report prepared for the Steering Committee by the Centre for Farm Planning and Land Management, University of Melbourne, Melbourne.
- Stephens N (2001) The contribution of farmers and individual landholders to commercial plantation development in Australia. Paper presented at *IUFRO Working Party (S6.06–03) Symposium: Forestry Extension – Assisting Forest Owner, Farmer and Stakeholder Decision-making*. 29 Oct–2 Nov 2001. <<http://www.anu.edu.au/forestry/IUFROFE2001/index.html>>.
- Stern NH (2007) 'The economics of climate change: the Stern review'. Cambridge University Press, Cambridge.
- Walker RH (2000) *The National Landcare Program: What has it Changed? A Compilation of Evaluations of the National Landcare Program, 1992–1998*. Department of Agriculture, Fisheries and Forestry, Canberra.
- Williams J and Saunders D (2002) Land use and natural ecosystems: a revolution in land use is the key to a sustainable landscape. Paper presented at *Symposium: Getting it Right: What are the Guiding Principles for Resource Management in the 21st Century?* March, Adelaide.
- Yamin F (Ed.) (2005) *Climate Change and Carbon Markets: A Handbook of Emission Reduction Mechanisms*. Earthscan, London.
- Yencken D and Wilkinson D (2000) *Resetting the Compass: Australia's Journey towards Sustainability*. CSIRO Publishing, Melbourne.

PART I

Environmental function of trees in the landscape

Agroforestry and the functional mimicry of natural ecosystems

EC Lefroy

This chapter examines the idea that agroforestry systems designed as structural and functional mimics of natural ecosystems could address the resource depletion and land degradation typical of conventional tillage agriculture. Four questions relating to this concept are examined. Is it necessary to mimic structure to achieve functional goals? Does perenniality inevitably imply a trade-off in productivity? Can competition be managed in synthetic polycultures of trees and crops? How can these complex farming systems be successfully managed to ensure a return to the farmer? It is concluded that, while natural ecosystems can serve as models for tighter cycling of water and nutrients, it is not necessary to assemble close structural mimics to achieve functional goals, and the altered soil and water conditions of most agricultural landscapes reduce the relevance of the pre-agricultural plant communities as models. Second, natural ecosystems tell us nothing about maximising harvestable product. We must turn to other strategies to ensure agroforestry systems are productive, notably artificial breeding and selection in the search for high-value products and services. Third, in mixtures of woody and herbaceous plants, competition tends to rule, particularly in the water-limited environments typical of southern Australia, and trees tend to win, requiring careful design and management of the interactions between trees and crops. Fourth, in terms of adoption and management, woody perennial systems are less flexible than conventional agriculture, have longer lag time to returns and higher investment

costs, and are less easily trialled. While these obstacles are not insurmountable, they collectively suggest that using agroforestry to mimic patch dynamics and exploit unused resources at landscape scale is more likely to achieve improved natural resource management in southern Australia than the smaller-scale approach of mimicking the structure and function of natural plant communities at paddock scale.

Introduction

The idea of looking to natural ecosystems as models for agriculture has a long and colourful history. Berry (cited in Jackson 1994) traces the history of nature as a measure or standard for agriculture back to Virgil over 2000 years ago, a theme later picked up by Spenser, Milton and Shakespeare. Alexander Pope in his *Epistle to Burlington* encouraged farmers to ‘Consult the genius of place in all’. As the environmental consequences of Australian agriculture have become more widely recognised, there has been increasing interest in consulting the *genius loci*, or spirit of this place, to understand the strategies that evolved within Australia’s native plant communities to enable them to survive on ancient leached soils in a highly variable climate. This chapter asks whether there are lessons for agroforestry in the study of native ecosystems, or whether the concept of nature as measured is best left with the Romantic poets.

Agroforestry is one of several practices to have emerged over the last 50 years in response to resource

degradation in farming systems (Table 2.1). In his book *Tree Crops: A Permanent Agriculture*, first published in 1958, Smith (1987) argued that the problem of agriculture undermining its resource base began when the agriculture of the plains was carried to the hills 8000–9000 years ago. His solution was to leave the alluvial soils of the valleys under annuals and farm the hill slopes with tree crops. Archaeological studies of the hills around Athens have revealed a sequence of settlement, erosion and abandonment, followed by deposition, then resettlement, erosion and abandonment repeated over hundreds of years. Pre-empting Smith by 2400 years, the Athenian politician Peisistratus argued for a law that made low-interest loans available to hill farmers to replace their annual crops with vines and olives. Smith's solution for the continental US was to prescribe agroforestry species suited to each climatic zone.

A common feature of the farming systems listed in Table 2.1 is that their boundary of concern has extended beyond paddock and farm to consider the wider impacts on the environment (Figure 2.1).

It is only over the last two decades that scientific inquiry in southern Australian agriculture has extended deeper than the root system of annual crops, outside the winter growing season and beyond the farm boundary. This emerging interest in ecological sustainability and the environmental impact of agriculture is neatly captured in Bawden and Srisankarajah's (1993) four phases of Australian agriculture. In the pioneering phase, the emphasis was on settlement and food self-sufficiency for the early colonies. By the turn of the 20th century, improved understanding of plant nutrition and fertilisers led to an emphasis on maximising produc-

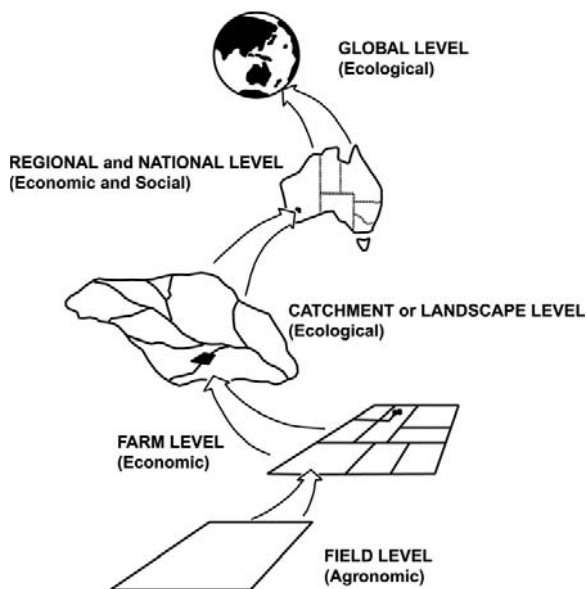


Figure 2.1: A hierarchical view of farming systems showing constraints at each scale.

tion at paddock scale. Declining terms of trade after the Second World War led to a necessary emphasis on efficiency and productivity and saw the rise of farm management groups. In the last decades of the 20th century, recognition of the threat posed by salinity, soil acidity and other land degradation issues, together with the emergence of the environmental movement and the discipline of landscape ecology, saw the boundaries of consideration and inquiry move to catchment and regional scales.

Three of the farming systems in Table 2.1 have been strongly influenced by observation of natural ecosystems. In the case of Savory (1989), observations of the grazing patterns of native African herbivores and an appreciation of the need to match grazing pressure with the phenology of pasture species (Voisin 1988) led to the development of holistic resource management. Permaculture was influenced by the recognition that perenniality and diversity were common features of natural systems (Mollison 1990), and these features were adopted as design criteria for sustainable food production. However, it is Jackson and co-workers (Jackson and Bender 1984; Jackson 1985; Jackson and Piper 1989; Jackson 1994; Jackson and Jackson 2000) who have pursued the idea of ecosystem mimicry to the greatest extent through their work since the mid 1980s, aimed at assembling high seed-yielding perennial

Table 2.1: Agricultural systems emerging over the last 50 years in response to resource depletion and degradation

Farming system	Reference
Permanent agriculture	Smith (1958, 1987)
Natural systems agriculture	Jackson (1985)
Agroforestry	Nair (1987)
Holistic resource management	Savory (1989)
Agroecology	Altieri (1990)
Permaculture	Mollison (1990)

polycultures as mimics of native grasslands. Jackson's model of sustainability was the mid-grass prairies of the Great Plains. He saw that wheat fields on sloping ground caused soil erosion beyond replacement levels and that farming them depended on fossil fuels and applications of chemicals with which humans have had no evolutionary experience. Alongside these, in comparison, were areas of never-ploughed native prairie running on sunlight, self-sufficient in nitrogen and making full use of rainfall (Jackson 1993).

Implicit in Jackson's prairie model is the assumption that the structure of natural ecosystems can serve as a guide to achieving the functional goals of sustainable agriculture, namely tighter cycling of water and nutrients and improved energy use efficiency. As the original plant communities that preceded most of southern Australia's farm lands were woodlands and heath, our model for sustainable agriculture under the mimic concept becomes agroforestry. This chapter explores four implications of the mimic concept with respect to agroforestry in southern Australia. How closely do we need to mimic structure to achieve functional goals? Does perenniality inevitably imply a trade-off in productivity? Can competition be managed in synthetic polycultures of trees and crops? How can complex farming systems be successfully managed?

Implications of the mimic concept

Mimicking structure to achieve functional goals

One of the major challenges facing agriculture in southern Australia is to tighten water and nutrient cycles. Leakage of water results in rising watertables, waterlogging and salinity. Leaching of nutrients below the root zone of annual crops and pastures results in pollution of ground and surface waters. One of the pioneering studies of the relationship between agroecosystem structure and function was the work of Jack Ewel in Costa Rica. After many years of visiting Costa Rica, Ewel observed that the rotation length of its slash-and-burn farming system was being shortened due to increased food demand. As the cycle shortened, fewer nutrients were held in the standing forest at

the time of clearing to be made available through the ash bed to subsequent crops. Yields declined, soil erosion and leaching of nutrients increased and a cycle of degradation set in, a pattern common in tropical forests around the world.

Ewel was interested in the design of a permanent agriculture as a way out of the cycle. In the mid 1970s he designed an experiment that involved taking a patch of recently cleared and burnt forest and imposing five different treatments. In the first, the natural successional processes were allowed to take place. In the second, the traditional farming practice of one or two crops of maize followed by cassava then regeneration was carried out. In the third, the land was continuously cropped. The fourth treatment was his template for a permanent agriculture: natural succession was mimicked using only exotic plants, substituting tree for tree, shrub for shrub and vine for vine with the aim of having the same representation of life forms. In the fifth treatment, natural succession was augmented with the exotic plants used in the fourth treatment. Eventually the economic potential of these exotic substitutes was to be investigated, but in the first instance it was the functional implications of tighter water and nutrient cycling that interested Ewel.

Ewel and co-workers studied the fate of water and nutrients under each of these management regimes. Their conclusion was that soil-nutrient dynamics similar to the successional vegetation could be achieved in a human-built mimic.

The implications of this finding for agroecosystem design are immense: create the structure and the nutrient retention will follow. This opens the way for substitution of species that are particularly desirable from economic, conservation or aesthetic perspectives, into complex systems (Ewel et al. 1991).

Pate and Bell (1999) applied this concept of mimicking natural ecosystems to an isolated *Bankisia* woodland community in south-western Australia, in a landscape where the original vegetation had been extensively cleared and replaced by cereal-legume crop rotations and legume-based pastures. Two consequences of this development were rising watertables and nitrate pollution of groundwater. Excavation of above- and below-ground biomass of 45 of the most common woody

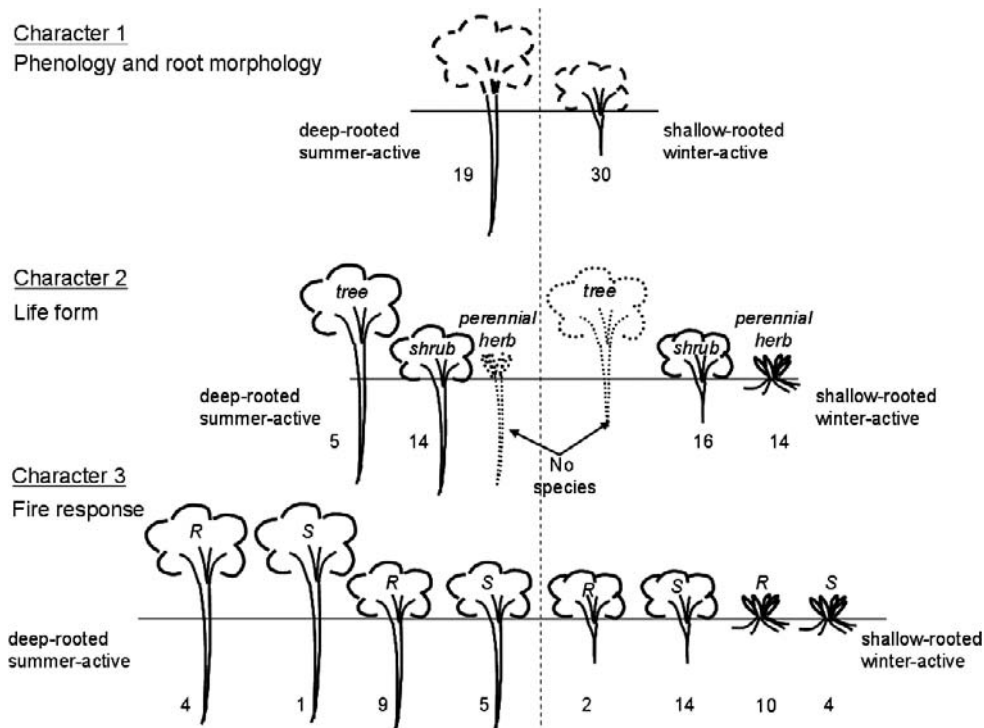


Figure 2.2: Two models for an ecosystem mimic of a *Banksia* woodland. (a) A restoration ecology model (Character 3) requiring eight plant types based on root morphology and seasonality of growth (deep-rooted summer active and shallow-rooted winter active) life form (tree and shrub) and fire response (seeders and re-sprouters). (b) A productive model requiring four plant types (Character 2). Numbers indicate species found in each class at the study site (modified from Pate and Bell 1999).

plant species, plus sampling of understorey herbaceous plants, revealed that trees accounted for 69% of the total biomass, shrubs 24%, herbaceous perennials 6.5% and herbaceous annuals less than 1%. From studies of root morphology, phenology, trophic specialisations and fire response, they developed criteria for selecting the composition of ecosystem mimics for two scenarios: a restoration ecology model where the mimic system replaces cleared virgin woodland not subject to incursions of water and nutrients from surrounding agriculture, and a production model designed to profitably rehabilitate agricultural land experiencing rising watertables and nitrate pollution. The second scenario highlights a limitation to the use of nature as model: over much of Australia's agricultural lands the initial conditions to which the native plant communities were so well-adapted no longer prevail, so an alternative model for sustainable agriculture must be used to suit the altered water and nutrient regimes.

For the first scenario (replacing cleared virgin woodland) Pate and Bell (1999) applied a four-stage species selection process based on growth phenology, root morphology, life form and fire response (Figure 2.2). The result is a minimum set of eight plant types required for a functional mimic. Adding four trophic specialisations typical of this woodland community (proteoid roots, mycorrhizal types, symbiotic nitrogen fixation, carnivorous and parasitic habit) elevates that to 32. Allowing for redundancy to compensate for establishment failure, the required number of species for a self-sustaining mimic rises to over 100.

This replacement scenario is based on a literal interpretation of structural and functional mimicry for the purposes of rehabilitation with no consideration given to productive capacity or harvest. It highlights the potential complexity of developing self-sufficient functional mimics. If we exclude fire and supply nutrients to replace those removed through harvest of commercial woody

species, we have a productive model based on a minimum of four plant types (Figure 2.2, Character 2). Here, management substitutes for diversity of form and function.

Pate and Bell (1999) effectively describe strong and weak forms of the mimic concept. The similarity of the weak version to the pre-agricultural community ends with the prescription for a predominance of summer-active, deep-rooted woody species. The differences are a need for faster growth rates to make inroads into elevated watertables, planting layouts that can achieve higher utilisation of groundwater per unit area than experienced in annual crops or native vegetation, and species capable of stripping excess nitrate and other nutrients from groundwater. Two caveats apply to these design rules. First, if woody legumes are used, when cut or grazed they typically make a greater net contribution to system nitrogen than they take up from soil and groundwater (Unkovich *et al.* 2000). Second, nutrient-stripping by deep-rooted species will only be effective if their biomass is removed from the site, for example as grain or timber.

A test of the Pate and Bell (1999) weak mimic comes from two studies at adjacent sites that examined the potential of perennial farming systems to achieve similar water balance to that of native vegetation. At an 8 ha site that had been cleared of *Banksia* woodland and farmed for 40 years, Lefroy *et al.* (2001) compared the components of the water balance in annual cropping, an alley cropping system with 20% tree cover, and a dense plantation. The tree species was the forage legume tagasaste (*Chamaecytisus proliferus* Link.) which was cut the previous year and allowed to regrow. A perched watertable had formed, rising to within 5 m of the surface and with a nitrate concentration of 1 ppm N. They found that the spaced agroforestry system was capable of significantly reducing deep drainage below the root zone of crops compared to annual cropping (32 mm and 193 mm respectively; Table 2.2, Figure 2.3). The plantation trees transpired at a rate equivalent to 2.3 times annual rainfall, resulting in uptake of 600 mm from groundwater in one year. The rapid growth of the trees meant that annual net primary productivity of the plantation was 18 t/ha⁻¹ of above-ground biomass, three to four times that of annual crops and six times that of the *Banksia* woodland (Pate and Bell 1999).

Table 2.2: The fate of rainfall under annual crop, tagasaste (*Chamaecytisus proliferus*) alley crop and tagasaste plantation (371 mm December 1997–December 1998)

	Sole crop	Alley crop	Plantation
Crop WU ^a	234	194	–
Tree WU (soil)	–	45	236
Tree WU (GW) ^b	–	122	599
Interception ^c	–	28	140
Soil water	–65	–50	0
Drainage	193	32	–604

a: Water use

b: Groundwater

c: Rainfall intercepted by the tree canopy

Source: Lefroy *et al.* (2001)

However, the heavy dependence of the tagasaste plantation on groundwater raises questions about the sustainability of that system if extensively planted. The hydrology of the area dictates that the right balance would need to be struck between the area under annuals supplying groundwater recharge, the area established to plantations and the discharge capacity of the groundwater system. The trees in the experimental plot are likely to succumb to rising groundwater, given the small scale of the plantation. This balance emphasises how far the system has been shifted from its pre-agricultural state and the limitations of the mimic concept in such altered environments. In managing water in agricultural landscapes, the boundary of consideration moves up to the catchment level, whereas the focus of the mimic concept as articulated by Jackson and Ewel has been on plant community structure at the patch or paddock scale. In this case, the higher-order constraints dominate the question of what constitutes sustainable land use.

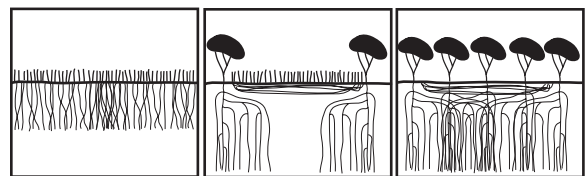


Figure 2.3: Root systems of sole crop, alley crop and plantation.

Ward *et al.* (2003) tested the effectiveness of a herbaceous perennial plant community in managing water in the same environment by comparing water budgets for the *Banksia* woodland community studied by Pate and Bell (1999) with an adjacent area of introduced pasture (*Medicago sativa* L.). In its establishment year, a one-in-50 high rainfall year for the region, drainage under the lucerne was measured at 180 mm compared to 80 mm under the *Banksia* woodland. The following year, the cumulative evapotranspiration of the lucerne was greater than that of the *Banksia* woodland, approaching that of potential ET, and the lucerne dried the soil to a depth of 4.5 m, the same extent as under the woodland.

Both lucerne and woodland plant communities effectively controlled excess water leakage, indicating that very different plant community structures and composition can be used to arrive at the same functional endpoint. The lucerne pasture, however, is wholly dependent on one species and is therefore more vulnerable to disturbance through disease, herbivory or weather extremes. The woodland features considerable redundancy through complementary patterns of growth and water use among a large number of species. Significantly, in this case a herbaceous perennial monoculture achieved the same result as a woody perennial polyculture, indicating that it is not necessary to mimic structure to be granted function, at least for water use. The test will be in the longevity and robustness of the lucerne system.

Perenniality and the trade-off between production and persistence

Developing production systems that mimic the structure and function of natural ecosystems almost inevitably implies relying on the harvest of perennial plants. This presents two significant challenges. First, it challenges the principle of biology that plants partition their resources towards reproduction or perenniality, but not both, leaving a smaller proportion of annual growth available for harvest. In water-limited environments such as the Mediterranean-type climate experienced over much of southern Australia's agricultural regions, survival over summer for most plant communities requires investment in permanent woody structure

above- and below-ground. This is necessary to access water and nutrients at depth in ancient leached soils with low water-holding capacity.

Second, it flies in the face of history as the success of agriculture for over 10 000 years has been primarily based on fitting high-yielding annual plants into short seasonal windows to avoid climatic extremes. In southern Australia, where replacement of predominantly woody ecosystems by synthetic annual grasslands has had dramatic consequences for water and nutrient cycles, the question is whether it is possible to have a permanent form of agriculture with acceptable levels of production.

A measure of the investment in structure required to persist in a Mediterranean-type climate on infertile leached soils comes from the work of Pate and Bell (1999) and Lefroy *et al.* (2001), who measured net primary productivity of a *Banksia* woodland, annual crops and pastures, and a coppiced tagasaste plantation (Figure 2.4).

Annual net primary productivity of the *Banksia* woodland amounted to only 3 t/ha⁻¹, or some 11% of the total biomass of 32 t/ha⁻¹. The harvest index of ~10% is typical of that reported for forest systems harvested annually for products such as latex or fruit (Ewel 1999). The cost of persistence is high: 64% of total biomass is invested in permanent stems and roots to ensure access to scarce water and nutrients through very deep roots and trophic specialisation. Annual crops grown on the same soil, but with additions of phosphorus and nitrogen, produced a total annual biomass of 10 t/ha⁻¹ with a harvest index of 50%, despite the fact that up to 40% of annual rainfall is typically unused and drains below the root zone. Coppiced tagasaste, by comparison, had a net annual productivity of 18 t/ha⁻¹ from an investment of 8 t/ha⁻¹ in below-ground biomass and 2 t/ha⁻¹ in above-ground biomass (the cut stump). There is a dramatic contrast between the near-climax community of the *Banksia* woodland and the relatively young tagasaste trees, cut to within 60 cm of ground level the previous year and exhibiting extremely fast growth rates as they restored root:shoot biomass ratios to pre-disturbance levels.

This comparison suggests that a strategy to minimise the trade-off between permanent structure and productivity in this environment is to keep the woody component in an active growth stage through

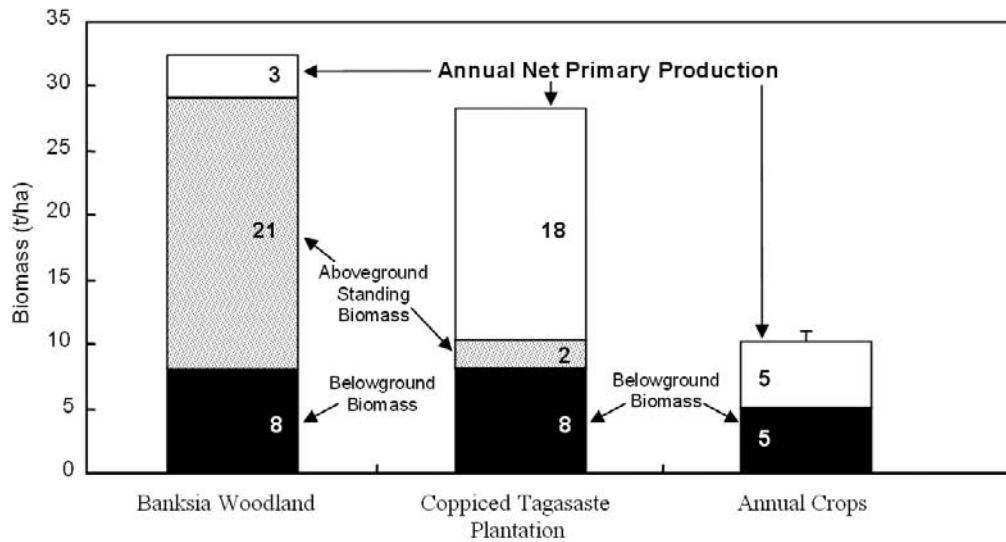


Figure 2.4: Annual net primary productivity in *Banksia* woodland, coppiced tagasaste plantation and annual crops and pastures grown on deep infertile sands near Moora, WA (based on data from Pate and Bell 1999; Lefroy *et al.* 2001).

regular disturbance. However, this has implications for competition (discussed below). Other strategies to compensate for low levels of production involve finding high-value products or markets for ecosystem services rather than physical products.

The most effective strategy, however, is domestication. Selection and breeding of fruit trees has resulted in dry matter yields comparable with those of annual crops, with average US yields in oranges, apples and pears of 2.5, 3.8 and 5.4 t/ha⁻¹ dry matter respectively (less peel and core), compared to average wheat yields of 2.5 t/ha⁻¹ (Jackson and Jackson 2000). Jackson and Jackson (2000) suggest that the differences between annual and perennial crops are neither as great nor as fundamental as they seem, and that maintaining high yield in woody perennials may present fewer challenges than in herbaceous perennials. They argue that, in both annuals and perennials, the challenge is to produce a canopy as rapidly as possible to accumulate the products of photosynthesis. In both cases, this requires meristems and start-up energy. In the annual, the meristems are the seeds in which the start-up energy is stored internally. In perennials, the meristems are the dormant buds and the start-up energy is stored in roots and shoots. In woody perennials, the number and distribution of meristems can be controlled through annual pruning; in herbaceous perennials there is

the greater challenge of maintaining the density of meristems over time.

In herbaceous perennials there is evidence that perenniality and high seed yield may not be mutually exclusive. Research on a native American grass, *Tripsacum dactyloides* (eastern gamagrass or sesame grass) showed that high seed yield (>1 t/ha) in a pistillate mutant did not compromise its perenniality (Jackson and Dewald 1994; Piper 1998). Additional evidence comes from a perennial wheat-breeding program at the University of California at Davis in the 1940s that produced intergeneric hybrids between wheat (*Triticum aestivum*) and a perennial relative, *Agropyron ponticum*. Lines bred specifically for perennial habit yielded within 70% of the best commercial wheats of their time (Suneson and Pope 1946).

In summary, while natural ecosystems can serve as useful models for tighter cycling of water and nutrients, they tell us little about maximising a harvestable product. Maximising total biomass productivity in woody perennials can be achieved through high levels of disturbance to keep stands in vegetative growth. Maximising reproductive harvest requires breeding, selection and more selective disturbance. There is encouraging evidence that the obstacles to high yield in perennials are neither as great nor as fundamental as they seem, but a major challenge is the proportion of

growth that plants must allocate for survival in water-limited environments.

Competition rules in early-stage succession

Valuable insights into competition in agroforestry have come from studies of alley farming in Africa. Alley cropping, a practice designed to reduce soil erosion and nutrient depletion in tropical and subtropical cropping systems, was widely promoted in Africa and south-east Asia in the 1980s (Kang *et al.* 1992). On adoption by farmers, however, it proved to be disappointing. Subsequent studies found that below-ground competition between trees and crops for water frequently outweighed any benefits to crops through soil fertility and microclimate, and increased the likelihood of crop failure. This finding seemed at odds with the ecological literature which reported that grassland benefited from proximity to trees. The productivity of grasses under mature savannah trees increased as rainfall decreased, with the tree canopy providing a beneficial niche for herbaceous species (Belsky 1994). This positive influence of spaced or parkland trees on understory species had also been observed in the Mediterranean Dehesa system of southern Spain and Portugal, where production of cork and acorns from widely spaced oak trees (*Quercus suber*) has been managed in conjunction with grazing by sheep, cattle and pigs for over 800 years (Joffre and Rambal 1993).

In reviewing this apparent contradiction, Ong and Leakey (1999) offered an explanation based on the different successional stages represented by young agroforestry systems and mature savannahs or open woodlands (Figure 2.5). As mature trees have a higher proportion of woody above-ground structure to foliage, more water is saved through

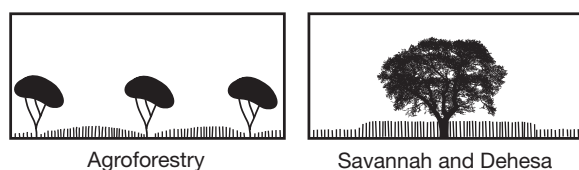


Figure 2.5: Competition rules in early-stage succession. A comparison between young agroforestry systems and mature trees in tropical savannahs (after Ong and Leakey 1999).

reduced soil evaporation under the canopy than is lost through transpiration. This leaves understory plants with better water relations than those in the open. Joffre *et al.* (1999) found that in the Dehesa system tree-induced modifications in soil properties improved the availability and uptake of water for plant growth under the canopy compared to the areas outside the canopy.

By contrast, high densities of young fast-growing trees with a high leaf:stem ratio are more likely to compete with crops for water and nutrients. Where selection of leafy species and frequent pruning are important for production, as in forage and other biomass-based agroforestry systems, competition is likely to be maintained. To achieve the advantages of mature systems requires 20–40 years, well beyond the planning horizon of most farmers (Ong and Leakey 1999).

The fundamental premise on which agroforestry is based is that trees can exploit resources unavailable to crops, resulting in an improved environment for crops and greater production per unit area than would be possible under sole cropping (Sanchez 1995). The work of Ong and Leakey (1999) and others (Cooper *et al.* 1996; Van Noordwijk and Ong 1996; Rao *et al.* 1998) in reviewing interactions in agroforestry systems has questioned this assumption, pointing out that tree and crop roots are likely to occupy similar soil zones, and that indirect benefits of trees through shelter are likely to be outweighed by competition. Ong and Leakey (1999) concluded that, in water-limited environments, below-ground competition is inevitable and crops tend to lose, with crop failure more likely in agroforestry than sole cropping in very dry years.

Clear benefits of shelter from trees have been demonstrated in cropping systems in more humid and fertile environments in the northern hemisphere (Brandle and Kort 1988). In Australia, a national study with data from four sites and multiple crops over three years, modelled using 30 years of climate data, suggested neutral to very slightly positive returns from planting windbreaks (Carberry *et al.* 2002). More positive response from shelter has been measured in grazing systems (Bird 1998).

Several strategies can be employed to overcome competition between trees and crops. One is to select tree species of equal or higher value than the

crop, to reduce the importance of competition. Another is to manage competition at the tree–crop interface through root pruning. A third is to minimise competition through careful selection of site and species. Oliver *et al.* (2005) identified several site and system characteristics that are more likely to produce positive impacts on crop yield. In a study of 21 alley cropping sites in Western Australia and New South Wales, they found that systems featuring trees more than 10 years old, established on water-gaining sites (with access to runoff or shallow groundwater), on heavier soils and with an aspect that protected crop from the south and west, were more likely to result in yield increases in adjacent crops than other combinations. However, the highly variable nature of the climate in southern Australia meant that even the most favourable combinations of site and species showed a negative response in a dry year, through competition. Other studies have found that yield response to shelter from trees is more likely with legume crops than cereals (Bicknell 1991; Nuberg *et al.* 2002).

A fourth strategy is to use temporal complementarity to avoid competition. Temporal complementarity involves selecting tree species that are dormant when the crop is growing and active when the crop is absent. This strategy will only work if there is residual water left after the crop or if rainfall occurs outside the cropping season. One of the few clear cases of temporal complementarity is the Sahelian tree *Faidherbia albida* (Poschen 1986; Ong *et al.* 1992). The use of deciduous trees in southern Australia would appear to fit this strategy, but competition in spring when crops are finishing and the trees are coming into their active phase is likely to result in competition, particularly in dry years.

A fifth strategy is to use spatial complementarity. This involves placing trees in landscape niches where resources accumulate, and avoiding direct interaction with crops. In terms of the mimic concept, this means mimicking the patch dynamics commonly observed in natural ecosystems, rather than plant community structure at the patch scale.

In summary, in water-limited environments, competition rules in tree–crop systems and the trees tend to win. While careful design of integrated systems such as alley cropping can reduce competition, using agroforestry to mimic patch dynamics and exploit unused resources at land-

scape scale is likely to be a more promising approach to achieving improved natural resource management than mimicking plant community structure at paddock scale.

Managing perenniality and competition

The first and most significant challenge to the management of agroforestry systems, regardless of their environmental benefits, is to develop forms that are sufficiently profitable to warrant the interest of farmers. Where they are profitable, natural resource management outcomes are likely to be achieved as beneficial side effects of commercial adoption. The preceding discussion highlights two main challenges to the profitability of agroforestry systems: the low levels of productivity inherent in perennial and particularly woody systems, and the effects of competition on the reliability of crop and pasture production. Identifying high-value woody species and strategies to minimise or eliminate competition are therefore high-priority areas for research and development.

Even where those conditions are met, inherent properties of agroforestry systems present challenges to their adoption and management. Compared to other agricultural innovations they are inflexible, slow to establish and produce return, difficult to try on a small scale and have high upfront costs (Pannell 1999). One of the great strengths of dryland agriculture in southern Australia has been the flexibility of mixed crop and livestock farming, and the ability to shift emphasis between enterprises and products in response to markets and climate. Agroforestry systems commit land to one form of use for long periods and thus can reduce the farmer's ability to manage variability and risk. On the other hand, they can increase capacity to manage variability and risk where they result in net benefits to crop and pasture production through improved microclimate or soil conditions (e.g. erosion or waterlogging). In general, these effects have been clearly demonstrated only in the higher-rainfall margins of Australia's agricultural regions.

The difficulty of trialling an agroforestry system presents a particular challenge, as first-hand experience is important to a farmer's decision to adopt



Figure 2.6: Agroforestry mimicking large-scale patch dynamics at landscape scale, showing a mixture of *Eucalyptus globulus* plantations, annual pasture and remnant vegetation near Albany, WA (photo by CALM).

an innovation. This is particularly so where the value of the system lies in its ability to reduce a degrading process such as salinity or soil erosion – the promise of an uncertain outcome has to be weighed up against the certainty of capital costs and opportunity costs. However, the up-front costs involved in agroforestry systems may sometimes work to their advantage. Blue gum (*Eucalyptus globulus*) agroforestry experienced impressive growth during the 1990s with over 100 000 ha established on farms in southern Australia. This was only possible through share farming schemes in which initially governments and later the private sector formed partnerships with landowners, sharing costs and risks.

Conclusion

Many of the problems of agriculture that led to the development of alternative farming systems stem from the homogenisation of the landscape (Jackson

1994). Land has been divided on the cadastral grid with any parcel treated much the same way as any other. Some parts of the landscape leak water and nutrients more than others, some are more prone to erosion. The ecosystem mimic concept is a reaction to this, that proposes a radical overhaul of farming systems and redesign at the patch scale using the structure and function of natural ecosystems as the template or model. This concept has a long history in its general form but only recent application in its specific form. That recent history has been in what Ewel refers to as a forgiving environment for agriculture (Ewel 1999), neither too cold, too dry nor too wet, and with a young substrate of deep soil left by glaciers that receded only 13 000 years ago.

This chapter examined the ecosystem mimic concept from an Australian perspective. It addressed four questions: the extent to which we need to mimic the structure of natural ecosystems to achieve the functional goals of tighter water and nutrient cycling; whether there is a trade-off

between perenniality and productivity and how might we get around it; how we manage competition in agroforestry systems; and how we could address the challenges to adoption and management of complex farming systems based on perennial, especially woody perennial, plants.

On the question of structure we saw that there are weak and strong interpretations of the mimic concept, depending on whether our goal is restoration or production, and that the altered conditions experienced in agricultural landscapes reduce the relevance of nature as model. We also saw, in the comparison between water use in lucerne and a *Banksia* woodland, that we don't need a structural analogue to achieve functional goals. On the question of productivity in perennials, we saw evidence of the substantial investment in permanent structure required to persist in water-limited environments, but also encouraging evidence of strategies to increase and maintain high levels of productivity in managed perennial systems. On the question of competition, we saw the suggestion that the complementarity sought between the woody and herbaceous components in agroforestry systems is more likely to be achieved with mature trees.

Taken together, these observations suggest that rather than attempting to mimic natural systems at the paddock or plant community scale, we should lift our boundary of consideration and examine where and how agroforestry systems can exploit unused resources at the landscape scale. Evidence of this landscape ecological view of agriculture can already be seen in practices such as farming to soil type, precision agriculture and mosaic farming, which represent a reintroduction of heterogeneity into the landscape based on an appreciation of place. This follows the spirit of Pope's advice: 'Consult the genius of place in all'. Improved natural resource management in southern Australia is more likely to come from mimicking patch dynamics at landscape scale rather than plant community structure at paddock scale.

Acknowledgements

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References

- Altieri MA (1990) *Agroecology*. Springer-Verlag, Berlin.
- Bawden RJ and Sriskandarajah N (1993) National perspectives in transition: the case of dryland salinity. In *Proceedings of a National Conference on Land Management for Dryland Salinity Control*. La Trobe University, Bendigo, Vic. (Eds JM Taylor and CA Clifton) pp. 13–17.
- Belsky AJ (1994) Influence of trees on savannah productivity: test of shade, nutrients and tree grass competition. *Ecology* **75**, 922–932.
- Bicknell D (1991) The role of trees in providing shelter and controlling erosion in the dry temperate southern agricultural area of Western Australia. In *Proceedings of A National Conference on the Role of Trees in Sustainable Agriculture*. Rural Industries Research and Development Corporation, Canberra. pp. 21–39.
- Bird PR (1998) Tree windbreaks and shelter benefits of pasture in temperate grazing systems. *Agroforestry Systems* **41**(1), 35–54.
- Carberry PS, Meike H, Poulton PL, Hargreaves JNG, Snell AJ and Sudmeyer RA (2002) Modelling crop growth and yield under the environmental changes induced by windbreaks. 2. Simulation of potential benefits at selected sites in Australia. *Australian Journal of Experimental Agriculture* **42**, 887–900.
- Cooper PJM, Leakey RRB, Rao MR and Reynolds L (1996) Agroforestry and the mitigation of land degradation in the humid and sub-humid tropics of Africa. *Experimental Agriculture* **32**, 235–290.
- Ewel JJ (1999) Natural systems as models for the design of sustainable land use. *Agroforestry Systems* **45**, 1–21.
- Ewel JJ, Mazzarino MJ and Berish CW (1991) Tropical soil fertility changes under monocultures and successional communities of different structure. *Ecological Applications* **1**, 289–302.

- Jackson W (1985) *New Roots for Agriculture*. University of Nebraska Press, Lincoln, Nebraska.
- Jackson W (1993) Meeting the expectations of the land. In *Proceedings of a Workshop: Visions for Agriculture*. (Ed. EC Lefroy). Merredin Dryland Research Institute Research Advisory Committee, Department of Agriculture, WA. Miscellaneous Publication 6/93.
- Jackson W (1994) *Becoming Native to this Place*. University of Kentucky Press, Kentucky.
- Jackson W and Bender M (1984) Investigations into perennial polyculture. In *Meeting the Expectations of the Land*. (Eds W Jackson, W Berry and B Colman) pp. 183–194. North Point Press, San Francisco.
- Jackson L and Dewald C (1994) Predicting evolutionary consequences of greater reproductive effort in *Tripsacum dactyloides*, a perennial grass. *Ecology* **75**(3), 627–641.
- Jackson W and Jackson L (2000) Developing high seed yielding perennial polycultures as a mimic of mid-grass prairie. In *Agriculture as a Mimic of Natural Ecosystems*. (Eds C Lefroy, RJ Hobbs, MH O'Connor and JS Pate) pp. 1–37. Kluwer, Dordrecht.
- Jackson W and Piper J (1989) The necessary marriage between ecology and agriculture. *Ecology* **70**, 1591–1593.
- Joffre R and Rambal R (1993) How tree cover influences water balance of Mediterranean rangelands. *Ecology* **74**, 570–582.
- Joffre R, Rambal R and Ratte JP (1999) The dehesa systems of southern Spain and Portugal as a natural ecosystem mimic. *Agroforestry Systems* **45**, 57–79.
- Kang BT, Reynolds L and Atta-Krah AN (1992) Alley farming. *Advances in Agronomy* **43**, 315–359.
- Kort J (1988) Benefits of windbreaks to field and forage crops. *Agriculture, Ecosystems & Environment* **22–23**, 165–190.
- Lefroy EC, Pate JS and Stirzaker RJ (2001) Growth, water use efficiency and adaptive features of the tree legume tagasaste (*Chamaecytisus proliferus* Link) on deep sands in south-western Australia. *Australian Journal of Agricultural Research* **52**, 221–234.
- Mollison B (1990) *Permaculture: A Practical Guide for a Sustainable Future*. Island Press, Washington DC.
- Nair PKR (1987) *Agroforestry Systems in Major Ecological Zones of the Tropics and Subtropics*. International Council for Research in Agroforestry, Nairobi.
- Nuberg IK, Mylius SJ, Edwards JM and Davey C (2002) Windbreak research in a South Australian cropping system. *Australian Journal of Experimental Agriculture* **42**, 781–795.
- Oliver YM, Lefroy EC, Stirzaker R and Davies C (2005) Deep drainage control and yield: the trade-off between trees and crops in agroforestry systems in the medium to low rainfall areas of Australia. *Australian Journal of Agricultural Research* **56**, 1011–1026.
- Ong CK and Leakey RRB (1999) Why tree–crop interactions in agroforestry seem at odds with tree–grass interactions in tropical savannahs. *Agroforestry Systems* **45**, 109–129.
- Ong CK, Odongo JCW, Marshall F and Black CR (1992) Water use of agroforestry systems in semiarid India. In *Proceedings of the International Symposium: Growth and Water Use of Plantations*. 7–11 February, Bangalore. (Eds IR Calder, LR Hall and PG Adlard) pp. 347–358. Wiley, Chichester.
- Pannell DJ (1999) Social and economic challenges in the development of complex farming systems. *Agroforestry Systems* **45**(1–3), 393–409.
- Pate JS and Bell TL (1999) Application of the ecosystem mimic concept to the species-rich Banksia woodland of Western Australia. *Agroforestry Systems* **45**, 303–341.
- Piper JK (1998) Growth and seed yield of three perennial grains within monocultures and mixed stands. *Agriculture Ecosystems & Environment* **68**(1–2), 1–11.
- Poschen P (1986) An evaluation of the *Acacia albida*-based agroforestry practices in the Hararge highlands of eastern Ethiopia. *Agroforestry Systems* **4**, 31–56.
- Rao MR, Nair PK and Ong CK (1998) Biophysical interactions in tropical agroforestry systems. *Agroforestry Systems* **38**, 3–49.
- Sanchez PA (1995) Science in agroforestry. *Agroforestry Systems* **30**, 5–55.
- Savory A (1989) *Holistic Resource Management*. Island Press, Washington DC.
- Smith JR (1987) *Tree Crops: A Permanent Agriculture*. Island Press, Washington DC.

- Suneson CA and Pope WK (1946) Progress with *Triticum x Agropyron* crosses in California. *Journal of the American Society of Agronomy* **38**, 956–963.
- Unkovich MJ, Pate JS, Lefroy EC and Arthur DJ (2000) Nitrogen isotope fractionation in the fodder tree legume tagasaste (*Chamaecytisus proliferus*) and assessment of N₂ fixation inputs in deep sandy soils of Western Australia. *Australian Journal of Plant Physiology* **27**(10), 921–929.
- Van Noordwijk M and Ong CK (1996) Lateral resource flow and capture: the key to scaling up agroforestry results. *Agroforestry Today* **7**, 29–31.
- Voisin A (1988) *Grass Productivity*. Island Press, Washington DC.
- Ward PR, Fillery IRP, Maharaj EA and Dunin FX (2003) Water budgets and nutrients in a native *Banksia* woodland and an adjacent *Medicago sativa* pasture. *Plant and Soil* **257**, 305–319.

Using trees to manage local and regional water balances

Keith Smettem and Richard Harper

In this chapter we review some of the key aspects to consider when planning revegetation strategies that use trees to manage local and regional water balances. We commence by reviewing how trees use water and how they respond to environmental conditions, including drought, waterlogging and salinity. Understanding these responses are critical when selecting suitable species for managing the water balance in specific landscape locations.

After providing definitions of typical groundwater systems we introduce the principle of ecological optimality and use this to explore available design options to manage the water balance using trees in dryland catchments (typically, 300–600 mm mean annual rainfall).

We conclude that the prospects for lowering watertables by revegetation with perennial vegetation would appear to be best in local groundwater systems, or where annual rates of groundwater inflow are considerably less than annual transpiration losses.

Introduction

Across much of the cropping region of Australia clearing of predominantly perennial, deep-rooted native vegetation and replacement by shallow-rooted annual crops and pastures has resulted in a changed hydrological regime, with decreased transpiration leading to increased runoff and increased recharge to groundwater systems (Hatton and Nulsen 1999). In consequence, groundwater systems are rising,

mobilising regolith salt stores and leading to secondary dryland salinity on a massive scale (Beresford *et al.* 2001; Bari and Smettem 2006a). Controlling the spread of dryland salinity requires hydrologically appropriate management systems to be developed and implemented by farmers and government (George *et al.* 1999).

To achieve a land use system with a water use more in balance with the pre-clearing scenario requires a significant enhancement of transpiration via the introduction of deep-rooted perennial species, and/or a significant enhancement of groundwater discharge via engineering options such as drainage and pumping.

There is ongoing debate over how much area needs to be replanted in order to restore the original water balance, or even if such restoration is appropriate. Figure 3.1 is a conceptual attempt to define where different perennial systems could be deployed in the landscape to manage salinity. Where annual rainfall exceeds 600 mm and lateral flow within the soil profile is reliable, it is possible to consider plantation forestry and hillslope belts that intercept and use lateral throughflow. As rainfall becomes more limited, alternate methods of deploying woody perennials are required. Two systems have been proposed: woodlot rotations and alley plantings. Both systems are described in detail in this chapter, with an emphasis on the key scientific questions that face land managers in the development and implementation of revegetation strategies. High-watertable plantings are discussed elsewhere in this book.

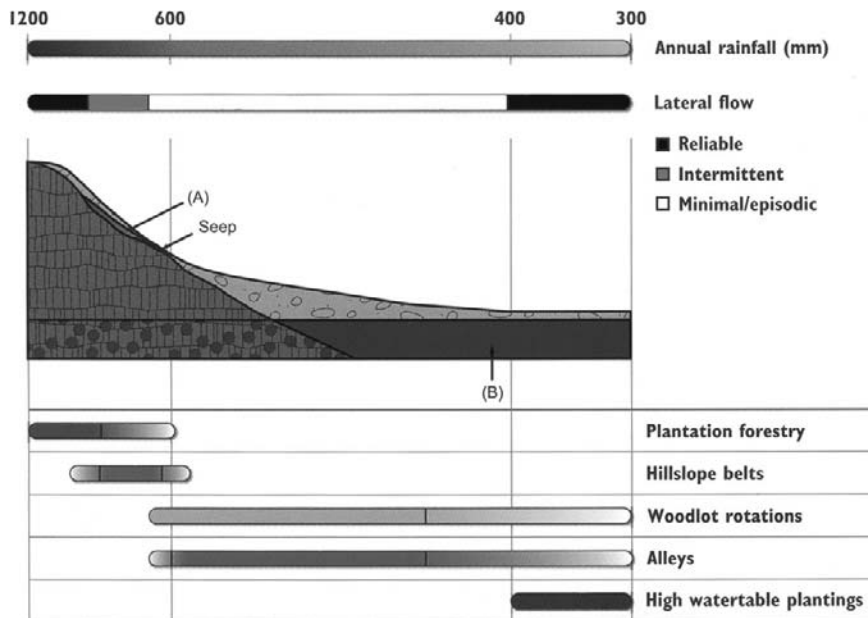


Figure 3.1: A hypothetical catchment depicting steep wetter uplands at the extreme left through to flat plains on the right. The bars above the diagram show the rainfall gradient and the zones where movement to trees is important. The bars below the diagram show the zones in the catchment suited to five different agroforestry strategies (used with permission, Stirzaker and Vertessy 2002).

How trees use water

A hydrophysiological overview

Water flow through plants is generally considered to be a passive process in all but the tallest trees. Flow is driven by differences in water pressure. Surface tension at the evaporating leaf surface lowers the water pressure on the leaf surface and causes water to flow up from the roots.

Appearing among the epidermal cells of the leaf are stomatal pores that open to the leaf interior. The size of the stomatal opening directly affects the rate of diffusion of water vapour and carbon dioxide across the leaf surface. Guard cells that respond to prevailing environmental conditions (light intensity, temperature, wind, leaf water potential) can control the size and shape of the stomatal opening and thus regulate the rate of water vapour and carbon dioxide exchange (Gates 1980). When the stomata are closed the only source of transpiration is by diffusion through the leaf cuticle. This accounts for approximately 10% of the total transpiration.

When soils are dry, the root system is unable to extract water fast enough to keep up with evapora-

tive demand so the stomata usually remain closed or only partially open in order to regulate evaporative loss. Interestingly, some tree species, such as *Eucalyptus grandis*, also close their stomata in response to dry air conditions. This can occur even if they are irrigated and their roots have more than adequate water supplies.

In the soil–plant–atmosphere continuum concept, the flow of water through the plant is often described using an analogue to Ohm’s law in electricity. Water is viewed as analogous to an electrical current and hydraulic conductance as analogous to electrical conductance. Resistances to flow are encountered along the water flow pathway from the soil to the evaporating surface (Figure 3.2). The first resistance is at the soil–root interface where there is a gradient in chemical-energy potential from the soil into the roots. As the soil dries, the rate of water uptake by the roots can become soil-controlled – it becomes increasingly related to the unsaturated hydraulic conductivity of the soil, which becomes progressively less as the soil dries. Water then encounters a resistance within the roots as it moves through the fine root system towards the xylem vessels. Water in the xylem vessels

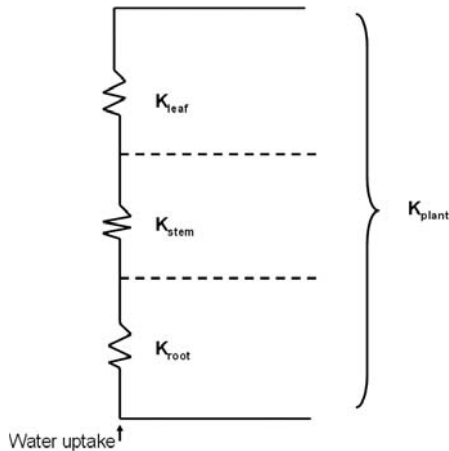


Figure 3.2: Simple Ohm's law analogy of conductance in series. The total conductance (K_{plant}) results from the conductance of the root, stem and leaves. Water flow is driven by the difference in water potential, which is lower at the leaf surface than at the root–soil interface.

responds to water potential and therefore moves up the stems into the leaves. Water must pass through mesophyll cells into the stomatal cavities whereby it is evaporated (either in the stomata or on the leaf surface) into the atmosphere.

Importantly, this analogy to Ohm's law leads to two significant predictions. First, the driving force of sap ascent is a continuous decrease in internal plant water pressure in the direction of sap flow. Second, the evaporative flux density from the leaves is proportional to the negative pressure gradient at any given cross-section along the transpiration stream. At any given point of a root, stem, leaf or vein we have (Tyree 1999):

$$-dP_x/dx = AE/K_h + \rho g dh/dx \quad (\text{Eqn 1})$$

where A is the leaf area supplied by a stem segment with hydraulic conductivity, K_h , and $\rho g dh/dx$ is the gravitational potential gradient, where ρ is the density of water, g is acceleration due to gravity, h is the vertical distance and x is the actual distance travelled by water in the stream segment.

Responses to drought

Under drought conditions trees clearly use less water than when it is readily available; this affects productivity and the potential survival of perennial species. Land managers therefore need to understand how species respond to drought in

order to make informed decisions when selecting woody perennials for salinity control.

The concept of 'wilting point' implies that when the leaf water potential, ψ_l , falls during drought a 'turgor loss point' is reached (turgor pressure falls to zero) and the leaf loses its shape, or 'wilts'. If cavitation (air entry) occurs in the xylem vessels then death usually results. Many perennial species maintain leaf shape through rigid leaf fibre cells, so wilting point is equated to the turgor loss point.

Many native plants growing in regions with seasonal rainfall patterns appear to be drought evaders, while others are drought tolerators. One evasion strategy is for a plant to be deciduous, another is to have deep roots and a highly conductive hydraulic system. On the other hand, drought tolerators can withstand highly negative internal pressures by having a vascular system resistant to cavitation that would otherwise block the passage of water. Such species can be shallow-rooted or grow in saline environments.

Responses to waterlogging

Plants can also experience dehydration if soils become saturated and oxygen diffusion to roots is too low to support metabolic activity, thereby diminishing their ability to conduct water (Kramer and Bouyer 1995). Feng *et al.* (2003) showed that at water contents around $0.3 \text{ cm}^3/\text{cm}^3$ in sands and sandy loams and $0.34 \text{ cm}^3/\text{cm}^3$ in non-swelling clays, the rate of oxygen diffusion drops considerably, to below a threshold value of $0.2 \mu\text{g}/\text{cm}^2/\text{min}^{-1}$. At this threshold, many agricultural plant species fail to grow (Lety and Stolzy 1967). This is an important consideration in the Australian agricultural landscape, where salinity and waterlogging often occur in the same landscape locations. Waterlogging-tolerant plants usually have morphological adaptations in the roots that involve root thickening with an increase in porosity, thereby increasing the rate of oxygen diffusion to root tips.

Modelling the root water uptake response

Modelling water movement between soil and plant roots requires some quantitative description of root water uptake from the soil. Direct measurement of this uptake is extremely difficult and it is commonly incorporated into a sink term in the governing flow equation (Simunek *et al.* 1996).

The sink term usually varies as a function of the distribution of root density with depth (Landsberg 1989). A macroscopic sink term, depending only on soil water pressure head, was defined by Feddes *et al.* (1978):

$$S = \alpha(h)S_{\max} \quad (\text{Eqn 2})$$

where S_{\max} is the non-limiting water uptake and $\alpha(h)$ is a dimensionless function of soil water pressure head.

Conceptually, the Feddes *et al.* (1978) model captures the water stress response of plants over the entire water potential range for saturation to wilting point (Figure 3.3). The response function in Figure 3.3 is characterised by five points that can be plant-specific. These points include:

- the soil water potential at which plant roots first begin to function (h_1);
- the points between which soil moisture is non-limiting and transpiration is controlled by atmospheric demand (h_2 and h_3);
- a segment after h_3 where root water uptake diminishes rapidly to h_3L ;
- a more gradual decline in root water uptake to the point where root water uptake ceases due to insufficient soil supply (h_4).

In practice, h_3L is often ignored due to insufficient data and a straight line from h_3 to h_4 is assumed (as shown in Figure 3.3). The Feddes model has been applied widely to agricultural crops and soils, including barley (Al-Khafaf *et al.* 1989) and potatoes (Belmans *et al.* 1982), but it has not been applied specifically to Australian native species.

Although other models of root water uptake exist (e.g. van Genuchten 1987), they do not depict the decrease in root water uptake due to oxygen limitations in the near-saturated range (between h_1 and h_2).

Combined effects of waterlogging and salinity on plant water use

Most salt stress and water stress studies have been carried out separately and a large amount of data are available for only one of these stresses. Generally, the so-called multiplicativity concept is applied to the joint water and salt stress. This is based upon the product of the separate reduction terms for soil water osmotic heads (h_o) and the soil

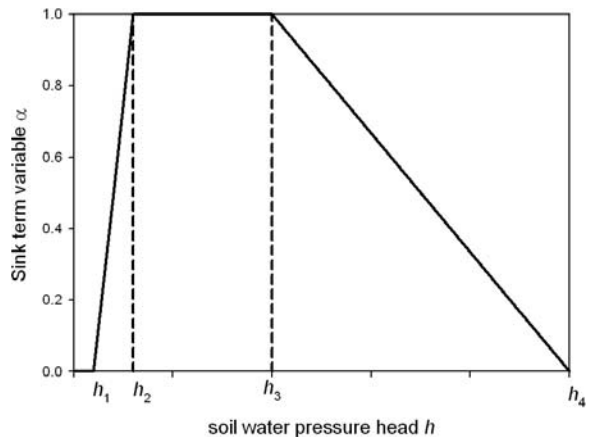


Figure 3.3: Transpiration sink term variable, α , versus soil water pressure head, h , for the Feddes model. Root uptake commences at h_1 , uptake is non-limiting between h_2 and h_3 and ceases at h_4 .

water pressure heads (h), as introduced by van Genuchten (1987).

Homaee *et al.* (2002) present and discuss three categories of reduction function: additive, multiplicative and the conceptual combined method. After encountering limitations with both the additive and multiplicative reduction functions, Homaee (1999) combined the reduction functions of Feddes *et al.* (1978) with that of Maas and Hoffman (1977) and proposed a combined reduction function:

$$\alpha(h, h_o) = \frac{h - (h_4 - h_o)}{h_3 - (h_4 - h_o)} x \left[1 - \frac{\alpha}{360} (h_o^* - h_o) \right] \quad (\text{Eqn 3})$$

where h is the soil water pressure head, h_o is the osmotic head, h_o^* is the osmotic threshold, h_3 is the soil water pressure head threshold value, h_4 is the soil water pressure head at wilting and the value 360 converts the salinity-based slope to osmotic head in cm (US Salinity Laboratory Staff 1954).

This equation is valid for $h_o \leq h_o^*$ and $(h_4 - h_o) \leq h \leq h_3$. Each dS/m salinity beyond the threshold value (EC^*) shifts the wilting point 360 cm to the left. This is a first approximation based on USDA Handbook 60 to transfer soil salinity to osmotic head. The model also differs conceptually from the additive and multiplicative models in that it assumes that the reduction function of Maas and Hoffman (1977) can be employed directly in the non-stress part of the Feddes *et al.* (1978) model.

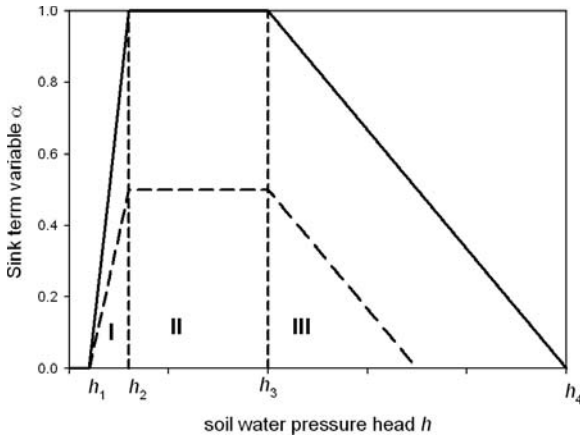


Figure 3.4: Illustrative effect of waterlogging and salinity on the sink term variable, α . The dotted line shows a reduction due to waterlogging in region I, and salinity reductions in regions II and III. The absolute amount of reduction (and the position of h_4) depends on species and salinity concentration.

An example of the concept is shown in Figure 3.4. It is important that plant water uptake (and hence transpiration) reduces as α decreases. Therefore, salinity can magnify the reduction in plant water uptake due to waterlogging in region I (Figure 3.4), may reduce the non-limiting (in the absence of salinity) uptake in region II and reduce the uptake in region III as well as shift the wilting point to the left. Thorburn (1997) has shown that where watertable reductions have occurred, trees accumulate salt in the root zone which reduces their water uptake and therefore lessens their ability to sustain reductions in watertable levels.

Salting out

In irrigated agriculture, the concept of a ‘leaching fraction’ is well understood: basically, a certain proportion of irrigated water must pass below the plant root zone to drains in order to prevent salt build-up in the root zone.

Because roots exclude almost all the salt at the root surface during transpiration, the root zone salt concentration can increase through time if leaching is absent. Ultimately, a point may be reached where the plant can no longer extract water. This point may be confounded by waterlogging, but if we consider only the case of water use by a belt of trees from the capillary fringe above a watertable, then the time required for the capillary

fringe to reach a salt concentration after which the trees can no longer extract water from it is approximated by (Stirzaker *et al.* 1999):

$$t_m = \frac{l\bar{\theta}}{E} \left(\frac{C_m}{C_o} - 1 \right) \quad (\text{eqn 4})$$

where t_m is the time in years to reach the maximum concentration, C_m (dS m^{-1}), C_o is the salt concentration in the groundwater (dS/m^{-1}), E is the water use of the tree from the capillary fringe (mm/yr^{-1}), l (mm) is the height of the capillary fringe above the the watertable where salt can be stored and $\bar{\theta}$ is the average water content of the capillary fringe ($\text{cm}^3/\text{cm}^{-3}$).

Stirzaker *et al.* (1999) do not report on values of C_m for native vegetation. The actual levels of salinity that can be tolerated depend on tree species and soil factors, and are still poorly known. Morris and Thompson (1983) conservatively estimate a tolerance threshold to be in the range of 1.4–2.2 dS/m^{-1} . George (1990) reported salinity levels up to 1.7 dS/m^{-1} in a growing plantation on a sandplain seep and Schofield *et al.* (1989) showed that watertables were lowered by eucalypts where the groundwater salinities were less than half seawater (2 dS/m^{-1}).

If we assume a C_m of 2. dS/m^{-1} then scenarios for typical soil and water use conditions in the 300–600 mm rainfall zone of southern Australia suggest that plantations could be salted out before they reach 10 years of age unless there is some periodic flushing of the capillary fringe by above-average rainfall.

Functionality of root architecture

Eucalypt roots have been reported to extend up to 20 m from the trunk of individual trees (Zohar 1985). At this extent, a regularly distributed density of 6 stems/ha would allow the outer edges of the root circles of adjacent trees to be contiguous if the trees are distributed in a regular pattern (Stirzaker *et al.* 1999). The implication is that a contiguous distribution of tree roots will effectively reduce groundwater recharge to near zero.

However, the primary factor affecting the pattern of water extraction by plants from soils is the rooting depth. Many tree species have dimorphic root systems, with a relatively high density of roots in the topsoil and a sparser network of sinker roots (Dawson and Pate 1996). Although the root density is considerably higher in the topsoil, during the dry

summer period in the Mediterranean climatic zone the topsoil can develop much lower water potentials than the leaves of the trees, yet tree water use is higher than during the winter period of low daily evaporation. The water use must therefore be supplied from deeper in the soil profile (Silberstein *et al.* 2002).

The absolute depth to which tree roots extend depends on species, location and soil conditions. The roots of jarrah (*Eucalyptus marginata*) have been found as deep as 40 m (Dell *et al.* 1983) and longleaf pine to 10 m (Kramer, 1983). Recent work has shown that water extraction by replanted eucalyptus species can reach 6–8 m within three years (Sochacki *et al.* 2006).

In native ecosystems, deeply rooted species may also provide water for shallower-rooted understorey species via hydraulic lift (Richards and Caldwell 1987). By this process, water is transported from deep roots (in contact with moist soil) to shallow roots overnight. Because the soil around the shallow roots has a greater potential than the deep roots, some rehydration of the soil occurs around the shallow roots. The use of this water by understorey species is parasitic (Dawson 1993) and a loss to the deep-rooted species.

Having reviewed some of the physiological and environmental controls on water uptake by perennial vegetation, we now turn to defining the different groundwater systems that require recharge control. The definitions are largely taken from Hatton *et al.* (2002) and provide a general framework.

Groundwater flow systems

Definitions of local, intermediate and regional scale systems

Local systems

Local groundwater flow systems respond rapidly to increased groundwater recharge. Watertables rise rapidly and saline discharge typically occurs within 30–50 years of clearing of native vegetation for agricultural development. Bari and Smettem (2006a) show an 18 m rise in groundwater over 20 years in a partially cleared local scale catchment, followed by a significant increase in stream salinity (from fresh to saline) when the groundwater inter-

sected the stream invert and changed the character of the annual stream flow from intermittent to perennial (Bari and Smettem 2006b).

Local systems can also respond relatively rapidly to salinity management practices, and afford opportunities to mitigate salinity at a farm scale. Typically, local systems have a horizontal scale of 1–3 km. Further subdivision into high and low discharge capacity local systems is possible. High discharge capacity systems are typically characterised by hillside seeps above relatively impermeable bedrock or local groundwater systems flowing through highly permeable colluvial sediments. Mostly, such systems are relatively fresh and highly transmissive and respond to revegetation.

Low discharge capacity systems are more problematic to treat. They are generally confined and characterised by some form of impedance to flow such as a bedrock high, change of slope, change to lower hydraulic conductivity material or presence of a dyke, to name but a few. Salinity is usually high in such systems; salt stores in the regolith can also be high and become mobilised as groundwater rises.

Intermediate systems

Intermediate groundwater flow systems have a greater storage capacity and generally higher permeability than local systems. Horizontal scales of intermediate systems are of the order 5–10 km and are usually associated with alluvial (or lacustrine) fill in foothills and valleys. They take longer to ‘fill’ following increased recharge. Increased discharge typically occurs within 50–100 years of clearing of native vegetation for agriculture. The extent and responsiveness of these groundwater systems present much greater challenges for dryland salinity management than do local groundwater flow systems.

Hatton *et al.* (2002) recognise three forms of intermediate systems:

- typical broad valley systems characterised by discharge into low-lying areas as a result of reductions in transmissivity. Such systems are widespread in Western Australia and South Australia but in New South Wales are restricted to the Permian-recent sediments such as Yarraman Creek and Lake Goran. The Lockyer valley in Queensland is this type (Hatton *et al.* 2002);

- discharge from confined or semi-confined aquifers at low points in the landscape, generally as a result of downstream reductions in transmissivity. This type of system is common in paleodrainage lines; systems associated with a linear zone of high transmissivity that cuts across a number of surface catchments and is recharged primarily by local recharge.

Regional systems

Regional groundwater flow systems have a large storage capacity and permeability. Horizontal scales exceed 50 km and they take much longer to develop increased groundwater discharge than local or intermediate flow systems – probably more than 100 years after clearing the native vegetation. The full extent of change may take thousands of years. The scale of regional systems is such that farm-based catchment management options are ineffective in re-establishing an acceptable water balance. These systems will require widespread community action and major land use change to secure improvements to water balance. In Western Australia, the North Sterling basin has been identified as a regional system, with groundwater discharge occurring from the deeper aquifer into superficial aquifers that evaporate at the soil surface (Hatton *et al.* 2002). In eastern Australia, the catchments of the Riverine Plains are of this type, as are the Cooke Plains in South Australia.

Transient shallow (perched) systems

Ephemeral ‘perched’ aquifers can occur above a major aquifer system at the interface between materials of contrasting texture and at a hillslope scale. They are typically shallow, small in extent and often fresh (George *et al.* 1997).

Typically, perched systems can be found in association with duplex (texture contrast) soils (George and Conacher 1993; White *et al.* 2000), or where surface soils have well-developed macrostructure that permits preferential flow to occur at the soil–bedrock interface.

Because perched groundwater flow (through-flow) is generally fresh, in some locations it can provide a major source of water (but not salt) to saline seeps (George and Conacher 1993) and provide dilution flows to rivers. Perched watertables can also provide rapid recharge to underlying

permanent groundwater systems via preferential flow (Williamson 1973; Dunin 2002).

Interactions between trees and runoff

In some catchments, understanding the interactions between trees and runoff is critical for environmentally sustainable management. This is particularly so if maintenance of freshwater flows is required for ecological functioning in rivers, or if safe groundwater abstraction rates are to be determined. Physically based catchment hydrologic models can provide insights into the potential effects of proposed replanting strategies within catchments, but need to be coupled with detailed site appraisal for planning salinity management strategies. The details of such models are beyond the scope of this chapter; different types of hydrologic models used for this purpose have been compared by Beverly *et al.* (2005).

Ecological optimality and the groundwater balance

The concept of ecological optimality (Eagleson and Tellers 1982) suggests that the canopy size of natural vegetation adjusts to maximise relative mean soil water concentration. Specht (1979) and Specht and Specht (1989) present empirical evidence supporting this concept for Australian conditions. From a synoptic perspective, the hydrologic implication is that in the <600 mm precipitation zone in western and southern Australia tree growth is water-limited and annual evapotranspiration by the native forest does not exceed precipitation, so actual evapotranspiration (including interception) is equal to rainfall minus runoff. Under these conditions, groundwater recharge is small because the native vegetation uses practically all the water it receives.

For groundwater to rise, the recharge must exceed groundwater discharge. As the groundwater begins to rise, the aquifer cross-section increases so groundwater discharge can also increase. However, even if aquifer hydraulic conductivity is high, the hydraulic gradients of catchments in the agricultural regions of western and southern Australia are generally very small (1/1000 or less. In Western Australia many aquifer discharge lines are impeded by dykes (Engel *et al.* 1987), bedrock highs or changes in aquifer thickness along the flow path. Without *a priori*

knowledge about the aquifer, it is necessary to start from a worst-case scenario and assume that groundwater discharge is effectively zero.

At a regional scale, re-establishing the conditions that would favour a return to the pre-clearing hydrologic equilibrium requires long-term adjustment of the vegetation to equal the original evapotranspiration of the native vegetation over the catchment. The current long-term annual crop or pasture evapotranspiration is somewhat less. We denote this as E_c (mm/yr) and note that it includes interception losses.

Assuming that runoff is negligible, we can write:

$$E_c = P - DP_{(\text{crop})} \quad (\text{Eqn 5})$$

where $DP_{(\text{crop})}$ is the deep percolation below the root zone (potential recharge). Equation 5 is a simple approximation because it assumes that all deep percolation is groundwater recharge, which may not always be the case on sloping ground where lateral throughflow can contribute to runoff rather than recharge. We shall return to this point later.

If catchment runoff is known, we can adjust Equation 5:

$$E_c = aP - DP_{(\text{crop})} \quad (\text{Eqn 6})$$

where a is the fraction of mean annual precipitation that does not run off.

Although a may decrease after clearing (runoff increases), as a fraction of mean annual precipitation the magnitude of the change is small in the <600 mm precipitation zone of western and southern Australia, although infrequent high-magnitude events appear more common after clearing for agriculture (McFarlane *et al.* 1992).

If concern is only to stop recharge (watertable height remains at present level for the zero discharge case) then it is necessary to impose a total evapotranspiration, E_{total} , that equals $E_c + DP$ over the region. If the regional annual groundwater discharge occurs at a known rate then we would have:

$$E_c = aP - DP - GW_{\text{discharge}} \quad (\text{Eqn 7})$$

where $GW_{\text{discharge}}$ is expressed in mm/yr.

Clearly, if the replanted perennial vegetation utilised only precipitation to meet the evaporative demand then the entire catchment would need to be revegetated. The evapotranspiration of the

replanted vegetation must therefore exceed precipitation if any of the catchment is to remain in an annual agricultural production system.

Optimality principles and dryland salinity management

For management of dryland salinity, it is relevant to ask how much cleared area needs to be replanted and how much water must the perennial system transpire if recharge is to be returned to pre-clearing levels. In some cases pre-clearing recharge may not be the target, but the same principles can be used to design other specified recharge targets (e.g. 50% reduction in recharge).

Experimental evidence shows that, when supplied with sufficient water, trees and herbaceous perennials can transpire greatly in excess of mean annual precipitation (Greenwood and Beresford 1979; Holmes 1960; Schofield *et al.* 1989). However, in the low advective environments characteristic of Australian cropping regions, increased evapotranspiration requires the perennial vegetation to access water sources in addition to incident precipitation. Before exploring the possibilities by which this can be achieved, we review an analysis of the area of land and evapotranspiration required for block plantings to return average recharge to pre-clearing levels.

Estimation of area required for block plantings to control recharge

Denoting the new tree evapotranspiration as E_{new} , the proportion of the total area, A , required to give E_{total} is:

$$E_{\text{total}} = AE_{\text{new}} + (1 - A)E_c \quad (\text{Eqn 8})$$

Introducing Equation 8 in to Equation 5 gives:

$$A = DP_{(\text{crop})} / (E_{\text{new}} - E_c) \quad (\text{Eqn 9})$$

Near-identical solutions to Equation 8 were derived by Peck (1976), Sedgley *et al.* (1981), Stewart (1984) and Stirzaker *et al.* (2002). Schofield (1990) also separated the areas of seep and residual native vegetation in a catchment, but if the area of seep is small and the residual native forest is assumed to transpire net precipitation, then Equation 8 still applies to the remaining area. There may be some justification for separating catchment areas on the basis of differences in deep drainage between major soil types if such information is

available (Pracilio *et al.* 2003). The deep drainage term in Equation 8 can also be expressed as the difference between the evapotranspiration of the original native vegetation and the evapotranspiration from the cleared cropping system. Schofield (1990) therefore did not need to determine DP in order to obtain estimates from Equation 8.

It is important to note that Equations 8 and 9 are steady-state solutions and do not give insight into the source of additional water. During the period immediately after establishment, perennials can effectively mine the increased soil water store beyond the reach of the annual root system and the recharge reduction is therefore directly proportional to the area replanted even though evapotranspiration exceeds that of the annual cropping system. This has an important practical implication, in that it suggests that early biomass gains through enhanced transpiration may not be sustainable after the soil moisture reserve is depleted and the plants rely solely on annual rainfall.

In order to calculate the block planting area in Equation 9 it must therefore be assumed that, for the level ground case, evapotranspiration in excess of annual rainfall is derived solely from groundwater uptake and not by adjustment to the soil water store.

An analysis of all existing experimental data where DP had been measured in Western Australia has been reported by Smettem (1998) and Hatton and George (2001). The resulting log-normal regression relation between annual agricultural systems and mean precipitation is given by:

$$DP = 7.86e^{0.0025P} \quad r^2 = 0.87; \quad n = 25 \quad \text{(Eqn 10)}$$

From this equation, the predicted long-term average for DP under annual systems across the wheatbelt of Western Australia only varies from 17 mm at the 300 mm rainfall isohyet to 27 mm at the 600 mm isohyet. The spatial pattern of DP across the Western Australian cropping region is shown in Figure 3.5, together with measures of DP under native vegetation.

Figure 3.5 also compares the data trend line from Equation 10 with the trend line for deep percolation below deep sandy soils obtained using the bucket-type AgET water balance model (Argent

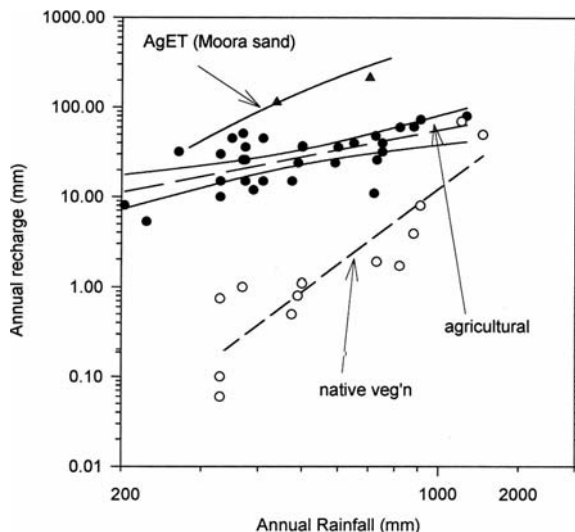


Figure 3.5: Summary of deep drainage measurements for south-west Western Australia with regression lines showing the strong relation with annual rainfall. Also shown are data (triangles) and a polynomial model fit to deep drainage estimates obtained from water balance simulations for a deep sand under wheat, using AgET. Cropping region lies between 300 mm and 600 mm mean annual rainfall.

and George 1997). This deep sand trend line was obtained by fitting a first-order polynomial ($r^2 = 0.99$) to predicted annual DP data using precipitation and pan evaporation data from Moora, WA, over 40 years of simulation with root growth parameters for wheat and monthly crop factors.

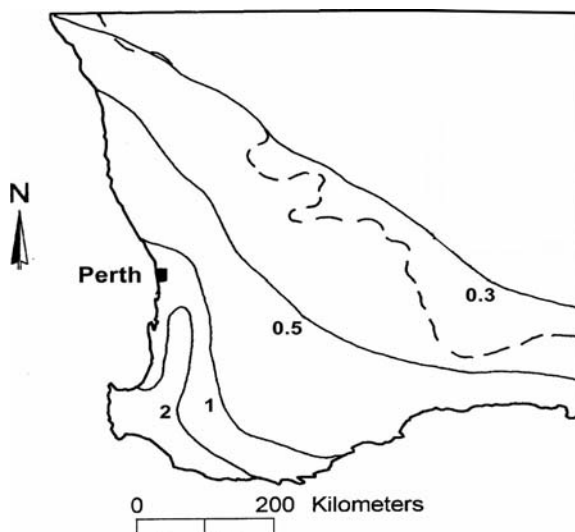


Figure 3.6: Predicted mean annual LAI for south-west Australia. Hatched line is 300 mm rainfall isohyet.

Soil water storage and hydraulic conductivity were measured at the Moora field site and reported by Anderson *et al.* (1998). Anderson *et al.* (1998) reported 114 mm DP for an annual precipitation of 438 mm on a deep sand. This is the most extreme example of deep percolation reported in the literature for the <600 mm precipitation zone. However, it appears reasonable for sandy soils, based on modelling work by Sedgley *et al.* (1981), more recent work by Asseng *et al.* (1998) using the APSIM model and work reported here using AgET. Additional measured recharge data (Sharma *et al.* 1985) for sandy soils in a higher precipitation zone on the Swan Coastal Plain is also included in Figure 3.6 and is consistent with the trend line.

We can now obtain $E_{\text{new}} (>E_c)$ for any value of A by rearranging Equation 9:

$$E_{\text{new}} = E_c + (DP_{(\text{crop})}/A) \quad (\text{Eqn 11})$$

Using Equation 10 to obtain $DP_{(\text{crop})}$ and Equation 7 to obtain E_c (under the assumption of no groundwater discharge and no runoff), it follows that average range of E_c across the Western Australian wheatbelt between 300 and 600 mm mean annual precipitation will be approximately: $300 - 17 = 283$ mm/yr and $600 - 27 = 573$ mm/yr.

Values of E_{new} (Equation 11) for different values of A at 300 mm and 600 mm mean annual precipitation are presented in Table 3.1.

Table 3.1 shows that, to be effective at achieving balanced water use, the replanted perennial vegetation must obtain more water than is provided by mean annual precipitation. There are four possible management strategies by which this can be achieved:

- use of stored soil water;
- direct use of groundwater;
- increasing the root area to canopy area ratio by strategic configuration of tree belts;
- bringing excess water to the trees by redirecting surface runoff or capturing downslope perched water flow.

Each of these options will now be examined.

Use of stored water by perennials

Most evidence suggests that it is well within the range of eucalypts and pines to transpire the E_{new} totals (Table 3.1) in the high evaporative environments of western and southern Australia, but how

Table 3.1: Estimation of E_{new} required to prevent deep drainage for various area fractions, A, of catchment revegetation with perennials across the WA wheatbelt between 300 and 600 mm mean annual precipitation

Area of catchment under perennial vegetation (A)	Mean annual precipitation (mm)	
	300	600
	E _{new} (mm/yr)	
0.2	368	708
0.4	325	640
0.6	311	618

long can the additional demand be met by stored water?

The answer primarily depends on root depth and plant available water over that root depth. For example, if a tree block replaces pasture that had roots to 0.5 m and the tree roots extend to 5 m depth, typical total plant available water values for 4.5 m depth (0.5–5 m) are sands 270 mm, deep gravels 180 mm, loam 360 mm and clay 540 mm. If the subsoil constrains root penetration, these values would need to be reduced. If it is assumed that the trees only transpire at E_{new} , the plant available water store will meet the additional transpiration requirement for about 4–5 years at 20% replant (A = 0.2) of a catchment in the 300–600 mm rainfall zone, if the DP_{crop} value in Equation 11 is estimated from Equation 10.

Because of the high evaporative demand across much of the southern and western Australian wheatbelt, the perennials could evaporate more than E_{new} and therefore deplete soil moisture stores more rapidly than estimated above. The perennials would need to be harvested and a new location replanted whenever the store is used, to preserve the benefit of enhanced transpiration. This is the rationale behind the concept of phase farming, described in detail by Harper *et al.* (2000b).

Deep percolation below the following annual system would have to replenish the depleted subsoil moisture store before substantial recharge could occur. A feasibility modelling study of this planting strategy has been performed by Hatton and Dawes (2000) for hypothetical sites within the 300–600 mm precipitation zone using WAVES (Zhang and Dawes 1998). Their results were not favourable for shallow soils and deep sands, which returned to high recharge rates after one year and four years of

rotating from a perennial to an annual cropping system. Deeper and heavier-textured soils required longer to return to annual cropping recharge rates after rotation from the perennial system.

At present, it is impossible to predict with certainty what area of phase farming would be required to return recharge to pre-clearing levels. At regional scale, for areas where the watertable is deeper than the root zone of the perennial system, the problem can be presented as the time required to fill the plant available water store. The key variables are the rate at which the soil store is replenished, the rooting depth of the perennial vegetation and the storage capacity of the root zone for the perennial system.

The rate at which the soil store is replenished can be equated to deep percolation below the annual system, so Equation 10 gives a first approximation. The available water store for a particular soil texture class can be estimated using pedotransfer functions for Australian soils (Smettem *et al.* 1999, 2004). The rooting depth defines the size of the store for a given soil texture and is the possibly the greatest source of uncertainty.

Direct uptake of groundwater by perennials

The concept of phase farming is to achieve recharge control by using stored water and creating dry soil buffers that require some time to refill after the perennial phase is rotated to another part of the catchment. If perennials are also required to drop the groundwater level directly, the DP term in Equation 11 must be enhanced by the targeted GW drop. For example, to drop the GW by 1 m the perennials would have to use an additional amount of DP enhancement equal to 1 m multiplied by the drainable porosity (or specific yield). For a drainable porosity of about 0.1, this equates to an equivalent of an additional 100 mm of DP per year.

In locations where unconfined groundwater is relatively fresh, considerable water use is possible. Lefroy and Stirzaker (1999) reported tagasaste water use from a watertable 5 m below the surface in a sandy soil. George (1990) reported on the reclamation of localised saline seeps by deployment of small (1–2 ha) eucalypt plantings to intercept fresh perched groundwater before it reached the saline area.

Jolly *et al.* (1993) reviewed studies of water uptake by trees from slightly saline (5 dS/m⁻¹) to very saline (50 dS/m⁻¹) watertables and reported

maximum annual uptake values of 440 mm/yr⁻¹, so salinity imposes a threshold to maximum transpiration.

Strategic configuration of tree belts: level ground case

Theoretically, there are advantages in terms of recharge reduction to planting perennials in belts (alleys) rather than blocks. In plan view, the belt configuration confers a hydrological footprint that is wider than the belt (Ellis *et al.* 2006, 2007).

We commence with a first-order approximation of no deep drainage below the perennial belt. For example, a 10 m wide belt with 50 m spacing between belts would give at least 17% reduction in deep drainage (10 m/60 m) over the area occupied by the belts. We assume initially that the perennials can only access annual precipitation.

The basic design principles were first reported by Ellis *et al.* (1999). In a simplified form, the fraction of recharge reduction (RR) achieved by perennial belts is given by:

$$RR = B/W \quad (\text{Eqn 12})$$

where W is the spacing of the belts (m) and B is the equivalent no recharge width (m), which is essentially the hydrologic footprint of the belt due to lateral root development into the adjacent land. In our example the minimum width of B is 10 m (the belt width), but it should be larger because of lateral root exploration. Ellis *et al.* (1999) derived a second-order approximation for B , relating it to the leaf area of the tree belt:

$$B = LLA/LAI \quad (\text{Eqn 13})$$

where LLA is the lineal leaf area (m²/m⁻¹ belt of perennials) and LAI is the leaf area index (m²/m⁻²).

Regionally, the LAI can be related to climatic indices of wetness or dryness that depend on the availability of water and energy (Budyko 1974). Ellis *et al.* (1999) showed that LAI is strongly correlated with P/E_o , a useful index of wetness (P is mean annual precipitation and E_o is mean annual pan evaporation). The regression correlation is:

$$LAI = 2.9P/E_o \quad (\text{Eqn 14})$$

The LAI isolines for Western Australia, estimated by applying Equation 14 to long-term mean annual precipitation and pan evaporation data, are shown in Figure 3.6.

Obtaining B in Equation 13 requires measurement of LLA for the perennial belts. Such measurements are not widely available, although Ellis *et al.* (2005) surveyed 21 farm tree belts on the south-west slopes of NSW for the purpose of estimating B. Ellis *et al.* (1999) gave one worked example for Victoria. For a 10 m wide tree belt, the LLA is $30 \text{ m}^2/\text{m}^{-1}$ (implying an LAI of 3 across 10 m of the belt). For Walpeup in Victoria, the LAI calculated from Equation 14 is 0.5, so B is 60 m. From Equation 12, this implies there would be no recharge for a spacing of 60 m and for a spacing of 100 m the recharge reduction would be 60%. Plotting LAI from Equation 14 for south-west Western Australia shows that an LAI of 0.5 is close to the 350 mm precipitation isohyet, so this calculation is relevant for the wheatbelt region of Western Australia.

Experimental data supporting the concept of a hydrological footprint that extends well beyond the belt has been presented by Robinson *et al.* (2006), who surveyed the performance of several sites across the climatic gradient of the Western Australia cropping region.

Strategic configuration of tree belts: sloping ground cases

The possible use of perched water by belts of trees planted orthogonal to the slope has been scoped by Silberstein *et al.* (2002). Some simple analytical solutions to the problem, based on drain theory, are presented by Stirzaker *et al.* (1999). The basic notion is that the additional water received by the belt is the perched water that is flowing downslope between the belts. It is implicitly assumed that there are no restrictions to uptake of this water by the tree belt. In light of the Feddes water uptake model described earlier, it is possible that saturated flow of perched water into the tree belt may not be taken up by the trees due to oxygen depletion. At this time, field data are required to further evaluate this proposed strategy.

Conclusion

In reviewing the use of water by perennial vegetation in different strategic configurations, we have provided some insights into the annual values of enhanced transpiration that could be achieved by revegetation. In practice, a revegetation project

should only be considered (in terms of delivering proposed salinity control benefits) if these transpiration rates appear to achieve the desired target for lowering the saline watertable within an acceptable timeframe. This in turn requires information on aquifer characteristics such as flow rate and aquifer yield per unit change in watertable elevation. As the discussion of aquifer classification shows, the prospects for lowering watertables by revegetation with perennial vegetation appear to be best in local groundwater systems, or where annual rates of groundwater inflow are considerably less than annual transpiration losses.

References

- Al-Khafaf S, Sharan FA, Wierenga PJ and Iyada AD (1989) Some empirical relations for the prediction of soil evaporation, transpiration and root water uptake under field conditions. *Agricultural Water Management* **16**, 323–335.
- Anderson GC, Fillery IRP, Dunin FX, Dolling PJ and Asseng S (1998) Nitrogen and water flows under pasture-wheat and lupin-wheat rotations in deep sands in Western Australia. II. Drainage and nitrate leaching. *Australian Journal of Agricultural Research* **49**, 345–361.
- Argent RM and George RJ (1997) Wattle: a water balance calculator for dryland salinity management. In *Proceedings of MODSIM 97. International Congress on Modelling and Simulation*. Hobart, Australia.
- Asseng S, Fillery IRP, Anderson GC, Dolling PJ, Dunin FX and Keating BA (1998) Use of the APSIM wheat model to predict yield, drainage, and NO_3^- leaching for a deep sand. *Australian Journal of Agricultural Research* **49**, 363–377.
- Bari M and Smettem KRJ (2006a) A daily salt balance model for representing stream salinity generation process following land use change. *Hydrology and Earth System Science* **10**, 519–534.
- Bari M and Smettem KRJ (2006b) A conceptual model of daily water balance following partial clearing from forest to pasture. *Hydrology and Earth System Science* **10**, 321–337.
- Belmans C, Dekker LW and Bouma J (1982) Obtaining soil physical field data for simulating soil moisture regimes and associated potato

- growth. *Agricultural Water Management* **5**, 319–333.
- Beresford Q, Bekle H, Phillips H and Mulcock J (2001) *The Salinity Crisis: Landscapes, Communities and Politics*. University of Western Australia Press, Perth.
- Beverly C, Bari MA, Christy B, Hocking M and Smettem KRJ (2005) Understanding catchment dynamics from land use change: comparison between a rapid assessment approach and a detailed modelling framework. *Australian Journal of Experimental Agriculture* **45**, 1433–1469.
- Budyko MI (1974) *Climate and Life*. New York. Academic Press.
- Cox JW (1988) Seepage interceptor drainage of duplex soils in south-western Australia. PhD thesis. Geology Department, University of Western Australia, Nedlands WA.
- Dawson TE (1993) Hydraulic lift and water parasitism by plants: implications for water balance, performance, and plant-plant interactions. *Oecologia* **95**, 565–574.
- Dawson TE and Pate JS (1996) Seasonal water uptake and movement in root systems of Australian phreatoepiphytic plants of dimorphic root morphology: a stable isotope investigation. *Oecologia* **107**, 13–20.
- Dell B, Bartle JR and Tacey WH (1983) Root occupation and root channels in jarrah forest subsoils. *Australian Journal of Botany* **31**, 615–627.
- Dunin FX (2002) Integrating agroforestry and perennial pastures to mitigate water logging and secondary salinity. *Agricultural Water Management*, **53**, 259–270.
- Eagleson PS and Tellers TE (1982) Ecological optimality in water-limited natural soil-vegetation systems. 2. Tests and applications. *Water Resources Research* **18**, 341–354.
- Ellis TW, Hatton TJ and Nuberg IK (1999) A simple method for estimating recharge from low rainfall agroforestry systems. In *Proceedings of Envirowater99. 2nd Inter-Regional Conference on Environment-Water*. 1–4 September, Lausanne, Switzerland. (Eds A Musey, L Santos Pereira and M Fritsch). Presses Polytechnique et Universitaires Romandes, Lausanne.
- Ellis T, Hatton T and Nuberg I (2005) An ecologically optimality approach for predicting deep drainage from tree belts of alley farms in water-limited environments. *Agricultural Water Management* **75**(2), 92–116.
- Ellis TW, Leguedois S, Hairsine PB and Tongway DJ (2006) Capture of overland flow by a tree belt on a pastured hillslope in south-eastern Australia. *Australian Journal of Soil Research* **44**, 117–125.
- Ellis TW, Potter N, Hairsine PB, Brophy J, Ticehurst J, Hickel K, Tongway D, Caitcheon G and Barley R (2007) ‘Using banded tree-agriculture systems to meet surface water management targets: a design framework’. RIRDC Project no. CSL-18A. RIRDC Publication no. 05/180.
- Engel R, McFarlane DJ and Street G (1987) The influence of doleritic dykes on saline seeps in south-western Australia. *Australian Journal of Soil Research* **25**, 125–136.
- Engel R and Negus T (1988) ‘Controlling saltland with trees’. Western Australian Department of Agriculture. Agdex 331/570, Farmnote 46/88.
- Feddes RA, Kowalik PJ and Zaradny H (1978) Simulation of field water use and crop yield. Centre for Agricultural Publishing and Documentation, Wageningen, Netherlands.
- Feng GL, Meiri A and Letey J (2003) Evaluation of a model for irrigation management under saline conditions. 1. Effects on plant growth. *Soil Science Society of America Journal* **67**, 71–76.
- Gates DM (1980) *Biophysical Ecology*. Springer-Verlag, New York.
- George RJ (1990) Reclaiming sandplain seeps by intercepting perched groundwater with eucalypts. *Land Degradation and Rehabilitation* **2**, 13–25.
- George RJ and Conacher A (1993) Interactions between perched and saprolite aquifers on a small, salt-affected and deeply weathered hillslope. *Earth Surface Processes and Landforms* **18**, 91–108.
- George RJ, Nulsen RA, Ferdowsian R and Raper GP (1999) Interactions between trees and groundwaters in recharge and discharge areas: a survey of Western Australian sites. *Agricultural Water Management* **39**, 91–113.
- Greenwood EAN and Beresford JD (1979) Evaporation from vegetation in landscapes developing secondary salinity using the ventilated chamber technique. I. Comparative transpiration

- from juvenile eucalypts above saline groundwater seeps. *Journal of Hydrology* **42**, 369–382.
- Greenwood EAN, Klein L, Beresford JD and Watson GD (1985) Differences in annual evaporation between grazed pasture and eucalypt species in plantations on a saline farm catchment. *Journal of Hydrology* **78**, 261–278.
- Gregory PJ, Tennant D, Hamblin AP and Eastham J (1992) Components of the water balance on duplex soils in Western Australia. *Australian Journal of Experimental Agriculture* **32**, 845–855.
- Harper RJ, Edwards JG and McGrath JF (2000a) Relating the growth of Tasmanian bluegums (*Eucalyptus globulus*) to site conditions in south-western Australia. *Climate Change Newsletter* **12**, 11–13.
- Harper RJ, Hatton TJ, Crombie DS, Dawes WR, Abbott LK, Challen RP and House C (2000b) 'Phase farming with trees: a scoping study of its potential for salinity control, soil quality enhancement and farm income improvement in dryland areas of southern Australia'. Rural Industries Research and Development Corporation, Canberra. RIRDC Publication no. 00/48.
- Hatton T and George R (2001) The role of afforestation in managing dryland salinity. In *Proceedings of a Workshop on Plantations, Farm Forestry and Water*. 20–21 July, Melbourne. Publication no. 01/20.
- Hatton T and Nulsen RA (1999) Towards achieving functional ecosystem mimicry with respect to water cycling in southern Australian agriculture. *Agroforestry Systems* **45**, 203–214.
- Hatton T and Dawes WR (2000) Biophysical simulation and interpretation of phase farming with trees. In 'Phase farming with trees: a scoping study of its potential for salinity control, soil quality enhancement and farm income improvement in dryland areas of southern Australia'. (Eds RJ Harper, TJ Hatton, DS Crombie, WR Dawes, LK Abbott, RP Challen and C House) pp. 13–19. Rural Industries Research and Development Corporation, Canberra. RIRDC Publication no. 00/48.
- Hatton T, Reggiani P and Hodgson G (2002) The role of trees in the water and salt balances of catchments. In 'Trees, water and salt: an Australian guide to using trees for healthy catchments and productive farms'. (Eds R Stirzaker, R Vertessy and A Sarre) pp. 28–42. Joint venture agroforestry program, Rural Industries Research and Development Corporation, Canberra. Agroforestry Design Guidelines. RIRDC Publication no. 01/086.
- Holmes JW (1960) Water balance and the water table in deep sandy soils of the upper south-east, South Australia. *Australian Journal of Agricultural Research* **11**, 970–988.
- Homae M (1999) Root water uptake under non-uniform transient salinity and water stress. PhD dissertation. Wageningen Agricultural University, Wageningen, Netherlands.
- Homae M, Feddes RA and Dirksen C (2002) Simulation of root water uptake. III. Non-uniform transient combined salinity and water stress. *Agricultural Water Management* **57**, 127–144.
- Jolly I, Walker G and Thorburn P (1993) Salt accumulation in semi-arid floodplain soils with implications for forest health. *Journal of Hydrology* **150**, 589–614.
- Kramer PJ (1983) *Water Relations of Plants*. Academic Press, New York.
- Kramer PJ and Bouyer JS (1995) *Water Relations of Plants and Soils*. Academic Press, New York.
- Landsberg J (1989) Tree water use and its implications in relation to agroforestry systems. In *The Ways Trees use Water*. (Ed. J Landsberg) pp. 1–37. Rural Industries Research and Development Corporation, Canberra.
- Laing IAF, Bligh KJ, Hauck EJ, Prince JA and Ortiz HA (1991) Variability of surface and sub-surface runoff from eight contour bays. In *Proceedings of International Hydrology and Water Resources Symposium*. Perth, WA. Vol. 3, pp. 898–905. Institution of Engineers, Australia, National Conference Publication no. 91/22.
- Lefroy E and Stirzaker R (1999) Agroforestry for water management in the cropping zone of southern Australia. *Agroforestry Systems* **45**, 227–302.
- Lety J and Stolzy H (1967) Limiting distances between root and gas phase for adequate oxygen supply. *Soil Science* **103**, 404–409.
- Maas EV and Hoffman GJ (1977) Crop salt tolerance: current assessment. *Journal of Irrigation*

- and Drainage Division ASCE **103** IR2, 115–134.
- McFarlane DJ, Howell MR, Ryder AT and Orr GJ (1992) The effect of agricultural development on the physical and hydraulic properties of four Western Australian soils. *Australian Journal of Soil Research* **30**, 517–532.
- Morris JD and Thomson LAJ (1983) The role of trees in dryland salinity control. *Proceedings of the Royal Society of Victoria* **95**, 121–131.
- Peck AJ (1976) Interaction between vegetation and stream water quality in Australia. In *Proceedings of the 5th Workshop of US/Australia Rangelands Panel. Watershed Management on Range and Forest Lands*. 15–22 June 1975, Boise, Idaho. (Eds HF Heady, DH Falkenberg and JP Riley) pp. 149–155.
- Pracilio G, Asseng S, Cook SE, Hodgson G, Wong MTF, Adams ML and Hatton TJ (2003) Estimating spatially variable deep drainage across a central-eastern wheatbelt catchment, Western Australia. *Australian Journal of Soil Research* **54**, 789–802.
- Richards JR and Caldwell MM (1987) Hydraulic lift: substantial nocturnal water transport between soil layers by *Artemisia tridentata* roots. *Oecologia* **74**, 486–489.
- Richards BG and Smettem KRJ (1992) Modeling water flow in two- and three-dimensional applications. II. Two case studies in hillslope flow and stability analysis. *Transactions of the American Society of Agricultural Engineers* **35**, 1505–1512.
- Robinson N, Harper RJ and Smettem KRJ (2006) Soil water depletion by *Eucalyptus* spp. integrated into dryland agricultural systems. *Plant and Soil* **286**, 141–151.
- Schofield NJ (1990) Determining reforestation area and distribution for salinity control. *Hydrological Sciences Journal* **35**, 1–19.
- Schofield NJ, Loh IC, Scott PR, Bartle JR, Ritson P, Bell RW, Borg H, Anson B and Moore R (1989) ‘Vegetation strategies to reduce salinities of water resource catchments in south-west Western Australia’. Water Authority of Western Australia. Report no. WS33.
- Sedgley RH, Smith RE and Tennant D (1981) Management of soil water budgets of recharge areas for control of salinity in south-western Australia. *Agricultural Water Management* **4**, 313–334.
- Sharma ML, Cresswell ID and Watson JD (1985) Estimates of natural groundwater recharge from the depth distribution of an applied tracer. In *Proceedings of the 21st Annual Conference, International Association of Hydraulic Research*. Melbourne. pp. 65–70.
- Silberstein R, Verteessy R, McJannet D and Hatton T (2002) Tree belts on hillslopes. In ‘Trees, water and salt: an Australian guide to using trees for healthy catchments and productive farms’. (Eds R Stirzaker, R Verteessy and A Sarre) pp. 57–76. Joint venture agroforestry program, Rural Industries Research and Development Corporation, Canberra. RIRDC Publication no. 01/086.
- Simunek J, Sejna M and van Genuchten MT (1996) The HYDRUS-2D software package for simulating water flow and solute transport in two-dimensional variably saturated media. Version 1.0, IGWMC –TPS-56. Colorado School of Mines, Golden, Colorado.
- Smettem KRJ (1998) ‘Deep drainage and nitrate losses under native and agricultural systems in the Mediterranean climate region of Australia’. Land and Water Research and Development Corporation. Occasional Paper RAPP02/98.
- Smettem KRJ, Oliver YM, Heng LK and Bristow KL (1999) Obtaining soil hydraulic properties for water balance and leaching models from survey data. 1. Water retention. *Australian Journal of Soil Research* **50**, 283–289.
- Smettem KRJ, Pracilio G, Oliver YM and Harper RJ (2004) Data availability and scale in hydrologic applications. In *Developments in Soil Science. Vol. 30: Development of Pedotransfer Functions in Soil Hydrology*. (Eds YA Pachepsky and WJ Rawls) pp. 253–271. Elsevier, Amsterdam.
- Sochacki S, Harper RJ and Smettem KRJ (2006) Biomass production from a short rotation bioenergy system in semi-arid Australia. *Biomass and Bioenergy* **31**, 608–616.
- Sonogan RMC and Patto RM (1985) ‘The use of trees and other vegetation in the management of seepage from earthen channels in the Wimmera-Mallee region’. Rural Water Commission of Victoria. Progress Report.

- Specht RL (1979) Water use by perennial evergreen plant communities in Australia and Papua New Guinea. *Australian Journal of Botany* **20**, 273–299.
- Specht RL and Specht A (1989) Canopy structure in eucalypt-dominated communities in Australia along climatic gradients. *Acta Oecologia, Oecologia Plantarum* **10**, 191–213.
- Stewart JB (1984) Measurement and prediction of evaporation from forested and agricultural catchments. *Agricultural Water Management* **8**, 1–28.
- Stirzaker RJ and Vertessy R (2002) Balancing productivity and catchment health. In ‘Trees, water and salt: an Australian guide to using trees for healthy catchments and productive farms’. (Eds RJ Stirzaker, R Vertessy and A Sarre) pp. 136–144. Joint venture agroforestry program, Rural Industries Research and Development Corporation, Canberra. RIRDC Publication no. 01/086.
- Stirzaker RJ, Cook FJ and Knight JH (1999) Where to plant trees on cropping land for control of dryland salinity: some approximate solutions. *Agricultural Water Management* **39**, 115–133.
- Stirzaker RJ, Lefroy EC and Ellis TW (2002) An index for quantifying the trade-off between drainage and productivity in tree-crop mixtures. *Agricultural Water Management* **53**, 187–199.
- Stolte WJ, McFarlane DJ and George RJ (1997) Flow systems, tree plantations and salinisation in a Western Australian catchment. *Australian Journal of Soil Research* **35**, 1213–1219.
- Thorburn PJ (1997) Land management impacts on evaporation from shallow, saline water tables. In *Sub-surface Hydrological Responses to Land Cover and Land Use Changes*. (Ed. M Taniguchi) pp. 21–34. Kluwer, Boston.
- Tyree MT (1999) Water relations of plants. In *Ecohydrology*. (Eds AJ Baird and RL Wilby) ch. 3. Routledge, London.
- US Salinity Laboratory Staff (1954) *Diagnosis and Improvement of Saline and Alkali Soils, Handbook 60*. US Government Printing Office, Washington DC.
- Van Genuchten MT (1987) ‘A numerical model for water and solute movement in and below the root zone’. US Salinity Laboratory, Riverside, CA. Research Report.
- White RE, Helyer KR, Ridley AM, Chen D, Heng LK, Evans J, Fisher R, Hirth JR, Mele PM, Morrison GR, Cresswell HP, Paydar Z, Dunin FX, Dove H and Simpson R (2000) Soil factors affecting the sustainability and productivity of perennial and annual pastures in the high rainfall zone of southeastern Australia. *Australian Journal of Experimental Agriculture* **40**, 267–283.
- Williamson DR (1973) Shallow groundwater resources of some sands in south western Australia. *Proceedings of National Conference on Hydrology*. pp. 85–90. Publication no. 73/3.
- Zhang L and Dawes WR (1998) ‘WAVES: an integrated energy and water balance model’. CSIRO Land and Water, Canberra. Technical Report 31/98.
- Zohar Y (1985) Root distribution of a eucalypt shelterbelt. *Forest Ecology and Management* **12**, 305–307.

Agroforestry for the management of water, salt and agricultural diffuse source pollutants

Tim Ellis and Albert van Dijk

This chapter describes the downstream effects of the increased leakiness of landscapes following vegetation clearing and agricultural practices. This disrupts natural source-sink sequences and delivers more sediment, salt and nutrients to streams and estuaries, where they become pollutants. Agroforestry plantings are one option for replacing sinks in the landscape to help restore water balances and mitigate the export of pollutants. We describe the effects of tree plantings on water and pollutant movements and provide guidelines for their design and placement.

Hillslope processes

Runoff and erosion are natural processes which redistribute water and nutrient resources over the landscape. In natural landscapes, sources and sinks often self-organise their size, nature and distribution such that the resource fluxes between them and vegetation communities they support are compatible (Noy-Meir 1979). These structures are most obvious in arid areas (Tongway *et al.* 2001) but can occur in many environments. Agriculture has changed the structure of Australian landscapes (McTainsh and Broughton 1993; Williams *et al.* 1998), and often increases the number and area of sources (e.g. bare soil) but eliminates many sinks (e.g. perennial vegetation).

Typically, water, sediment, salt and nutrient movements change after clearing. Groundwater recharge increases, stored salt is mobilised and sedi-

ment and nutrient fluxes may be increased to pollutant levels (Ritter and Shirmohamadi 2000). Sediment becomes a pollutant when it physically alters streams and reduces river habitat, e.g. by deposition of large sand slugs. Salinisation is pollution of land and streams by salt. It can significantly reduce biodiversity and primary production and contaminate water supplies. Nitrate NO_3 and nitrite NO_2 in runoff can be leached to groundwater and are potentially toxic in humans. High phosphorus concentrations in aquatic environments can lead to eutrophication, reduce dissolved oxygen and cause fish kills. Large amounts of algae in water supplies demand specialised filtration, an expensive and difficult exercise. Blue-green algal blooms can produce toxins which are dangerous to aquatic life and to humans.

Agricultural pesticides can be transported in dissolved form or adsorbed to suspended sediment and are being increasingly detected in groundwater and streams (Ritter and Shirmohamadi 2000). Appropriately placed agroforestry plantings can act as sinks to excess water and pollutants and help mitigate agricultural non point-source pollution of land and water supplies. The capture of water and nutrients promotes localised vegetative growth and other associated biological activity. This feedback increases the capacity to trap and immobilise excess nutrients and pesticides.

Pollutant generation, runoff and capture

The physical condition of the soil surface, degree of protection from rainfall impact and the level of

biological activity have strong links to soil surface stability, runoff and pollutant generation (Roth 2004). The impact of raindrops on an unprotected soil surface will detach particles from the soil matrix and move them over short distances (up to 20 cm; Van Dijk *et al.* 2003). Nutrients and pesticides adsorbed to soil particles (particularly fine particles, such as clay and silt) or in the soil water solution are also mobilised by raindrop impact. Vegetation and plant residue protects the soil surface from splash erosion and from the formation of a physical crust which reduces infiltration (Morin and Benyamini 1977). On the other hand, biological crusts such as moss, lichen and cyanobacteria strengthen soil surfaces, reduce splash erosion and increase infiltration (Belnap *et al.* 2005). The activity of soil macrofauna (beetles, ants, earthworms) also increases aggregate stability (Lavelle and Spain 2001).

Surface runoff occurs when the rainfall rate exceeds infiltration into the soil, when rain falls on saturated soil, or if the watertable meets the soil surface (exfiltration, e.g. a spring). It can transport detached soil particles and dissolved compounds. The amount of soil particles transported by runoff depends on the 'stream power' of the flow, which is proportional to the product of flow rate and slope. The magnitude of the stream power determines the size of particles which can be suspended. Coarse particles tend to roll or hop (saltation) along the soil surface at the base of the flow; this is called bed load. Finer particles are buffeted by turbulence and tend to remain in suspension. They are called the suspended load. At low stream power (e.g. shallow runoff from a gentle hillslope), the suspended load will comprise only clay and fine silt-sized particles and the bed load is likely to be fine sand. As runoff tends to accumulate downhill, stream power increases with slope and slope length. High stream power flows can detach more soil particles, suspend anything from clay to gravel and roll boulders along as bed load.

Filter elements on the hillslope, such as vegetation patches, can intercept runoff and pollutants. Water infiltrating the soil surface during a runoff event will take with it some dissolved pollutants and, if there is macro pore flow, suspended sediment. Reduction in stream power (by a reduced slope, increased roughness or flow divergence) will result in the deposition of suspended sediment. A

backwater will form upstream of a flow obstruction (e.g. vegetation) and cause deposition of most of the coarse suspended load, and the bed load (Ghadiri *et al.* 2001).

Finer particles and aggregates remain suspended and can be deposited within the obstruction, or may pass through the obstruction. The longer and less concentrated the flow path through the obstruction, the more likely it is that suspended sediment will be deposited within it. Dissolved pollutants such as nutrients or pesticides may be adsorbed to soil and organic matter during their passage through the filter.

Nitrogen in runoff can exist as dissolved NO_3 but also as $\text{NH}_3\text{-N}$ cations, adsorbed to negatively charged soil particles. On entering a sink, the fate of each compound will depend on a number of factors. If the nitrogen is not taken up by plants, the soluble NO_3 could be leached from soil. The adsorbed $\text{NH}_4\text{-N}$ is likely to undergo other transformations before it is transported further or lost to the atmosphere as NO , N_2O and N_2 (Ritter and Shirmohamadi 2000). Phosphorus can be transported by runoff in adsorbed and dissolved forms. Compared to nitrogen, it is non-toxic and relatively immobile and can be sequestered via chemical adsorption or by immobilisation in microbial biomass. Once trapped by infiltration or deposition, phosphorus is relatively immobile except in sandy soils, organic soils or soils low in iron or aluminium. Soil texture and pH have the most significant effects on the sorption and degradation of most pesticides in a terrestrial sink. Some chemicals can be degraded by microbial action or sunlight; others are taken up by plants and animals and stored in plant tissue. Soluble forms can leach into groundwater or be washed through river systems and end up in lakes, wetlands or estuaries.

Salt is delivered to all landscapes in Australia in trace amounts, via rainfall. Because pure water is evaporated from the soil surface and transpired by plants, the meteoric salt is retained in the soil profile (Herczeg *et al.* 2001). In high-rainfall areas (>800 mm), where the evaporation is less than rainfall, this salt is leached out of the soil profile. Because this is a continual process, the salt concentration of the leachate is low. Where rainfall is lower, salt accumulates in the soil or below, in the regolith. Under natural conditions, very low rates of leaching (<0.01 mm/y^{-1}) remove salt from root

zones and store it lower in the soil profile. Disturbances to the landscape and increased drainage from the soil can remobilise this stored salt. The pathways that salt can follow are many and varied, and depend on local hydrogeology. Stirzaker *et al.* (2002) provide a concise summary of some relevant scenarios for southern Australia, with specific reference to agroforestry plantings.

Agroforestry plantings as sinks for water and pollutants

Trapping water

Planting trees changes the local water balance, and if planting occurs on a large enough scale this can cause changes in the amount of stream flow (Brown *et al.* 2005). On flat land in low- to medium-rainfall areas, with relatively impermeable subsoils, agroforestry is likely to use all the rainfall and can deplete previously existing soil water stores (Ellis *et al.* 2005).

Researching sloping land, Stirzaker *et al.* (2002) focused on the potential of trees to intercept and use subsurface lateral flow and provided guidelines for optimising this design. Detailed hydrologic studies of such plantings are described by McJanet *et al.* (2000), who concluded that subsurface lateral flow did not occur in their study site, and by Ticehurst (2004), who showed that it comprised only a very small proportion of the water budget. Conversely, White *et al.* (2002) undertook a similar study and showed that contour-planted eucalypts, over a 12 month period, used up to 150 mm of subsurface lateral flow, approximately 25% of the whole water consumption.

These different observations were primarily due to different soil types. In strongly duplex soils with sandy A-horizons, and in large areas of Western Australia, subsurface lateral flow is likely to be significant. For most of south-east Australia and Queensland, however, surface runoff is likely to be the most significant mechanism for the movement of excess water (and adsorbed and dissolved pollutants) to trees on hillslopes (Ticehurst 2004; Ellis *et al.* 2006).

In a wet tropical environment, McKergow *et al.* (2004a) showed that grass buffers were unable to cope with extreme conditions. Large runoff events

exceeded buffer infiltration capacity and caused gully erosion in drainage lines within the buffers. Once saturated, the grass buffers were a source of exfiltration which increased erosion hazard.

Very few large-scale plantings of tree belts or alley farms have been established in Australia, and their effect on water use at the catchment scale has only been hypothesised (Ellis *et al.* 2005). As a general rule, widespread agroforestry is likely to reduce runoff at the catchment scale but there have been few studies to confirm this. Liu *et al.* (2004), in a paired catchment study in the Himalayas (825 mm/yr rainfall), showed that agroforestry, compared to pasture, reduced catchment runoff but increased average soil water content. A modelling study in western France (Brittany) concluded that the extensive hedgerow system (bocage) would increase annual average evaporation at the catchment scale by 5–30% (Viaud *et al.* 2005).

Trapping pollutants

Well-managed tree plantings will have better soil structure and greater surface roughness (due to understorey or tree litter) and can act as filter strips. Generally, adequately designed filter strips can reduce surface runoff and suspended sediment loads (Dosskey 2001), nutrient loads (Blanco-Canqui *et al.* 2004) and pesticide loads (Krutz *et al.* 2005) from agricultural land. Agroforestry-based filter strips and buffers can perform similar tasks. The deeper root systems of trees offer a large capacity for resource capture, nutrient cycling and pollutant immobilisation.

In Australia, Leguedois *et al.* (submitted) showed that 90–100% of the suspended sediment delivered in runoff was trapped by a non-grazed tree belt. Deposition occurred in the backwater which formed immediately upslope of the tree belt, and during the passage of runoff over and through the tree leaf litter. The capture of surface runoff described by Ellis *et al.* (2006) also reduced the transport capacity of the flow passing through the same belt and therefore contributed to the deposition of suspended material. This litter formed microterraces that slowed and spread the flow and allowed greater opportunity for infiltration. Exclusion of stock from the belt also improved trapping capacity compared to trafficked areas outside the belt, which were bare and compacted.

Riparian tree buffers, if sufficiently wide and appropriately maintained, are known to reduce pollutant delivery to streams adjacent to broadacre agriculture (Hickey and Doran 2004) and range-land (Hook 2003), and to reduce stream bank erosion (McKergow *et al.* 2003). The exclusion of stock from these areas also significantly reduces bank erosion and is critical for the soil structure and surface vegetation (or litter) cover required for water and pollutant capture. Schultz *et al.* (2004), reviewing the performance of riparian buffers in the Bear Creek catchment, Iowa, recommend three-zone buffers comprising grass, shrub and tree species for intercepting suspended and dissolved pollutant loads. Grasses provide ground cover, erosion protection and hydraulic resistance; shrubs provide a more permanent perennial cover, a larger nutrient sink and fauna habitat; trees provide stream bank stability, large nutrient sinks, stream shading and woody debris (for stream habitat).

In the extreme runoff and erosion conditions in the Queensland wet tropics, McKergow *et al.* (2004a) reported that grass filter strips on smooth hillslopes trapped large amounts of incoming suspended sediment and bed load. Combined grass and forest buffers on hillslopes with drainage lines, although they reduced erosion hazard, did not trap significant amounts of sediment. Where sediment was transported through the grass section but deposited in the riparian forest, it was eroded again by subsequent events. In a temperate Western Australian catchment, McKergow *et al.* (2003) measured sediment, phosphorus and nitrogen loads before and after the planting of a stream reach to eucalypt trees. They reported an order of magnitude reduction in sediment load, mainly due to improved stream bank stability, but little change in nitrogen and phosphorus loads, most likely due to the poor sorption capacity of the sandy duplex soils. In a North American heavily fertilised system, Nair and Graetz (2004) showed that deeper tree roots in silvo-pasture and alley cropping systems significantly reduced the likelihood of nitrogen, phosphorus and pesticides being leached from the landscape. This is due to the higher long-term water use of trees (hence less drainage), and sequestration of pollutants.

While the benefits of filter strips and riparian buffers have been reported at the local scale, there

are few reports of their beneficial effects on the quality of stream flows or wetlands downstream (Ritter and Shirmohamadi 2000). This is probably due to the spatial extent of typical on-ground treatment with filter strips or agroforestry (i.e. they tend to be small patches, never covering a complete catchment) and the lack of related large-scale stream monitoring exercises.

Guiding principles for designing plantings to trap sediments

Stirzaker *et al.* (2002) provide comprehensive guidelines for the design and siting of agroforestry to manage dryland salinity. They give particular emphasis to capturing subsurface lateral flow for hillslopes. We provide guiding principles for the design of agroforestry plantings and riparian buffer strips for the capture of pollutants transported by surface runoff.

Location

The first and obvious requirement is that plantings be located where they will receive surface runoff. They should be sited on hillslopes or in the riparian zone, at locations where they will receive sheet, rather than concentrated, runoff. Gullies are likely to require additional works to divert flow from them or to disperse output flows.

Composition

Capture of particulate and adsorbed pollutants occurs by deposition, and capture of dissolved pollutants occurs via infiltration. It is therefore implicit that plantings have a greater hydraulic roughness or a higher infiltration capacity, or both, than the upslope contributing area. It is also essential that a grass understorey, leaf litter or both (>40% cover) be present, and that livestock be excluded or allowed access for only short periods to maintain soil cover and protect the soil surface structure (Ellis *et al.* 2006; Leguedois *et al.* submitted). Over longer periods (years to decades) biological processes will continue to improve soil structure and increase infiltration capacity (Lavelle and Spain 2001).

A planting must have storage capacity for sediment within plant material or litter at the soil surface, and for water in the soil profile. Following

water infiltration and sediment deposition, these storages will be reset by grass growth, litter fall and transpiration. It is therefore essential that the species selected is capable of surviving drought periods and continuing to perform these functions. Many high water use tree species have perished in Australian agroforestry plantings following drought or when previously accumulated soil water stores have been depleted (McJannet *et al.* 2000). There must also be sufficient capacity for sediment accumulation in backwater zones, where 90% of deposition occurs.

Coverage and width

The capture of water and dissolved pollutants depends on flow path length and input pollutant concentration. The effect of the ratio of runoff generation area to capture area, called the area ratio, is discussed by Krutz *et al.* (2005). Area ratios between 15:1 and 30:1 trapped similar amounts of strongly sorbed pesticides, but lower area ratios (15:1) were shown to be more effective for dissolved pesticides, presumably extracted via direct contact with vegetation.

The width of a planting in the flow direction is not critical to coarse sediment deposition (Krutz *et al.* 2005). Depending on the soil type, most coarse suspended sediments will be deposited in the backwater zone (Ghadiri *et al.* 2001).

For fine sediment and dissolved pollutants, the length of the flow path is important. Little or no deposition will occur within narrow (<1 m) filter strips. Deposition of fine sediment will increase with flow path length up to 15 m, usually with little further increase thereafter (Blanco-Canqui *et al.* 2004; Abu-Zreig *et al.* 2004). In a modelling exercise, Munoz-Carpena and Parsons (2004) recommended flow path lengths of up to 4 m for a sandy clay suspended sediment but up to 44 m for clay suspended sediment. These designs were simulated to capture 75% of sediment generated from a 1 in 10 year storm.

Design tools

There is a pressing need for tools to guide the design and placement of agroforestry plantings on farms to maximise their potential for water and pollutant management. This is a complex issue that is highly dependent on local conditions and multiple pur-

poses of the intended planting. It will be some time before multi-criteria tools are widely available (Dosskey 2002). For planning, it may be necessary to consider several, sometimes competing, objectives such as salinity and water management, farm productivity and pollutant delivery reduction. Assigning a cost or benefit to the water or pollutant components continues to elude routine quantitative analyses. Assessment of these integrated effects inevitably requires a degree of personal judgement and local knowledge.

There is a range of methods and tools, of varying complexity, for predicting individual effects of tree planting. Ticehurst (2004) provides a decision tree, requiring knowledge of soil type and terrain, to help interpret the likely processes by which tree plantings would access water (shallow watertable, runoff, subsurface lateral flow). For sloping land, Stirzaker *et al.* (2002) provide a simple method for predicting which combinations of slope and soil type will result in significant subsurface lateral flow. Hairsine and Van Dijk (2006) provide a simplified framework in which likely impacts on stream flow, salinity, sediment and nutrients can be compared for different commercial and environmental planting types and designs.

For flat land, or where runoff is not significant, Ellis *et al.* (2005) provide two simple formulae for estimating the likely effect of alley farms on deep drainage:

$$RD = \frac{\text{drainage from an alley farm}}{\text{drainage from a conventional farm}} = 1 - \frac{B}{W} \quad (\text{Eqn 1})$$

where W (m) is the centre-to-centre belt spacing of the alley farm and B (m) is the equivalent no drainage zone (ENOD) associated with the tree belts. It can be estimated as:

$$B = \frac{LLA}{LAI} \quad (\text{Eqn 2})$$

where LLA is the lineal leaf area of the tree belt (m^2/m^{-1}) and LAI is the leaf area index of local natural vegetation (m^2/m^{-2}). Ellis *et al.* (2001) show how this can be applied at larger scales where alley farms might be considered within the Murray-Darling Basin, and provide LLA values for a range of tree belt types and sizes. Trees occupy

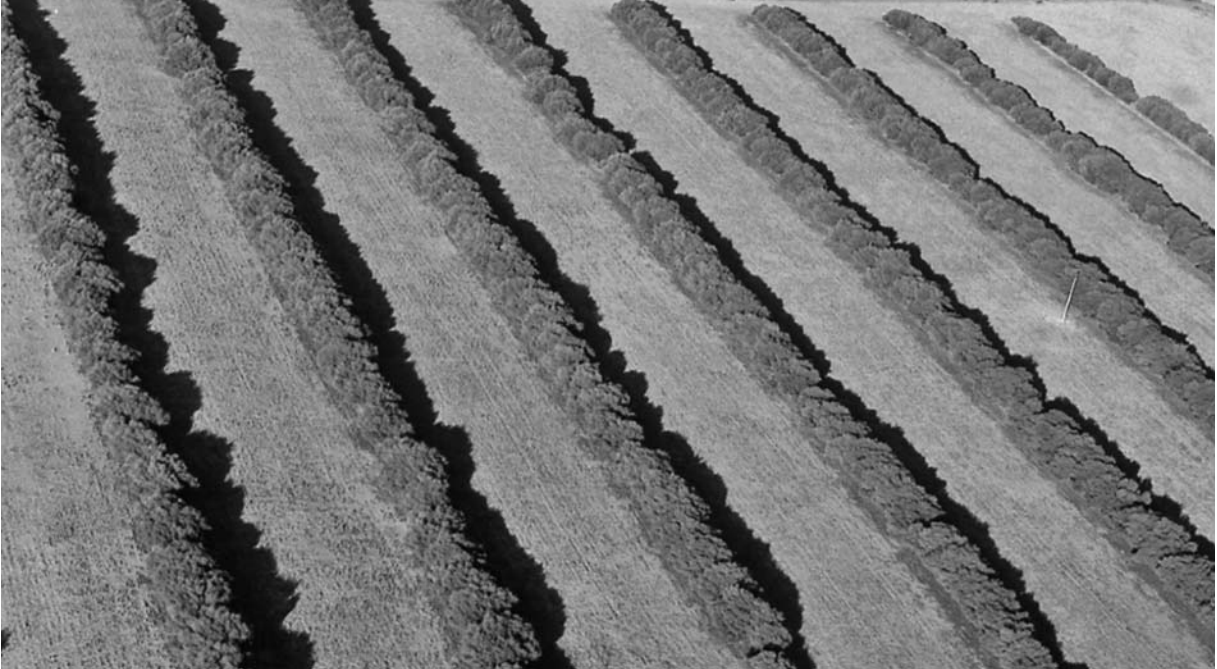


Figure 4.1: Aerial view of an alley farm on flat land in South Australia, showing rows of *Acacia saligna* separated by grazed cereal stubble (photo by Alex Knight).

cropping land and typically reduce growth of immediately adjacent crops, so Stirzaker *et al.* (2002) extended the method and used it to estimate the trade-off between drainage reduction and yield forgone. This was applied widely in south-west Western Australia and southern New South Wales (Oliver *et al.* 2005).

Flanagan *et al.* (1989) provided an equation (modified below) for estimating the sediment delivery ratio (SDR) expected for a vegetative grass filter strip if the input sediment load from a surface runoff event is known:

$$SDR = \sum_{i=1}^I f_i \left(\frac{U}{w} \right)^{\beta v_i} \quad (\text{Eqn 3})$$

where U and w are upslope length (m) and width of the filter strip (m), f_i and v_i are the sediment load fraction and fall velocity (mm/s^{-1}) of the i th sediment fraction, respectively, and β is a turbulence factor ($\beta = 1$ for shallow flow; 0.5 for deep flow). This method requires knowledge of input sediment concentrations for the soil fractions of interest (e.g. clay or sand), which must be measured or modelled.

As a more comprehensive design approach, Munoz-Carpena and Parsons (2004) have developed a vegetative filter strip model (VFSSMOD) for estimating both the pollutant load and the likely capture. Kookana *et al.* (2005) describe a pesticide impact rating index (PIRI) and its application in Australia, which calculates an overall off-site risk to water quality from combinations of pesticide loads and transport mechanisms to surface and groundwater.

Summary

Summarising the principles outlined above, agroforestry plantings for the capture of coarse suspended sediment pollutants should be:

- sited where they will receive runoff;
- composed of a mix of trees, understorey, grass and leaf litter;
- fenced to exclude stock and protect soil cover and structure;
- several metres wide in the direction of flow.

For the capture of fine suspended sediment and adsorbed nitrogen, phosphorus and pesticides,

plantings should be 15–44 m wide in the direction of flow.

Other considerations in designing agroforestry plantings and riparian buffers include:

- the problem that real flow paths are often concentrated, rather than the idealised sheet flow we considered above (Dosskey *et al.* 2002; Helmers *et al.* 2005). Longer filters will be required in these instances and perhaps additional mechanical rehabilitation works;
- the potential for large deposition events or long-term sediment build-up which can alter local flow paths and sometimes initiate gullyng;
- local design aims – whether to plan for minimisation of the impacts of design events (e.g. 1 in 100 yr storm on bare ground; monsoonal storms in the dry tropics) or for long-term average conditions, where rainfall events are less variable and more evenly distributed (e.g. southern Australia);
- that riparian buffers should be 30 m rather than the typical 1–10 m to have sufficient width for pollutant trapping and other ecological functions required of them (Hickey and Doran 2004).

Various single-purpose design tools exist, but, it will be some time before multi-criteria tools are widely available.

Catchment water balance and stream flow

Water use of trees compared to grass and crops

Catchment water balance and stream flow are largely functions of rainfall and evapotranspiration. Over the course of a year, an area of trees can use more water (evapotranspire more) than the same area of grass or agricultural crops. In regions of Australia where rainfall or evaporative demand is strongly seasonal, the species used commonly in (agro)forestry are largely evergreen. Their deep roots give them access to water which was stored deep in the soil profile during rainy periods, enabling water use to continue through dry periods when crops are not present and grass is dormant.

Water use of agroforestry plantings

Isolated trees and trees on the edges of plantings are likely to use more water than trees within a planting. The size and shape of agroforestry plantings can therefore have an important influence on their water use. This is because trees on the edges:

- are more exposed to sunshine and drying wind (clothesline effect) – in Australia this will be most important on west- and north-facing edges;
- can extend their roots sideways into the adjacent cropping land or pasture (up to tens of metres in some species) and therefore have greater access to water than trees within the planting;
- can intercept and use water that flows from the adjacent land as overland flow, subsurface lateral inflows through the soil or water from deeper sources that rises up to the soil.

The perimeter-to-area ratio (P/A) of a planting can be used as a measure of the influence on total water use. The P/A ratio of many agroforestry designs is substantially larger than that of commercial plantings. This is normally deliberate, since the processes above mean that they will give more shade and shelter, can reduce recharge more effectively and can trap sediment and nutrients in overland flow. Equation 4 gives a rough estimate of the edge effect F_{edge} , expressed as the water use of a planting relative to that of an equivalent area



Figure 4.2: The interface between a belt of *Eucalyptus occidentalis* and *E. leucoxylon* and a field pea crop in South Australia. Although effects can vary between species and seasons, the trees have competed aggressively for resources, severely reducing crop growth 10–15 m from the tree stems.

embedded within a larger area of forest (Hairsine and Van Dijk 2006):

$$F_{\text{edge}} = 1 + \frac{W_{\text{edge}} L_{\text{perimeter}}}{A} \quad (\text{Eqn 4})$$

where W_{edge} (m) represents an equivalent width around the outside of the planting from which water is used at the same rate as within the planting, $L_{\text{perimeter}}$ (m) the perimeter of the planting and A (m^2) the total area planted.

The extent of W_{edge} has been shown to vary between tree species and soils with different layering and texture (Sudmeyer *et al.* 2004) and increases with tree age and height. It can be assumed to differ between the upslope and downslope side of the planting (McJannet and Vertessy 2001) and between edges with different aspects. The width of W_{edge} can sometimes be visually estimated from lesser grass or crop growth next to the forest. There are field methods to estimate it from the difference in the amount of leaves of trees on the edge of the planting, versus the amount of leaves on trees within the planting or in a block of forest nearby (Ellis *et al.* 2005). W_{edge} seems to be around 10–20 m for a mature forest in a medium-rainfall zone. This suggests that a square 1 ha planting may use as much as 60% more water than the same planting embedded within a larger forest.

Impacts of agroforestry on catchment water balance and stream flow

The increase in total water use in agroforestry systems may be a cause of concern if it occurs in an area that produces stream flow important for downstream water users. The stream flow impacts of agroforestry have received little attention so far, but the impact of plantation forestry on downstream water supplies has been a cause of public concern for several years in some regions. Decreases in catchment stream flow after afforestation have been observed in Australia (Holmes and Sinclair 1986; Vertessy *et al.* 2003; Brown *et al.* 2005) and around the world (Bosch and Hewlett 1982; Brujnzeel 2000). Several methods have been developed to predict impacts of afforestation on stream flow. A simple but robust method is the set of ‘Zhang curves’ (Zhang *et al.* 2001, 2004; Figure 4.3).

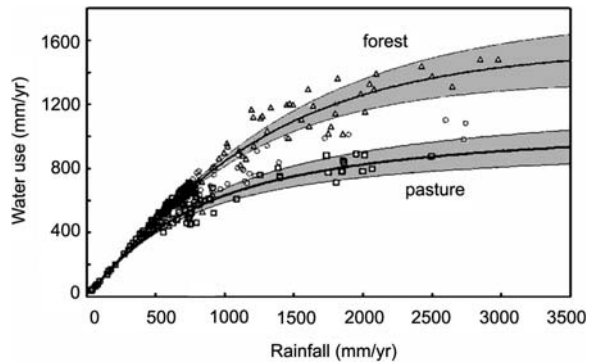


Figure 4.3: The relationship between annual rainfall, catchment vegetation type and annual water use, which represents the difference between rainfall and water yield if it is assumed that catchment water storage does not change significantly over longer periods (Zhang *et al.* 2001).

These curves express the relationship between long-term average catchment rainfall (P), potential water use (potential evapotranspiration, PET) and actual water use (E). Zhang curves may be used to obtain a rough estimate of the magnitude of the change in water yield that can be expected after converting an area of grassland to trees. If the area under trees and grass is known for a given catchment, the likely percentage change in stream flow from this catchment can be estimated. However, the curves should be considered as a guide only.

The lateral redistribution of water can also be important, as unused water may become available at lower topographic positions from surface runoff, unsaturated flow in the soil or groundwater flow (Figure 4.4).

Impacts of agroforestry on stream salinity

Causes of salinity

Dryland and stream salinity is a natural phenomenon in many of the drier regions in Australia. Secondary dryland salinity can also occur when the water balance is altered. Groundwater salinity decreases with increasing rainfall (Figure 4.5) and salinity problems rarely occur in regions with 800 mm or more annual rainfall.

Secondary dryland salinity has become widespread in Australia as a result of clearing of native

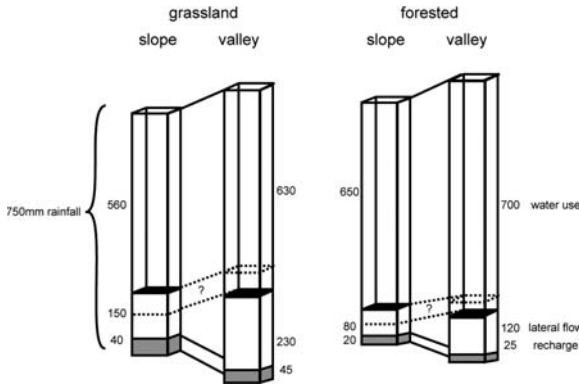


Figure 4.4: A hypothetical water balance for grassland and forest with slope position. Vegetation on the slopes does not receive water inputs other than rainfall and therefore the total of water balance terms equals rainfall. The valley units receive additional lateral water inputs from upslope (over the surface or through the soil) and therefore the total of water balance components is greater than rainfall (dashed lines). Numbers are in mm per year and illustrative only (Hairsine and Van Dijk 2006).

vegetation for agriculture. The replacement of deep-rooted perennial vegetation with shallower-rooted seasonal crops has reduced evapotranspiration, increasing deep drainage and mobilising stored salt. This extra salt is often leached to groundwater from where it can enter streams. These secondary dryland salinity problems cause damage to agricultural land, soils, infrastructure such as roads and buildings, water resources and aquatic ecosystems.

Restoring the salt balance by revegetation

It is often assumed that returning trees to the landscape can help reduce these problems. Indeed, there is ample evidence that the greater water use of trees results in a significant reduction in groundwater recharge (Petheram *et al.* 2002). Good results have been achieved in using trees to reduce local dryland salinity problems, such as salt outbreaks and related soil degradation problems. In principle, agroforestry and other forms of tree planting should help to reduce stream salinity, but in practice these benefits are much harder to achieve. An important factor influencing the effectiveness of reforestation is the nature and size of the underlying groundwater system that is discharging saline water into the streams. Where large groundwater

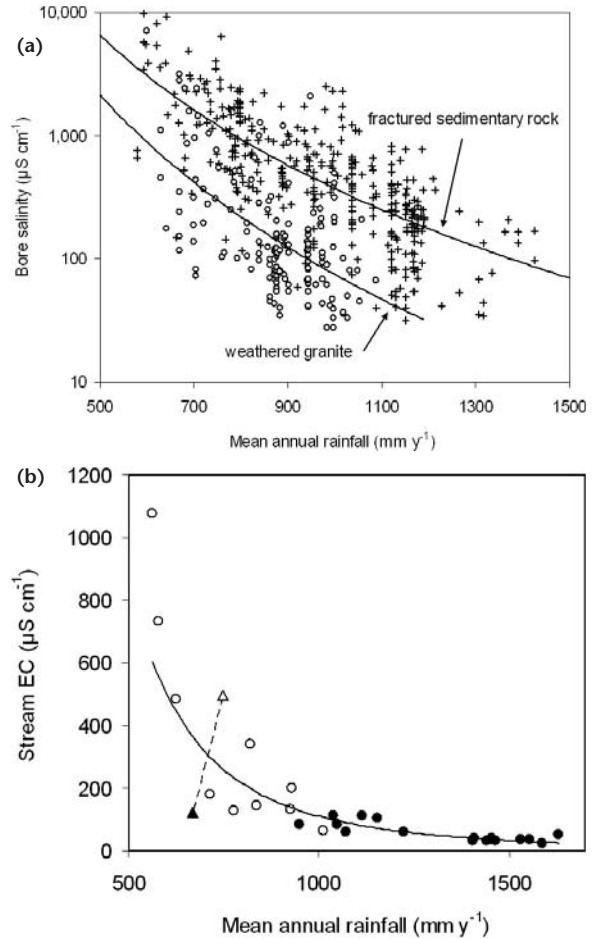


Figure 4.5: Relationships between mean annual rainfall with (a) groundwater salinity measured in bores (Van Dijk *et al.* 2004a), and (b) with stream salinity for 27 subcatchments in the Goulburn and Broken catchments (Van Dijk *et al.* 2007). Solid dots indicate catchments with >50% forest cover, open dots those with ≤50%. For comparison, data are also shown for a small catchment for the first four years after full afforestation (open triangle) and thereafter (closed triangle, cf Figure 4.7).

systems exist, there must be large areas of revegetation to alter the water balance and hence salt movement. Time lags mean the effect may not be realised for decades or even centuries.

In upland areas, groundwater systems may follow the drainage pattern and so be much smaller. Together with the smaller amount of water stored in these systems and the greater groundwater flow rates, tree planting can have a quicker effect. In such cases, catchment salt exports can be reduced considerably by afforestation. However, reforestation

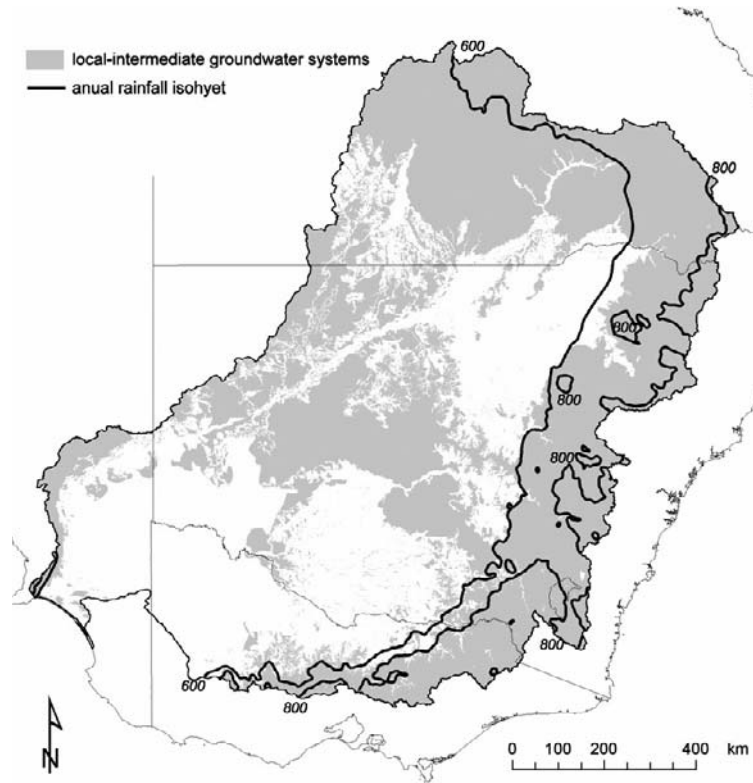


Figure 4.6: Sites in the Murray-Darling Basin where local to intermediate groundwater systems are found in conjunction with less than 600–800 mm average annual rainfall.

will also reduce water yields. Therefore, for stream salinity (the concentration of salt in stream flow) to be reduced, the relative reduction in salt export needs to exceed the relative reduction in water yield. This balance becomes increasingly beneficial towards lower-rainfall zones. Because of the relationship between relief and rainfall in many regions, and certainly in the Murray-Darling Basin, this means that there is a defined ‘zone of opportunity’ where quick-responding groundwater systems and low-to-medium rainfall can be found together, and therefore reasonably rapid stream salinity reductions achieved (Figure 4.6).

It should be emphasised that:

- stream salinity may initially increase before decreasing;
- substantial reductions in salinity require a degree of land use change that will almost inevitably reduce significantly stream flow;
- local stream salinity reductions do not necessarily result in salinity reductions further downstream (Figure 4.7).

This example illustrates that a reduction in salt load following revegetation of a subcatchment will invariably be accompanied by a reduction in stream flow. If, prior to revegetation, the subcatchment stream flow was fresher than further downstream, reduced stream flow from the revegetated subcatchment might actually increase salt concentrations downstream even if the salt load from the catchment has been reduced.

The contribution of an area of trees to reducing salinity can decrease rapidly downstream. For example, an important salinity management target for the Murray-Darling Basin Commission is to reduce stream salinity in the Lower Murray (‘end-of-valley’ targets also exist for tributary catchments). Because of the sheer size of the area that contributes to the River Murray salinity, and because of the overwhelming salt input from the large and saline groundwater systems in the lower basin, the feasibility for revegetation to contribute to the target is under scrutiny. The potential for stream flow reduction associated with large-scale revegetation means careful planning is required. This requires models

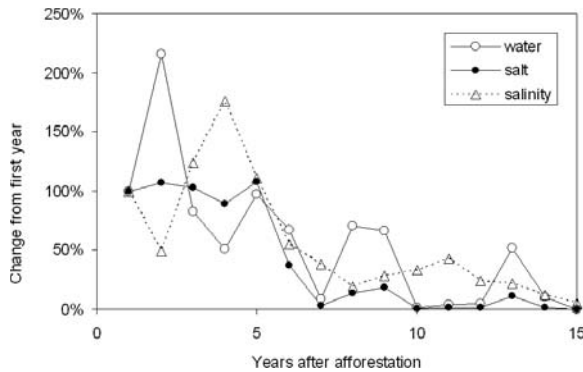


Figure 4.7: Annual water and salt export and flow-weighted stream salinity after 100% reforestation of the 3.2 km² Pine Creek catchment was completed in 1988. A value of 100% on the Y-axis represents runoff of 100 mm, salt export of 289 t/km⁻² and flow-weighted salinity of 443 μS/cm⁻¹ (Van Dijk *et al.* 2004a). Pine Creek is located in the south-west of the Goulburn-Broken region. For this period, mean annual rainfall was 691 mm/y⁻¹ and PET was 1293 mm/y⁻¹.

that can provide spatial predictions of changes in water yield as well as salt export.

Guiding principles and modelling tools for catchment-scale planning

For catchment-scale planning of revegetation strategies, assessment of the net benefits of proposed revegetation schemes requires predictions of the likely changes in stream flow, total pollutant loads and pollutant concentrations both locally and downstream. Choosing sites to maximise desirable effects and minimise undesirable ones is a complex task. This section discusses the factors which need to be considered for catchment-scale planning and describes some planning tools.

At the higher level, a natural resource management agency may want to determine if and how the return on investment in environmental services in a specific region can be increased by treating only the areas that will give the greatest benefit. On the ground, a landholder may want to know how to distribute a given number of trees over their property to achieve the maximum reduction in land degradation with the minimum of expense and production loss. Between these, there are huge differences in:

- the motivation for planning;
- the optimised trade-off or efficiency gain that is to be achieved through planning;

- the total area under consideration;
- the level of detail in the definition of possible scenarios in term of design and positioning.

These differences frequently lead to the wrong tools being used. Covering the spectrum from large-scale prioritisation to local-scale design invariably requires more than one tool.

The first tool might identify catchments within a larger catchment or basin that are more likely to show the desired outcomes than others, based on catchment average climate, terrain and present land use characteristics. In many cases the most efficient approach will be to use models, with catchments as the fundamental unit of modelling. In the second stage, it may be necessary to identify areas within a catchment where land use change can achieve the most desired (set of) outcomes, given within-catchment patterns of relief, soils, hydrogeology and (micro)climate. Lateral flow of water (and salt) over the surface and through soil and groundwater can become important, and this needs more complex modelling. This information is potentially useful for NRM agencies and for landholders or managers, for farm planning. As the spatial scale of modelling becomes smaller, the data, effort and time required for model application become an increasingly important constraint. An example of a staged analysis for salinity management is given in Van Dijk *et al.* (2007). Below, we discuss models that may be suitable for the respective stages.

Tools for selecting catchments within a basin

The catchment modelling toolkit (www.toolkit.net.au) provides a suite of catchment-scale water quality models that can simulate the spatial distribution of sediment, nitrogen and phosphorus generation within a catchment.

The most direct approach to spatial planning for stream salinity control is to use stream measurements of flow and salt load, then divide these by the catchment area to calculate water and salt generation rates. This has a relatively high degree of confidence at this spatial level, despite the considerable degree of uncertainty caused by measurement errors. However, it has some disadvantages. In particular, the ability to prioritise is directly dependent on the number and location of gauging stations, as no spatial information

within the gauged areas is used. A large proportion of water or pollutants may be generated in parts of the catchment where climate, geology and land use lead to greater salt mobilisation or pollutant generation. Furthermore, the present occurrence of stream pollution is not necessarily a good indicator of the ability of revegetation to reduce it.

Methods to produce spatial predictions of the impact of tree planting on catchment water yield in Australia commonly use the Zhang curves (see <http://toolkit.net.au>). This approach has limitations: it was developed for catchments, for long-term average climate variables and for broad vegetation classes. The curves are commonly used outside this range, and have been applied in raster-based calculations (Van Dijk *et al.* 2004a) and in climate variability and change studies (Zhang *et al.* 2005). They have been modified to account for intermediate vegetation types or forest management practices (Keating *et al.* 2004).

A large-scale model for spatial planning of revegetation for stream salinity management is the Biophysical Capacity to Change (BC2C; Dawes *et al.* 2004a, b). This model and related tools are available from the Catchment Modelling Toolkit website, www.toolkit.net.au. It is a simplified model, intended to investigate the relative efficiency gains that can be expected from selecting catchments (the smallest unit of modelling, typically ≥ 1000 ha in size) that show greater and more rapid response to revegetation than others. It allows a spatial trade-off to compare reductions in salt load and water yield. The BC2C approach gives catchment managers a tool to prioritise subcatchments, separating less and more responsive catchments, and identifying catchments where unwanted impacts (an increase in stream salinity after planting) would occur. Groundwater flow system maps have been generated at varying levels of spatial detail across Australia, based on geology and topography using a classification described by Coram *et al.* (2000). However, the BC2C model has the same limitations as the underlying Zhang curves. Its application is limited to upland catchments for which surface and groundwater hydrological boundaries can be considered identical, and therefore subterranean leakage can be ignored.

Tools for planning within the catchment

Although some model tools for planning revegetation within smaller catchments have been devel-

oped, they are often difficult to use. At this scale, models are required to simulate the flow of water and pollutants along the hillslope and to the stream. This means that a large amount of detailed terrain information and much modelling expertise is needed to set up and run these models. Examples of sediment generation models that operate at this scale include LISEM (De Roo *et al.* 1996) and WEPP (Laflen *et al.* 1997). In Australia, these have only been used in research projects.

There are several models to describe the interaction of spatial patterns in climate, vegetation, soil and groundwater characteristics within catchments. The Catchment Scale Salt Balance Model (CATSALT; Tuteja *et al.* 2002, 2003) is a quasi-physical model developed by New South Wales agencies to obtain daily salt balances for medium-sized catchments ranging from 500 to 2000 km². The Catchment Analysis Tool (CAT; C. Beverly, DPI Victoria, *pers. comm.* 2004) was developed to link farming and forestry systems within a landscape context, with explicit linkages to groundwater and stream impacts. To introduce a consistent and freely available model for predicting upland stream salinity response to land use change, the CRC for Catchment Hydrology developed a model that, as much as possible, reflects a consensus among key salinity research centres. The result is the semi-distributed 2CSalt model (Littleboy *et al.* 2005; Stenson *et al.* 2005).

To account for the lateral redistribution of water through surface and unsaturated flow, Gallant *et al.* (2005) developed a modelling framework (FLUSH^{CMT}, Framework for Land Use and Hydrology). Although freely available, both 2CSalt and FLUSH demand a considerable degree of modelling and salinity expertise from the user.

Conclusion

The disturbance of natural source-sink sequences by land clearing and agriculture has generally increased water, sediment, salt and nutrient fluxes, causing pollution of rivers, lakes and estuaries. Fertilisers and pesticides add to these pollutant loads. Carefully placed and designed agroforestry plantings can act as sinks to water and pollutants, and provide farm products such as posts or fuel wood. Although much is known about the effects of tree plantings on local water balance and the trapping of pollutants, these effects are highly vari-

able and sometimes difficult to predict. This chapter has summarised a number of experimental and modelling studies and provided general guidelines for the design and placement of agroforestry plantings for water and pollutant management.

References

- Abu-Zreig M, Rudra RP, Lalonde MN, Whiteley HR and Kaushik NK (2004) Experimental investigation of runoff reduction and sediment removal by vegetated filter strips. *Hydrological Processes* **18**, 2029–2037.
- Belnap J, Welter JR, Grimm NB, Barger N and Ludwig JA (2005) Linkages between microbial and hydrologic processes in arid and semiarid watersheds. *Ecology* **86**, 298–307.
- Blanco-Canqui H, Gantzer CJ, Anderson SH, Alberts EE and Thompson AL (2004) Grass barrier and vegetative filter strip effectiveness in reducing runoff, sediment, nitrogen, and phosphorus loss. *Soil Science Society of America Journal* **68**, 1670–1678.
- Bosch JM and Hewlett JD (1982) A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. *Journal of Hydrology* **55**, 3–23.
- Brown AE, Zhang L, McMahon TA, Western AW and Vertessy RA (2005) A review of paired catchment studies for determining changes in water yield resulting from alterations in vegetation. *Journal of Hydrology* **310**, 28–61.
- Bruijnzeel LA (2000) Forest hydrology. In *The Forests Handbook*. (Ed. J Evans) pp. 301–343. Blackwell Science, Oxford.
- Coram JE, Dyson PR, Houlter PA and Evans WR (2000) Australian groundwater flow systems contributing to dryland salinity. NLWRA, BRS, Canberra.
- Dawes WR, Gilfedder M, Walker GR and Evans WR (2004a) Biophysical modelling of catchment-scale surface water and groundwater response to land-use change. *Mathematics and Computers in Simulation* **64**, 3–12.
- Dawes WR, Gilfedder M, Walker GR, Evans WR, Stenson MP, Dowling TI, Austin J and Best A (2004b) 'BC2C technical documentation'. CSIRO Land and Water, Canberra. Technical Report 36/04.
- De Roo APJ, Wesseling CG and Ritsema CJ (1996) LISEM: a single-event physically based hydrological and soil erosion model for drainage basins. I. Theory, input and output. *Hydrological Processes* **10**, 1107–1117.
- Dosskey MG (2001) Toward quantifying water pollution abatement in response to installing buffers on crop land. *Environmental Management* **28**, 577–598.
- Dosskey MG (2002) Setting priorities for research on pollution reduction functions of agricultural buffers. *Environmental Management* **30**, 641–650.
- Dosskey MG, Helmers MJ, Eisenhauer DE, Franti TG and Hoagland KD (2002) Assessment of concentrated flow through riparian buffers. *Journal of Soil and Water Conservation* **57**, 336–343.
- Ellis T, Bessard Y and Brophy J (2001) CSIRO Land and Water Technical Report 4/01. April 2001.
- Ellis T, Hatton T and Nuberg I (2005) An ecological optimality approach for predicting deep drainage from tree belts of alley farms in water-limited environments. *Agricultural Water Management* **75**, 92–116.
- Ellis T, Leguedois S, Hairsine P and Tongway D (2006) Capture of overland flow by a tree belt on a pastured hillslope. *Australian Journal of Soil Science* **44**, 117–125.
- Flanagan DC, Foster GR, Neibling WH and Burt JP (1989) Simplified equations for filter strip design. *Transactions of the ASAE* **32**, 2001–2007.
- Gallant J, van Dijk AIJM and Leighton B (2005) 'FLUSH: a farm-scale modelling framework of stream flow and salinity changes after reforestation'. CSIRO Land and Water, Canberra. Public CEF client report.
- Ghadiri H, Rose CW and Hogarth WL (2001) The influence of grass and porous barrier strips on runoff hydrology and sediment transport. *Transactions of the ASAE* **44**, 259–268.
- Hairsine PB and van Dijk AIJM (2005) Comparing the in-stream outcomes of commercial and environmental tree plantings. CSIRO Land and Water, Canberra. Public CEF client report.
- Helmers M, Eisenbaur D, Dosskey M, Franti T, Brothers J and McCullough M (2005) Flow pathways and sediment trapping in a field-scale vegetative filter. *Transactions of the ASAE* **48**, 955–968.
- Herczeg AL, Dogramaci S and Leaney FWJ (2001) Origin of dissolved salts in a large, semi-arid

- groundwater system, Murray Basin, Australia. *Marine and Freshwater Research* **52**, 41–52.
- Hickey MBC and Doran B (2004) A review of the efficiency of buffer strips for the maintenance and enhancement of riparian ecosystems. *Water Quality Research Journal of Canada* **39**, 311–317.
- Holmes JW and Sinclair JA (1986) Streamflow from some afforested catchments in Victoria. In *Proceedings of the Hydrology and Water Resources Symposium*. Brisbane. pp. 214–218. The Institution of Engineers, Australia, National Conference Publication no. 86/13.
- Hook PB (2003) Sediment retention in rangeland riparian buffers. *Journal of Environmental Quality* **32**, 1130–1137.
- Keating BA, Gaydon D, Huth NI, Probert ME, Verburg K, Smith CJ and Bond W (2002) Use of modelling to explore the water balance of dryland farming systems in the Murray Darling Basin, Australia. *European Journal of Agronomy* **18**, 159–169.
- Kookana R, Correll R and Miller R (2005) Pesticide impact rating index: a pesticide indicator for water quality. *Water, Air and Soil Pollution: Focus* **5**, 45–65. See also <<http://www.cmis.csiro.au/envir/Research/PesticideRisk/>>.
- Krutz LJ, Senseman SA, Zablutowicz RM and Matocha MA (2005) Reducing herbicide runoff from agricultural fields with vegetative filter strips: a review. *Weed Science* **53**, 353–367.
- Lacas JG, Voltz M, Gouy V, Carlier N and Gril JJ (2005) Using grassed strips to limit pesticide transfer to surface water: a review. *Agronomy for Sustainable Development* **25**, 253–266.
- Lafren JM, Elliot WJ, Flanagan DC, Meyer CR, Meyer CR and Nearing MA (1997) WEPP: predicting water erosion using a process-based model. *Journal of Soil and Water Conservation* **52**, 96–102.
- Lane PNJ, Best AE, Hickel K and Zhang L (2005) The response of flow duration curves to afforestation. *Journal of Hydrology* **310**, 253–265.
- Lavelle P and Spain A (2001) *Soil Ecology*. Kluwer Academic, Dordrecht.
- Le Bissonnais Y, Lecomte V and Cerdan O (2004) Grass strip effects on runoff and soil loss. *Agronomie* **24**, 129–136.
- Leguedois S, Ellis TW, Hairsine PB and Tongway DJ (2008) Sediment trapping by a tree belt – processes and consequences for delivery. *Hydrological Processes* **22** (17), 3523–3534.
- Littleboy M (2005) 'Evaluation of 2CSalt, Kyeamba, Tarcutta and Jugiong Creeks in the Murrumbidgee, New South Wales'. Draft 4.0. NSW Department of Infrastructure Planning and Natural Resources.
- Liu GC, Tian GL, Shu DC, Lin SY and Liu SZ (2004) Streamflow and soil moisture of agroforestry and grass watersheds in hilly area. *Pedosphere* **14**, 263–268.
- McJannet D and Vertessy R (2001) Effects of thinning on wood production, leaf area index, transpiration and canopy interception of a plantation subject to drought. *Tree Physiology* **21**, 1001–1008.
- McJannet DL, Vertessy RA and Clifton CA (2000) Observations of evapotranspiration in a break of slope plantation susceptible to periodic drought stress. *Tree Physiology* **20**, 169–177.
- McKergow LA, Prosser IP, Grayson RB and Heiner D (2004a) Performance of grass and rainforest riparian buffers in the wet tropics, far north Queensland. 2. Water quality. *Australian Journal of Soil Research* **42**, 485–498.
- McKergow LA, Prosser IP, Grayson RB and Heiner D (2004b) Performance of grass and rainforest riparian buffers in the wet tropics, far north Queensland. 1. Riparian hydrology. *Australian Journal of Soil Research* **42**, 473–484.
- McKergow LA, Weaver DM, Prosser IP, Grayson RB and Reed AEG (2003) Before and after riparian management: sediment and nutrient exports from a small agricultural catchment, Western Australia. *Journal of Hydrology* **270**, 253–272.
- McTainsh G and Broughton W (1993) *Land Degradation Processes in Australia*. Longman Cheshire, Melbourne.
- Morin J and Benyamini Y (1977) Rainfall infiltration into bare soils. *Water Resources Research* **13**, 813–817.
- Munoz-Carpena R and Parsons JE (2004) A design procedure for vegetative filter strips using Vfsmod-W *Transactions of the ASAE* **47**, 1933–1941. See also <<http://www3.bae.ncsu.edu/vfsmo>>.
- Munoz-Carpena R, Parsons J and Gillam J (1999) Modelling hydrology and sediment transport

- in vegetative filter strips. *Journal of Hydrology* **214**, 111–129.
- Nair VD and Graetz DA (2004) Agroforestry as an approach to minimizing nutrient loss from heavily fertilized soils: the Florida experience. *Agroforestry Systems* **61**, 269–279.
- Noy-Meir I (1979) Desert ecosystems: environment and producers. *Annual Review of Ecology and Systematics* **4**, 25–51.
- Oelbermann M and Gordon AM (2000) Quantity and quality of autumnal litterfall into a rehabilitated agricultural stream. *Journal of Environmental Quality* **29**, 603–611.
- Oliver YM, Lefroy EC, Stirzaker R and Davies CL (2005) Deep-drainage control and yield: the trade-off between trees and crops in agroforestry systems in the medium to low rainfall areas of Australia. *Australian Journal of Agricultural Research* **56**(10), 1011–1026.
- Petheram C, Walker G, Grayson R, Thierfelder T and Zhang L (2002) Towards a framework for predicting impacts of land-use on recharge. I. A review of recharge studies in Australia. *Australian Journal of Soil Research* **40**, 397–417.
- Ritter WF and Shirmohamadi A (2000) *Agricultural Non-point Source Pollution: Watershed Management and Hydrology*. Lewis, Boca Raton.
- Roth CH (2004) A framework relating soil surface condition to infiltration and sediment and nutrient mobilization in grazed rangelands of northeastern Queensland, Australia. *Earth Surface Processes and Landforms* **29**, 1093–1104.
- Schultz RC, Isenhardt TM, Simpkins WW and Colletti JP (2004) Riparian forest buffers in agroecosystems: lessons learned from the Bear Creek watershed, Central Iowa, USA. *Agroforestry Systems* **61**, 35–50.
- Stenson M, Littleboy M and Gilfedder M (2005) Modelling water and salt export from unregulated upland catchments: the 2CSalt model. In *Proceedings of the International Water Conference*. 28 November–2 December, Auckland. NZHS, NZSSS & IAH (Aust.).
- Stirzaker RJ, Lefroy EC and Ellis TW (2002a) An index for quantifying the trade-off between drainage and productivity in tree-crop mixtures. *Agricultural Water Management* **53**, 187–199.
- Stirzaker R, Vertessy R and Sarre A (2002b) *Trees, Water and Salt: An Australian Guide to using Trees for Healthy Catchments and Productive Farms*. Rural Industries Research and Development Corporation, Canberra.
- Sudmeyer RA, Speijers J and Nicholas BD (2004) Root distribution of *Pinus pinaster*, *P. radiata*, *Eucalyptus globulus* and *E. kochii* and associated soil chemistry in agricultural land adjacent to tree lines. *Tree Physiology* **24**, 1333–1346.
- Ticehurst J (2004) Hydrologic analysis for the integration of tree belt plantations into Australia's agricultural systems. PhD thesis. Centre for Resource and Environmental Studies, Australian National University.
- Tongway DJ, Valentin C and Seghieri J (2001) Banded vegetation patterning in arid and semi-arid environments. *Ecological Studies* **149**. Springer Verlag, New York.
- Tuteja NK, Beale G, Dawes W, Vaze J, Murphy B, Barnett P, Rancic A, Evans R, Geeves G, Rassam DW and Miller M (2003) Predicting the effects of landuse change on water and salt balance: a case study of a catchment affected by dryland salinity in NSW, Australia. *Journal of Hydrology* **283**(1–4), 67–90.
- Van Dijk AIJM, Bruijnzeel LA and Eisma EH (2003) A methodology to study rain splash and wash processes under natural rainfall. *Hydrological Processes* **17**, 153–167.
- Van Dijk AIJM, Jenet A and Hairsine PB (2004a) 'Plantation scenarios for hydrological modelling: defining scenarios for commercial environmental forestry in the southwest Goulburn catchment in a form suitable for modelling the impacts on stream flow and stream salinity'. CSIRO Technical report. Available at <<http://www.clw.csiro.au/publications/consultancy/2004/>>.
- Van Dijk AIJM, Cheng X, Austin J, Gilfedder M and Hairsine PB (2004b) 'Predicted stream flow and salinity changes after afforestation in the southwest Goulburn'. CSIRO Land and Water, Canberra. Public CEF client report. Available at <<http://www.clw.csiro.au/publications/consultancy/2004/>>.
- Van Dijk AIJM, Hairsine PB, Arancibia JP and Dowling TI (2007) Reforestation, water availability and stream salinity: a multi-scale analysis in the Murray-Darling Basin, Australia. *Forest Ecology and Management* **251**, 94–109.

- Vertessy RA, Zhang L and Dawes WR (2003) Plantations, river flows and river salinity. *Australian Forestry* **66**, 901–999.
- Viaud V, Durand P, Merot P, Sauboua E and Saadi Z (2005) Modeling the impact of the spatial structure of a hedge network on the hydrology of a small catchment in a temperate climate. *Agricultural Water Management* **74**, 135–163.
- Wetzel R (2001) *Limnology: Lake and River Ecosystems*. Elsevier Academic.
- White DA, Dunin FX, Turner NC, Ward BH and Galbraith JH (2002) Water use by contour-planted belts of trees comprised of four eucalyptus species. *Agricultural Water Management* **53**, 133–152.
- Williams J, Hook R and Gascoigne H (1998) *Farming Action, Catchment Reaction*. CSIRO Publishing, Melbourne.
- Zhang L, Austin J, Dawes WR, Hairsine P, Durack P and Jones R (2005) 'Implications of climate change for natural resource management: A preliminary assessment of the impact of climate change on catchment salt and water balances for selected catchments in Victoria'. Client Report for the Australian Greenhouse Office, CSIRO Land and Water, Canberra, and CSIRO Atmospheric Research, Aspendale.
- Zhang L, Dawes WR and Walker GR (2001) The response of mean annual evapotranspiration to vegetation changes at catchment scale. *Water Resources Research* **37**, 701–708.
- Zhang L, Hickel K, Dawes WR, Chiew FHS, Western and Briggs PR (2004) A rational function approach for estimating mean annual evapotranspiration. *Water Resources Research* **40**, W02502.

Trees protecting dryland crops and soil

Ian Nuberg and Michael Bennell

Introduction

The promotion of tree planting on farms has a long history in Australia that recognises their role in soil conservation. Other important reasons for the growing interest in tree planting are to mitigate dryland salinity and conserve biodiversity. More recently, concerns about global warming and the international development of carbon trading are providing additional motivation for tree planting. However, a farmer's decision to plant trees will be strongly influenced by how they impact on crop, pasture and animal production – the core farm income streams. Farmers will naturally be reluctant to invest in changed management options unless the potential benefits and costs are clearly understood. There is an abundance of European and North American literature showing how the shelter provided by trees enhances crop, pasture and animal productivity. The physical and physiological mechanisms are well-known and shown to operate cumulatively over the growing season and during short-term severe events (Nuberg 1998). Although optimistic claims have been based on the extrapolation of these results to Australia, the benefits could not be universally upheld, particularly in low-rainfall environments where the competitive effects of trees may override the shelter benefits.

To clarify this situation, the Joint Venture Agroforestry Program (JVAP) initiated a five-year program of research in 1993, the National Windbreaks

Program (NWP), to quantify the interaction between windbreaks, microclimate, crop and pasture growth (Cleugh *et al.* 2002). A further three years of research focused on the effect of shelter on crop damage and soil erosion (Bennell and Cleugh 2002). This combined research dispelled some myths and quantified the real value of trees for shelter in the Australian agricultural landscape.

This chapter outlines some results from the two periods of research, to describe the protective function of trees in cropping systems. It begins with the basic physics and physiology of the effect of shelter and shade on plant production and discusses the major potential impacts of severe wind events and their mechanisms. It presents the essentials for understanding the aerodynamics of windbreaks and how they influence windbreak design. The chapter draws from and builds on 'Trees for Shelter', published by JVAP (Cleugh 2003). The effect of shelter on animal production is covered in Chapter 13, 'Trees in grazing systems'.

Early understanding of the value of windbreaks

Microclimate modification

Much had been written about the value of windbreaks prior to the NWP, that has established a general understanding of windbreak dynamics. This understanding comprises the set of principles of windbreak aerodynamics and design which are

BOX 5.1

Factors affecting wind speed and windbreak design

The primary structural elements of a windbreak affecting wind speed are height, porosity, orientation and location in the landscape. Windbreak design elements such as length, width, species choice and management will have a secondary effect on wind speed.

- Height.** Windbreak height is the most important factor determining the flow of wind across the landscape. We use multiples of tree height (H) when referring to the distance away from the windbreak. The effect of a windbreak on wind speed is commonly reported to be marginal at distances beyond $30H$ leeward and $7H$ windward. The distance at which wind speed is reduced to 80% of open field values generally between $15H$ – $20H$. With a 10 m high windbreak we may expect a reduction of wind speed to 80% of open field values between 150–200 m from the windbreak (Figure 5.1a).

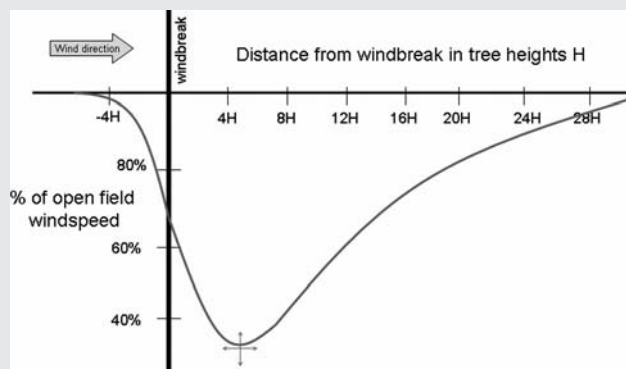


Figure 5.1a: A 10 m high windbreak can reduce wind speed to 80% of open field values, 150–200 m from the windbreak.

- Porosity.** Porosity or permeability refers to the degree to which the windbreak obstructs airflow and reduces the kinetic energy of the wind. A porous windbreak may slow wind while allowing it to diffuse through it; a less-porous windbreak will tend to deflect wind over its top. The resulting windfields can be quite different (Figure 5.1b).

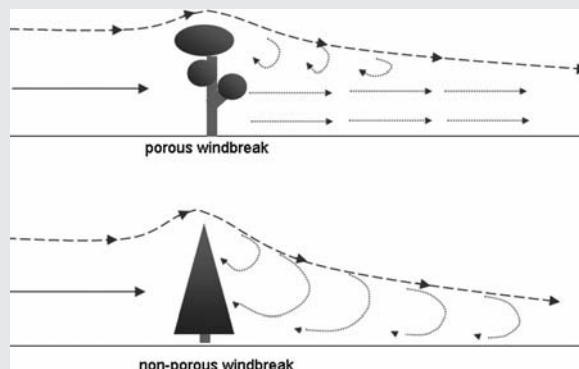


Figure 5.1b: Windfields differ according to porosity of a windbreak.

- **Orientation.** The ideal windbreak will be oriented at right angles to the prevailing problem wind. The area protected by a windbreak will be reduced as the approaching wind swings away from the perpendicular. If a windbreak is sufficiently long (its length is more than 20 H), shifts in wind direction up to an angle of about 30° from the perpendicular produce only small reductions in the distance sheltered. At greater angles the shelter distance declines rapidly, but even when the wind is blowing parallel to the line of trees the windbreak continues to shelter a small adjacent area because of the drag effect of the trees on wind flow (Figure 5.1c).
- **Location.** Windbreaks located on tops of ridges or other high points in the landscape provide shelter over larger areas than those planted along streams and other low points.
- **Length.** The sheltered area from a linear planting assumes the shape of blunt triangle. As a rule of thumb, windbreaks are most effective when they stretch for distances exceeding 12 H.
- **Width.** The main effect of windbreak width is simply related to the extent to which it influences porosity. The rule of thumb says that windbreak width should not exceed 5 H. If a windbreak is wider than this, the turbulence created above the windbreak means that there will be little sheltered area as the wind passes beyond the trees. Width is determined by number of rows and tree spacing, but porosity is also influenced by the presence of understorey species in any of the rows.

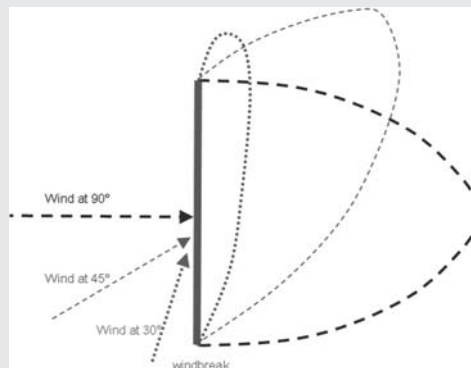


Figure 5.1c: A windbreak can provide shelter even when the wind is blowing parallel to it.

described in Box 5.1. With this knowledge comes the expectation that the shelter provided by trees will enhance the productivity of adjacent crops and pastures (Box 5.2); microclimate modification is the main mechanism leading to these benefits. However, measurements of this microclimate effect are variable and the mechanisms involved are many and complex. Much of the scientific research originated from countries with very different farming systems from Australia, with different tree species, soils and weather patterns. It is therefore appropriate to summarise this research to clarify the assumptions held

about the value of windbreaks in Australia, before comparing it to the results of the NWP.

Between 1932 and 1995 there were 80 reports on the responses of crops to shelter, involving approximately 700 field-years of measurement (Nuberg 1998). The majority of this literature focused on the relative response of crops in the sheltered zone of the windbreak, not reporting the net paddock yield when the area of land lost to trees was considered. Nevertheless, the overall average yield increases reported over the literature were 20% for

BOX 5.2

Mechanisms by which shelter enhances productivity of crops and pastures

There are several ways by which shelter is believed to improve plant productivity and reduce the variations in productivity due to climatic and biological fluctuations.

- **Shelter can reduce water loss** by shading or reducing wind speed. This can prolong pasture growth in summer and improve crop water use efficiency. As wind speed is reduced, soil moisture extraction is decreased and relative humidity and soil and air temperature is increased. This allows stomata to remain open, which will allow photosynthesis to proceed at a maximum rate.
- **Shelter modifies temperature.** Shelter will retain heat in the air and soil during cool seasons and prevent overheating in hot seasons. This can improve plant photosynthetic and metabolic efficiencies. Trees can also protect the ground from frost by reducing inward radiation during the day and reducing outward radiation by night.
- **Shelter reduces the mechanical damage** and sandblasting from strong winds. Small abrasions of leaf tissue can interfere with evapotranspirative efficiency and provide entry points for pathogens. Strong winds can flatten a crop, break branches of fruit trees and cause cosmetic damage to fruit.
- **Shelter may increase pollination efficiency** and fruit set in horticultural crops.
- **Shelterbelts are used to reduce drift** of chemical sprays from cotton fields and thereby extend opportunities for spraying in otherwise unsuitable weather.
- **Windbreak trees may provide habitat** for predatory birds and insects which may help control some insect pests.

cereals in cold temperate regions, 37% for non-cereals such as millet and maize grown in hot climates, 44% for forage crops such as lucerne and maize-silage and 26% for pulse and oilseed crops. There seems to have been less interest in the effect of shelter on pasture production, but similar aggregate values for temperate pastures are 28%, and cold-climate (e.g. Uzbekistan) pastures show a spectacular 180% increase in productivity (Bird 1998). Within these average values is great variation, because crop yield responses to shelter can differ greatly across seasons and the differences do not operate in a universally consistent manner. Part of the variation can be explained by the many mechanisms through which the shelter provided by windbreaks can affect crop and pasture production. There has been particular interest in microclimate as the mechanism to favour plant growth through conserving soil moisture.

Windbreaks can modify soil moisture in several ways. Of course they extract soil moisture for tree growth, but they can also reduce soil evaporation by shading and reducing the turbulent transfer of water vapour. They can create a rain shadow on the leeward side and trap rainfall on the windward side. The most frequently reported mechanism of soil moisture modification has been snow entrapment. In Siberia, meltwater from trapped snow can add up to 50 mm to soil moisture and the cereal crops grown in the sheltered zone. Such a bonus to the soil moisture store of an average Australian wheat crop would lift the yield by 65%. It's a pity it does not snow in the cropping zones of Australia.

In areas where it does not snow, the modification of crop energy balance and water relations has often been considered the primary mechanism for enhanced yield (discussed later). The crop energy balance of an agroforestry system is exceptionally

complex (Brenner 1996), but can be summarised as follows. Energy enters the system as incoming radiation and departs as outgoing thermal and reflected shortwave radiation, or energy is used in evapotranspiration and convective heat loss from the crop plant's leaf. Transpiration from the leaf is related to the difference in vapour pressure between the leaf and the air and resistance to the transport of water vapour. Heat loss from the leaf is related to the temperature difference between the leaf and the air and resistance to heat transfer. The resistance components are determined by the wind speed, atmospheric turbulence and leaf physiology. The main effect of trees on this energy balance is to intercept radiation, reduce wind speed and alter the turbulent structure of the air flow.

The shading effect of trees may not be significant in Australian rain-fed production systems where competition for light in water-limited environments is of minor importance compared to competition for water (Ong *et al.* 1991). The critical effect of trees on the energy balance is wind speed reduction. As air movement transfers heat away from the soil and leaf surfaces, daytime temperatures will typically be higher under sheltered conditions. The change in temperature is rarely more than 2°C but it can have an incremental and cumulative effect on crop phenology and physiology (Kelleher 1984).

A more critical effect of wind speed reduction under Australian cropping situations is the effect on transpiration and soil water. Reduced wind movement may lead to increased humidity at the crop canopy because less water vapour is transported away. This reduction in the vapour pressure gradient between air and leaf can lead to reduced transpiration and a saving of stored soil moisture for later use. However, this does not always occur when leaf temperatures and stomatal conductances are particularly high. An easy way to understand this is to refer to the Penman-Monteith equation, which describes transpiration from a leaf as a function of both energy and aerodynamic components (see Equation 1).

Canopy conductance is a measure of the ability of water vapour to move from the substomatal cavities through the stomata to the leaf surface. Importantly, it is an element of both the energy and aerodynamic components of Equation 1. Therefore, an increase in wind speed will lead to an

$$E = \frac{S\Phi_n}{\lambda \left[S + \gamma \left(1 + \frac{g_a}{g_c} \right) \right]} + \frac{\gamma \cdot g_a \Delta \rho_{va}}{S + \gamma \left(1 + \frac{g_a}{g_c} \right)}$$

Equation 1: The Penman-Monteith equation describes transpiration rate as a function of energy available for evaporation Φ_n , the vapour density deficit $\Delta \rho_{va}$, the canopy and boundary layer conductances g_c and g_a , saturation vapour density of water S , the latent heat of vaporisation of water λ and a psychrometric parameter γ .

increase in the aerodynamic component but a decrease in the energy-driven component.

The relative magnitude of the two components will determine if transpiration is increased or decreased (Thornley and Johnson 1990), which is why it is difficult to make generalised statements about the effect of shelter on transpiration and water use. Trees can favourably influence the energy balance of adjacent crops such that the evapotranspiration is reduced and soil moisture increased, resulting in less water deficit. This has been shown for paulownia-wheat agroforestry systems in China (Wu and Dalmacio 1991) and *Grevillia robusta* maize systems in Kenya (Huxley *et al.* 1994). However, transpiration may actually increase with a decrease in wind speed where the difference between stomatal and boundary layer conductances result in the water vapour gradient being much greater than the temperature gradient (Brenner 1996). In summary, soil water reserves may be conserved or depleted in the sheltered zone.

The Australian National Windbreak Program focused on the effect of shelter on crop yield through the mechanism of crop water and energy budgets. The results showed that the effect of shelter on plant production in Australian farming systems was not just a result of microclimate. The severe events and negative impacts of land lost to production and competition were also important in a dynamic mix with seasonal conditions, soil types and crop management issues. These mechanisms are described in greater detail later in this chapter.

Physical damage processes

There are several physical mechanisms by which wind damages crop growth. These effects are infrequent and severe, potentially occurring throughout the annual cycle with the timing likely to lead to a particular mechanism being observed.

This section provides a brief review of these mechanisms; more comprehensive reviews can be found in Miller *et al.* (1995), Cleugh *et al.* (1998) and Bennell and Cleugh (2002).

Wind erosion and severe dust storms are a common feature of life in southern Australia on farms and in the cities – large plumes of airborne dust periodically envelop urban areas. In South Australia, for example, a severe event in May 1994 caused a significant dust storm with a mass of about 8.6 million tonnes of soil (Butler *et al.* 1995). Drought conditions in the months leading up to the event and the lack of vegetative cover on cultivated paddocks ready for sowing were key factors. Such events not only have a significant impact on soil (and thus nutrient) loss and reduced crop yield, but also on public infrastructure and health.

The Mediterranean climate and friable sandy soils combine to create a significant wind erosion hazard, with wind-blown soil damaging plants by sandblasting. Other forms of wind damage commonly reported are flower abortion under hot dry winds and head loss at ripening in barley crops. Crop lodging also occurs but is not found to be common or damaging in southern Australia.

Direct damage: leaf tearing and stripping

Leaf tearing during severe wind events is reported as common for plants with large leaves in tropical regions. Cyclonic winds can have a significant effect: severe tearing in bananas results in smaller plants with reduced leaf area and reduction of all bunch yield components. Sugarcane losses included leaf loss, cane lodging and breakage. However, the role of leaf stripping in field crops due to severe wind events has not been the subject of intensive study. Instead, researchers have used mechanical treatments, such as clipping to simulate insect and storm damage, to provide useful information on the consequences of leaf loss and damage on plant productivity. For example, removing just the flag leaf or the top two leaves on wheat plants results in yield reductions, while grain nitrogen is even more sensitive to leaf loss than yield. Defoliation between heading and flowering has the greatest impact on yield.

Wind may induce leaf folding during the whip-lash motion of grass lamina and the cuticle may be broken in the folded region, leading to greater water loss, wilting, yellowing and death of leaf tips. Pit-

cairn *et al.* (1986) reported that microscopic leaf damage to *Festuca arundinacea* due to controlled polishing and abrasion impacted on plant performance through increased stomatal conductance. Wind drag can also remove healthy leaves on petioles, especially after some of the abscission layer has developed. This will not always reduce total photosynthesis of a plant, as the rate of photosynthesis in the remaining leaves often increases to compensate for lost leaf area.

Wind erosion

Wind erosion is an interacting set of physical processes that are broadly grouped into:

- weather conditions (in particular, infrequent high wind events in dry periods with low soil moisture);
- soil state (composition, texture, particle size characteristics and crusting);
- surface roughness (non-erodable soil aggregates and vegetation cover).

Apart from causing direct crop damage via the damage mechanisms described above (sandblasting, lodging and burial), wind erosion can impact on farm productivity through degradation of the soil resource. The most obvious impact is soil loss, with removal of fertile fine fractions and organic particles. The wind removes soil and nutrients from the paddock by winnowing. When the wind speed is high enough to lift and carry soil particles 0.1–0.5 mm in size they are bounced across the ground. As they return to the surface they splash up more particles, which in turn bounce across the surface. This results in an avalanching effect as more and more particles are mobilised. During this process dust particles (<0.1 mm) are carried into suspension. The larger particles (0.05 mm) gradually return to the surface within a few kilometres but the finer fractions (0.01–0.001 mm) may remain suspended for hundreds or thousands of kilometres. Nutrient loss is often not considered in the face of more gross erosion impacts of buried fences and damaged crops, however, the impact on future productivity can be significant. For example, the dust removed from a NSW paddock can have 16 times the total nitrogen and 11 times the organic carbon than the soil from which it was derived (Leys and McTainsh 1994).

Windbreaks reduce wind erosion

The establishment of windbreaks is a way to reduce wind speed across areas vulnerable to erosion, but involves the loss of land from production. Effective wind shelter requires successive belts of trees for across-paddock protection, as a windbreak only provides complete shelter for 15–25 times windbreak height. There are several other alternative agronomic strategies to control erosion that a farm manager needs to consider.

As soils vary in productive capability and erosion risk, they need to be farmed according to that capability. Soil texture is the best indicator of inherent erodibility, for example, the dunes and swales of the Murray mallee in South Australia have highly erodible light sandy soils on the dunes and heavier clay soils in the swales, with a low erosion risk. In some areas with sandy soils, water repellence is a major factor in the problem of low productivity and sand drift. Farmers spread clay to manipulate soil texture in response to this problem.

Improving cover through reduced tillage methods reduces erosion risk at crop establishment and improves organic carbon levels and greater soil aggregation. However, minimum tillage is not universally adopted nor appropriate and the degree of utilisation is partial, with extensive portions of the wheat-sheep zone still vulnerable during crop establishment. Managing grazing pressure is critical regardless of crop establishment methods to ensure that crop stubble protects soil during the fallow periods. For stubble to be effective, farmers need to manage the intensity of grazing it by destocking early and keeping cover levels greater than 50%.

These changes in soil management can effectively reduce wind erosion risk but windbreaks can contribute to risk management when, as often occurs, prolonged dry periods create situations where even the best managers struggle to maintain adequate cover.

Sandblasting

Sandblasting occurs when moving soil particles strike plant surfaces, thereby combining the processes of abrasion and tissue removal to affect the physiological performance of the plant (Cleugh *et al.* 1998). The risk of soil erosion varies as it depends on the duration and strength of winds, soil type,

amount of anchored plant residue, soil moisture and crop cover. While the risk of erosion can be reduced through agronomic practices such as minimising tillage and maintaining vegetation cover, in practice this is not always possible due to variable and low rainfall.

The probability of sandblasting is very difficult to determine, with a complex group of causal factors influencing the outcome. The extent of injury to a particular plant species depends upon wind speed, density and energy of the sand particles, duration of exposure, size, shape and density of the abrasive material, growth stage and condition of the plant, growing conditions and gustiness of the wind. The vulnerability of the crop species is critical in determining the impact of a sandblasting event on plant productivity. For example, farmers and agronomists in southern Australia have frequently expressed concern about the susceptibility of lupin to sandblasting damage. Lupins are the major legume species at risk, especially in Western Australia where there is a predominance of acidic sandy soils which are also highly erodible.

Unlike cereals, where the shoot apex remains underground during vegetative growth, the lupin meristem is above-ground after seedling emergence and is vulnerable to physical damage from sandblasting. Consequently the buds are easily damaged and the plants cannot recover by producing new shoots. The likelihood is that lupin will suffer greater damage and subsequent yield depression than cereals when subject to an equivalent amount of sandblasting. Lupins are particularly vulnerable during the establishment phase as the accumulation of leaf area and cover is slow during the first half of the crop life, when compared to cereals, and predisposes the crop to a greater risk of sandblast damage on wind-erodible soils.

Flower abortion

Hot and dry wind events characterised by low relative humidity (<25%), high temperature (>30°C) and high wind speed (>8 m/s) occur frequently in semi-arid to arid regions of the world with a Mediterranean climate. These conditions can have severe impacts on field crop production. In southern Australia they are noted for causing yield losses due to flower abortion and interference in grain filling in pulse and cereal crops. Pulse crops,

including lupin, faba bean and field peas, are particularly susceptible to damage (Bicknell 1991).

Generally there is a high degree of flower abortion with the number of pods harvested only a small percentage of the original number of flowers (Stoddard 1993). Pod set can vary in response to a lack of pollinating agents, low light conditions and drought or waterlogging. The interactive effects of moisture stress and temperature on faba bean are important and both can play a role in flower abortion and reduced pod set. The early pod stage has been found to be the most sensitive to moisture stress, with severe stress causing a reduction in yields. High levels of abscisic acid associated with stress induced by moisture deficit may also be a factor in flower abortion. Reproductive development can be damaged by heat stress through low pollen availability and may be particularly sensitive before anthesis.

High temperatures ($>30^{\circ}\text{C}$) during flower development in cereals may severely affect yield and quality. Sensitivity to temperature occurs at anthesis and early grain development and can reduce grain number and single-grain weight. The negative impact of hot dry days on wheat yield was measured in a semi-arid region of Israel. The general response to the occurrence of hot windy days was a yield decrease of approximately 1.2 t/ha^{-1} in low-rainfall conditions and 0.6 t/ha^{-1} in higher-rainfall conditions, compared with an average yield of 2.9 t/ha^{-1} (Lomas and Shashoua 1974).

The sensitivity of field crops to hot dry wind events at flowering is a potentially significant factor affecting final yields. The severity of this effect is not clearly understood due to a lack of knowledge of the processes involved and plant responses to the environmental drivers (temperature, humidity, wind speed, soil moisture and duration) at the time of an event.

Lodging

Two main types of lodging may result from severe wind (Cleugh *et al.* 1998). Stem lodging occurs when the plant stem breaks or bends, while root lodging occurs when the entire root system fails and the plant falls over. Cereal breeding programs have developed cultivars that are relatively resilient to stem lodging, while the wet conditions conducive to root lodging are not prevalent in the cereal-

growing regions of Australia. For these reasons, lodging as a form of direct wind damage to crops is not perceived as a large problem. Furthermore, even if a lodging event occurs, most farmers believe that the grain can still be harvested and so yield losses are minimised.

Another form of lodging of concern in southern Australia is the damage and removal of barley heads in response to hot dry winds at maturity. This was recognised in the 1960s in South Australia, where the Australian Bureau of Meteorology conducted a series of field experiments to develop predictive relationships between head losses and meteorological conditions, to provide an early warning forecasting service for the barley-growing regions of South Australia. While a range of damage is possible, from fractured necks to damaged spears, the greatest yield losses result when the fracture of the neck leads to loss of the seed head. Yield losses from this type of damage can be minimised by rolling or windrowing the crop if sufficient advance warning of adverse weather is provided.

Australian National Windbreaks Program

There has been almost a century of international windbreak research into the diversity of mechanisms by which shelter can enhance plant growth and we know that the intensity of their effects is determined by the climate, soil and farming system. Australia has a unique mix of these, thus international research can only say so much about the likely significance of windbreaks in Australian farming systems.

In Australia, there was very little windbreak research before the National Windbreaks Program (NWP), but what existed created an atmosphere of encouragement for propagating windbreaks across our dryland farming systems (Bicknell 1991 and Burke 1991, described in Nuberg 1998). However, natural resource management agencies need scientifically rigorous quantitative information before they can convincingly promote windbreaks. The NWP provided this quantitative understanding of the interaction between windbreaks, microclimate and crop and pasture growth, not without some surprises. It provided some definitive answers to

BOX 5.3

Shelter effects on microclimate and plant growth – results of NWP 1993–98

Bleed flow/competition zone (0–2 H)

- Competition for water, light and nutrients reduced yields at all field sites.
- Windbreak structure is important as gaps can lead to wind erosion and sandblasting damage.
- Shading can offset increases in air temperature that result from shelter (Figure 5.2).

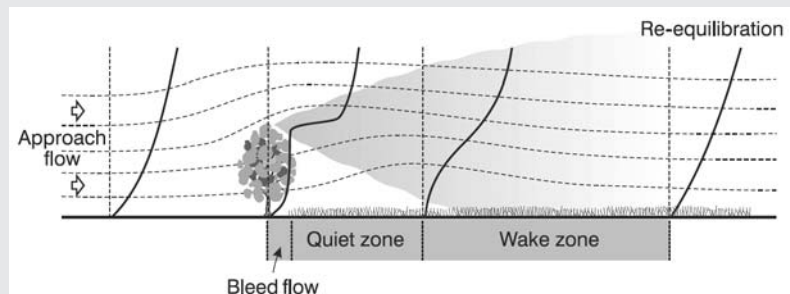


Figure 5.2: Shading can offset increases in air temperature.

Quiet zone (2–8 H)

- Calmer, warmer and/or more humid by day.
- Reduced soil evaporation may improve crop establishment.
- Atmospheric demand can be increased or decreased, depending on the humidity of the regional flow. In dry conditions, a reduction in atmospheric demand may lead to improved water use efficiency. This translates to more biomass and/or yield for the same water use as the crop upwind, or less water use than the upwind crop for the same biomass and/or yield.
- While enhanced phenological development and biomass production are possible, this does not always translate into yield gains.

Wake zone (>8 H)

- Effects of wind shelter on temperature and humidity are small.
- Shelter from wind reduces the risk of direct damage to plants from leaf tearing and stripping, plant lodging and sandblasting.

the values of windbreak in Australian dryland farming systems.

The partners involved in the NWP were spread broadly in terms of geography and types of farming systems studied. In Western Australia, research-

ers at Esperance studied wheat, canola, barley and lupins; in South Australia at Roseworthy wheat, canola and faba beans were studied. In Victoria, wheat and lupins were studied at Rutherglen (north Victoria) while grazed perennial pasture was the

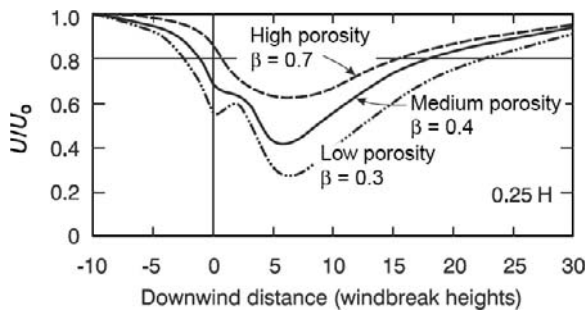


Figure 5.3: Relative wind speeds for model windbreaks of three different porosities (Cleugh 2003). β is the windbreak porosity.

focus at Hamilton. In Queensland, maize and potatoes were studied at Atherton, and at Warwick the crop modellers gathered extra data from studying mung beans and irrigated wheat. The research was largely in the form of field experiments, using both the conventional quadrant-plot measurements and GPS-assisted yield monitoring, complemented by experiments using artificial shelters, wind tunnels and crop simulation models.

Aerodynamic and microclimate changes behind windbreaks

A summary of the effects of shelter provided by windbreaks on microclimate and plant growth is given in Box 5.3. These were determined using wind tunnel and field experiments (Cleugh and Hughes 2002). The summary shows the presence of two zones downwind of a windbreak. The quiet zone is the zone of maximum wind speed reduction, where it is possible to detect significant modification of microclimate variables such as increased daytime temperature, humidity and reduced soil evaporation. The speed of the wind in the quiet zone has been reduced by transferring its kinetic energy into tree movement as it passes through the windbreak. The wind that passes over the top of the windbreak forms a turbulent mixing layer which eventually mixes with air at the ground surface in the wake zone. The wind speed is still reduced in this wake zone, but the microclimate effects are much smaller.

Before the NWP, porous windbreaks were often considered more useful than less-porous windbreaks because they absorb more energy from the wind. While a denser windbreak may reduce wind

speed more (to a maximum of about 80%), the effect was believed to extend to a reduced distance downwind because dense windbreaks create a faster-growing mixing layer that has the effect of more quickly re-establishing upwind conditions. Consequently, the windbreak literature often states that a windbreak with 40–50% permeability gives the greatest area of shelter. However, an important conclusion from the NWP is that for the range of porosities of windbreaks likely to be found in Australia (30–70%), there is little difference in the amount of sheltered area behind windbreaks (Figure 5.3).

For practical purposes, the downwind extent of shelter behind a windbreak is determined by windbreak height, wind direction and surrounding terrain. Nevertheless, porosity does determine wind speed and the degree of shelter is roughly similar to windbreak density, i.e. a windbreak with 30% porosity will reduce wind speed to 70% of the open-field speed at the most sheltered location.

Consistency of shelter is another factor affecting the practical value of windbreaks. The synoptic regime affecting cropping systems of southern Australia is characterised by a pattern of alternating high- and low-pressure weather systems. The high-pressure system brings fine weather and light easterly winds, followed by north-westerly winds ahead of the cold front associated with low-pressure systems over the Southern Ocean. These winds may strengthen and grow colder as they swing around to the west and south-west. Many farm windbreaks in southern Australia are oriented in a north-south direction to protect crops and livestock from these westerly winds. Long windbreaks still provide significant shelter, though over a shorter distance, even when the wind flows obliquely within 45° of normal. However, the microclimate advantages for plant growth in the quiet zone will be restricted to times when the wind is coming from the west. At other times these advantages are lost and the aggregate microclimate advantage over the whole growing season is diminished.

The microclimate advantages of shelter concern reduced turbulent flux, or mixing and movement, of heat and water between the soil, crop and atmosphere and therefore more conservative use of soil water and more efficient photosynthesis. All this

happens in the relatively small area of the quiet zone. As soon as the wake zone is reached the turbulent fluxes are actually greater than upwind of the windbreak. In the NWP, the little evidence there was for increased soil water storage in the quiet zone showed that it resulted in only slightly greater crop biomass, not greater grain yield (Nuberg and Mylius 2002). This is not surprising given the complexity of the effect of shelter on transpiration outlined above (referring to Equation 1). Combined with the inconsistent shelter due to weather patterns, microclimate advantages are subtle and limited. Indeed, crop simulations using APSIM (Agricultural Production Systems Simulator) estimated that wheat grown in the shelter of a hypothetical windbreak at Roseworthy, South Australia, which only experienced winds originating within a 90° arc perpendicular to the windbreak, would show a yield gain of 7.2% at 5 H (Carberry *et al.* 2002). As shown below, such yield enhancements were not realised because of the inconsistency of shelter, as well as soil factors, under field conditions.

Crop yield responses to shelter

The field responses observed in the NWP were as varied as the farming systems studied, but the results showed that in general two broad areas of plant response can be expected downwind of a windbreak: a zone of reduced yield caused by competition from the trees that extended from 1 H to 3 H, and a zone of unchanged or slightly increased yield that extended downwind from there to 10–20 H. The effect of shelter-induced microclimate changes on crop yields was not very great compared with measurements made overseas. This was particularly the case for cereal crops, unsurprising given that they are naturally well-adapted for windy grassland environments. Simulation models using long-term historical data indicate that this relatively modest response to shelter-induced microclimate changes will be found in other crop-growing regions in Australia (Carberry *et al.* 2002). Nevertheless, a closer look at some specific yield observations in the NWP reveals that there may still be very good reason for planting tree windbreaks in Australian farming systems.

On the south coast of Western Australia the yields of various crops were measured in the shel-

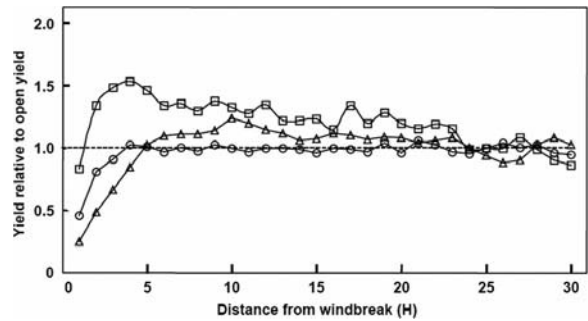


Figure 5.4: Mean crop yield in the lee of windbreaks relative to open conditions (20–30 H) in the Esperance district, WA, in a dry year (Δ 1994), years receiving average rainfall (\circ 1995–97) and a year with severe wind erosion (\square 1996) (Sudmeyer *et al.* 2002). Distances from windbreak are expressed as multiples of tree height (H).

tered zone of windbreaks at 63 fields over three years (see Figure 5.4). The strength of the response varied with crop type, windbreak orientation and seasonal condition. Windbreaks had the strongest shelter effect on cereal yields in dry years. However, even then the net result was minimal because trees compete for resources as far as 4 H into the paddock. Lupins were the only crop that consistently showed higher net yields on a sheltered paddock, with a mean increase from 1–20 H of 4% (Sudmeyer *et al.* 2002).

As part of the follow-up study on severe wind effects, grain yield data were collected from windbreak sites through the eastern agricultural districts of South Australia using a harvester equipped with a yield monitor.

Variability in shelter response occurs within field crops for a variety of reasons such as soil factors, nutrients, disease, rainfall distribution and prior land use in addition to the impact of wind. Analysis is a difficult task, particularly with the limited number of data points that can be gathered in quadrants harvested by hand or plot harvester. The use of a combine harvester fitted with precision yield-monitoring equipment to map spatial variation in grain yield gave an opportunity for analysis of variability that had previously been unavailable in field crops.

Figure 5.5 illustrates the type of generalised yield map generated using this approach. It shows a yield map for faba beans, the crop most responsive to the shelter provided by windbreaks. This is

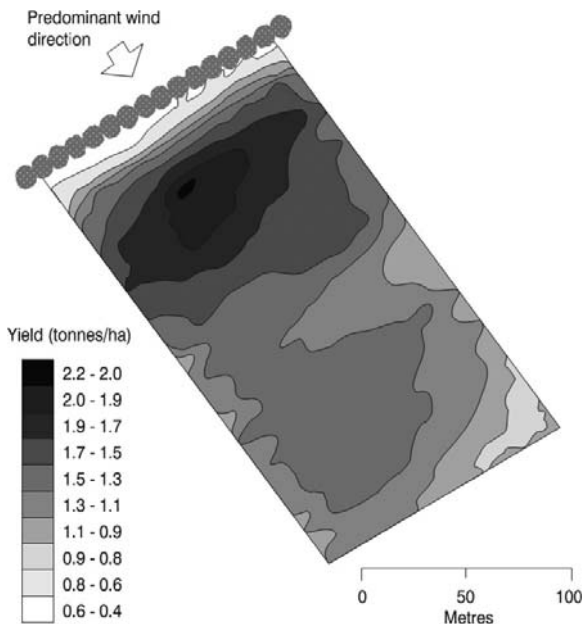


Figure 5.5: Yield map of faba bean in the lee of a NE-SW windbreak providing shelter from north-west winds in South Australia. The map clearly illustrates decreased yield due to competition adjacent to the windbreak, followed by a zone of significantly increased yield in the sheltered zone (Bennell and Cleugh 2002).

because faba beans are very sensitive to microclimate as well as flower abortion under hot dry winds. Cereal crops, with leaves and flowers adapted to windy environments, are much less responsive. Figure 5.6 illustrates the aggregate results from the South Australian yield monitor trials. While cereal crops showed a modest yield enhancement in the sheltered zone, this is virtually negated by the competition from the windbreak trees and confirms the earlier results from the NWP. In contrast, significant yield returns could be consistently expected from faba beans.

The study concluded that in areas where cereals are the predominant crop, the net yield gains due to shelter from windbreaks would be small, even if root pruning could be successfully undertaken. Much better gains are expected from legume crops such as lupin and faba bean, which seem much more sensitive to shelter.

The relatively poor net yield enhancements in cereals due to shelter in Australia are due to the relative wind-hardiness of cereals and the predominance of shallow soils with low water-holding capacity. The effect of shelter on crop energy balance and water use is complex and may increase or decrease transpiration and the conservation of soil moisture. It appears that, in Australian agricultural systems, where favourable microclimatic conditions may be observed in the sheltered zone, these do not usually lead to large yield benefits. They certainly do not increase net paddock yields, when tree-crop competition is included.

The largest yield gains observed in the NWP came from protection against infrequent strong winds that cause plant damage and soil erosion. We now turn to the role of shelter in protection against physical damage.

Protecting crops from physical damage

A key finding from the National Windbreaks Program is that wind damage resulting from severe wind events is likely to play a much more important role than previously expected in the response of crop yields to wind shelter. A cost-benefit analysis of windbreaks in Western Australia showed them to be a good form of insurance if sandblasting events occur more than once every seven cropping seasons

→Distance in tree heights away from windbreak→																				Net gain in shelter zone
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	
windbreak		Competition zone			Sheltered zone						Unsheltered zone									<1%
		+2% CEREALS																		11%
		+14% PULSES																		19%
		+20% FAB BEANS																		

Figure 5.6: Enhanced yields and net gain in the sheltered zone of three crop types between 1997 and 2000 in South Australia (Bennell and Cleugh 2002).

(Jones and Sudmeyer 2002). Following the first phase of the NWP, a follow-up study investigated the extent to which protection from damaging winds can modify productivity. This involved wind tunnel experiments and economic simulation models (Bennell and Cleugh 2002; Bennell *et al.* 2007).

Wind tunnel experiments

Wind damage events occur intermittently; they are characterised as low frequency–high magnitude events and are analysed in terms of probabilities of occurrence. The main risk factors for mechanical damage in southern Australia include sandblasting, flower abortion and head loss in mature barley crops. Direct physical crop damage by leaf tearing is not considered a problem for field crops.

As the occurrence of damaging wind events is unpredictable, the best way to quantify the relationships between wind damage and crop yield is to use a portable wind tunnel. Such devices can provide the high wind speeds needed to simulate sandblasting of seedlings, a hot dry wind on flowering plants or the impact of wind only on yield.

Wind tunnel experiments found that the grain yield of narrow-leaf lupins was reduced by 18% for a modest sandblasting event (a sand flux of 248 kg/m) that has the potential to occur every year. Extreme events are known to be characterised by sand fluxes over an order of magnitude greater. Where the wind tunnel was used to simulate hot dry wind events with an air temperature of 30°C and low relative humidity, rates of flower abortion increased with wind speed up to 12 m/s, by which point there was a 35% reduction in pod set below that observed in the control plants at flower development stages up to and including anthesis.

As the flowers develop they become less sensitive to the hot windy conditions, with abortion declining gradually from early developmental stages and showing a sharp decline in sensitivity after anthesis. Once the pod has set it is not vulnerable to extreme wind conditions and has a high chance of continuing to develop if moisture is available. The actual yield reduction observed in the field will depend on seasonal conditions and the timing of the event. Late in the growing season, lack of soil moisture will stop plant growth so flowers affected by the wind event may not reach a harvestable stage.

Examination of long-term climate records can provide insight into the risk of damage in a particular region. For example, meteorological records for Adelaide were used to estimate the probability of damaging events affecting pod set and grain yield in pulse crops in South Australia. Events where temperatures exceeding 28°C coincided with maximum wind speeds in excess of 10 m/s occurred with a frequency of one severe event every 7.2 years in September and one every 2.4 years in October. The September events are most likely to have an impact on yield, as flowers setting during this period have the greatest chance of developing through to harvestable pods.

Cost–benefit analysis of windbreaks

The NWP provided great insight into the mechanisms of shelter as they apply in Australian farming systems. There remained the question of the net financial costs and benefits of windbreaks, given that there are costs associated with planting and maintaining them and that their benefits may not be realised every year. The analysis required is complex because of the numerous interactions between physical factors (climate, soil types, windbreak design), biological factors (tree and crop species), management (rotations, tillage, tree-root ripping) and the financial costs of windbreak establishment and potential for commercial products. Bennell and Cleugh (2002) developed a simulation model to determine the potential net financial value of windbreaks integrated into cropping systems of South Australia.

The model simulated a hypothetical South Australian farm with an array of possible regional climates, crop rotations, soil types, tillage practices, windbreak type and spacing and windbreak management (root ripping to reduce competition with crops). The model incorporated existing crop yield, sand flux and farm economic models and used 25 years of historical climate records to predict the net financial returns to the hypothetical farm business under different scenarios. The simulated farm comprised three separate fields with each crop of the rotation cycle being cultivated in each year. This approach captured the impact of infrequent severe damaging events on all the constituent crops.

The model showed quite clearly that the net financial benefit of windbreaks varies greatly with region (soils, climate) and cropping system. For example, the outcomes for three scenarios representing current agricultural practices in South Australia were as follows.

- Windbreaks will provide positive financial returns where there are lupins in the crop rotation and there is a significant risk of sandblasting, i.e. lower annual rainfall and erodible soils. While this risk could be managed by maintaining high cover levels, not all farmers practise conservation tillage. Other factors such as drought will also limit the amount of cover. In such situations, windbreaks will provide positive financial returns. Systems with multiple parallel belts (alley farming) will provide more shelter, and net financial return, than a single windbreak along a paddock boundary. In drought years, when maintaining above-ground cover is particularly difficult, windbreaks will be the only way to reduce the risk of wind erosion, yielding a much longer-term financial and environmental gain as wind erosion strips paddocks of valuable nutrient-rich topsoil.
- Where cereal crops are grown in rotation with a pasture rather than lupins, the financial returns from windbreaks are negative. Windbreaks would be best considered as a strategy to manage the risk of infrequent severe wind events causing soil erosion, sandblasting, flower abortion and head loss but may not be economically profitable, even with root ripping.
- In heavier soils with improved rainfall, faba beans are often part of the crop rotation. Simulations showed that significant yield gains in faba beans could be achieved through the use of windbreaks. However, the minimal yield gains in the cereal part of the rotation, combined with other windbreak costs (establishment, maintenance and lost productive land), negated gains in the faba beans and the outcome was a negative return on the windbreak investment. Root-ripping windbreaks in these higher-rainfall areas led to only modest yield gains in the cereals and did not significantly improve the economic returns. Heavy soil types removed the impact of sandblasting on productivity, so mitigated the production benefits provided by windbreaks.

These results complement those from the south-east coast of Western Australia where, without wind damage, windbreaks reduced net agricultural returns (Jones and Sudmeyer 2002). In combined grazing-cropping systems, windbreaks spaced at about 200 m can improve net returns through the reduction in stock losses conferred by shelter (Bennell and Cleugh 2002). In the cropping and grazing lands of Australia, the multiple benefits of windbreaks must be captured. Much of the benefit will arise from the reduced risk of infrequent but damaging events, in both financial and environmental terms.

Conclusion

Windbreaks provide multiple services to cropping systems of southern Australia. While the crop itself retains its primacy in a farming system, windbreaks can be established as part of a whole-farm plan to confer benefits of:

- management of groundwater (Chapter 3, this book) and surface water and pollutants (Chapter 4);
- connecting remnant vegetation patches and providing habitat (Chapter 6);
- aesthetic plantings to soften and nourish the visual landscape (Chapter 8);
- opportunities for low-rainfall timber (Chapter 10) or firewood production (Chapter 11);
- enhancing the productivity of the livestock component in mixed farming systems (Chapter 13).

This chapter has shown that the value of windbreaks in enhancing the productivity of cropping systems lies mainly in protection from mechanical damage rather than from microclimate effects. This is because our cropping systems are dominated by cereal crops which are naturally adapted to windy environments. Other crop types, such as pulses and oilseeds which are open-flowering and have above-ground growth meristems, respond better to shelter (Grace 1988). These other crops also respond favourably to microclimate effects of shelter, especially in dry years. However, the combined loss of production due to competition effects at the tree–crop interface, and the loss of land from the windbreak itself, are likely to negate the beneficial effects of shelter in many southern Australian cropping systems. Furthermore, a fence-line wind-

break will shelter only part of a cropping paddock, and as wind will come from all directions over the course of a season there is little case for expecting a net financial gain from establishing windbreaks on the basis of enhanced crop yield alone.

There are clear exceptions to this. Windbreaks will provide positive financial returns where there is a significant risk of sandblasting and where wind-sensitive plants play a significant role in the crop rotation, e.g. the southern region of Western Australia where lupins are commonly grown. Sandblasting is the most likely negative wind effect in areas of light soils and frequent severe wind events. Sandblasting can also be managed by retaining high levels of ground cover, which is perhaps a better solution than windbreaks as minimum tillage options have other benefits for the farm. However, not all farmers practise minimum tillage and drought will limit the amount of cover. In drought years, when maintaining cover is particularly difficult, windbreaks will be the only way to reduce the risk of wind erosion, yielding a much longer-term economic and environmental gain as wind erosion strips paddocks of valuable nutrient-rich topsoil.

For cropping farmers, windbreaks may be a good insurance policy against crop damage and soil erosion, especially in dry years. As our climate is changing, the incidence of hot dry years and strong winds may increase and the protective value of windbreaks will grow. It would be folly to dismiss the value of windbreaks based on financial evaluations from historical climate data alone. Evaluation must include the other functions of the trees.

Given that there is a role for windbreaks in cropping systems, what should be their design?

The principles outlined in Box 5.1 are universal and can be applied to the design of windbreaks for Australian cropping systems. We know that:

- the consistency of windbreak porosity (lack of gaps) is probably more important than the porosity itself;
- within the range of windbreak porosities found in the field, the actual location of maximum shelter does not change;
- the relationship between porosity and level of wind speed reduction is relatively linear.

The vexing question for farmers and land use planners is how much of the landscape can be usefully occupied by windbreaks.

Fence-line windbreaks offer limited shelter to large cropping paddocks. For example, the actual sheltered zone of a 5 m high windbreak will only extend a maximum of 95 m into the paddock. A 40 ha paddock may be over 600 m so multiple windbreaks or alley farming systems will be needed to spread the shelter across the paddock. A practical minimum spacing for such a system would be intervals of 20–25 H, which provides useful wind speed reductions and thereby protection from mechanical damage. Livestock also greatly benefit from such shelter. Depending on orientation, this density of planting means that the field will be sheltered from winds from most directions.

Closer spacings at intervals of about 10–12 H would secure the maximum amount of shelter by increasing the frequency of quiet zones. Such a system may only be worthwhile when the trees themselves provide some productive value to offset the opportunity cost of lost cropping, and the interbelt crop would benefit from enhanced microclimate. This may be the case for a fodder-shrub alley system with lucerne. However, most fodder-shrubs rely on clear management of grazing duration to maintain their productive potential. They may be best in blocks in areas of the farm where lower returns from cropping could be expected. Tree belt or alley systems are suggested for the production of oil mallee in Western Australia (Chapter 15) because they trap excess water in the landscape via surface and subsurface lateral flows. In this situation, the shelter for the interbelt crop is a benefit secondary to those of groundwater management and salinity mitigation.

This is really the core guiding rule of effective windbreak design in cropping systems – that they provide multiple functions that enhance the whole-farm productivity and sustainability.

References

- Bennell M and Cleugh H (2002) 'Integrating windbreaks into southern Australia farming systems: managing the impacts of severe wind events'. Report for the RIRDC/Land and Water Australia/FWPRDC/MDBC Joint Venture Agroforestry Program, RIRDC Project Nos SAR-19A and CSL-10A, Canberra.
- Bennell MR, Leys JF and Cleugh HA (2007) Sandblasting damage of narrow-leaf lupin (*Lupinus*

- angustifolius* L.): a field wind tunnel simulation. *Australian Journal of Soil Research* **45**, 1–10.
- Bicknell D (1991) The role of trees in providing shelter and controlling erosion in the dry temperate and semi-arid southern agricultural areas of Western Australia. In *Proceedings of a National Conference. The Role of Trees in Sustainable Agriculture*. Albury, Vic., pp. 21–39. National Agroforestry Working Group/Bureau of Rural Resources, Dept of Primary Industries and Energy, Canberra.
- Bird PR (1998) Tree windbreaks and benefits to pastures in temperate grazing systems. *Agroforestry Systems* **41**, 35–54.
- Brenner AJ (1996) Microclimate modifications in agroforestry. In *Tree–Crop Interactions: A Physiological Approach*. (Eds CK Ong and P Huxley). CAB International/ICRAF.
- Burke S (1991) Effect of shelterbelts on crop yields at Rutherglen, Victoria. In *Proceedings of a National Conference. The Role of Trees in Sustainable Agriculture*. Albury, Vic., pp. 89–99. National Agroforestry Working Group/Bureau of Rural Resources, Dept of Primary Industries and Energy, Canberra.
- Butler P, Davies WJ and Leys JF (1995) ‘Dust storms in South Australia on 24–25th May 1994’. Dept of Primary Industries, South Australia. Technical Report no. 243.
- Carberry PS, Meinke H, Poulton PL, Hargreaves JNG, Snell AJ and Sudmeyer RA (2002) Modelling crop growth and yield under the environmental changes induced by windbreaks. 2. Simulation of potential benefits at selected sites in Australia. *Australian Journal of Experimental Agriculture* **42**(6), 887–900.
- Cleugh HA (2003) ‘Trees for shelter: a guide to using windbreaks on Australian Farms’. Joint Venture Agroforestry Program, Rural Industries Research and Development Corporation, Canberra. RIRDC Publication no. 02/059.
- Cleugh HA and Hughes DE (2002) Impact of shelter on crop microclimates: a synthesis of results from wind tunnel and field experiments. *Australian Journal of Experimental Agriculture* **42**(6), 679–701.
- Cleugh HA, Miller JM and Bohm M (1998) Direct mechanical effects of wind on crops. *Agroforestry Systems* **41**, 85–112.
- Cleugh HA, Prinsley R, Bird PR, Brooks SJ, Carberry PS, Crawford MC, Jackson TT, Meinke H, Mylius SJ, Nuberg IK, Sudmeyer RA and Wright AJ (2002) The Australian National Windbreaks Program: overview and summary of results. *Australian Journal of Experimental Agriculture* **42**(6) 649–664.
- Grace J (1988) Plant response to wind. *Agriculture, Ecosystems and Environment* **22/23**, 71–88.
- Huxley PA, Pinney A, Akunda E and Muraya P (1994) A tree/crop interface orientation experiment with a *Grevillea robusta* hedgerow and maize. *Agroforestry Systems* **26**(1), 23–45.
- Jones H and Sudmeyer RA (2002) Economic assessment of windbreaks on the southeast coast of Western Australia. *Australian Journal of Experimental Agriculture* **42**(6), 751–761.
- Kelleher FM (1984) Climate and crop distribution. In *Principles of Field Crop Production*. (Ed. JE Pratley). Sydney University Press, Sydney.
- Leys JF and McTainsh GH (1994) Soil loss and nutrient decline by wind erosion: cause for concern. *Australian Journal of Soil and Water Conservation* **7**(3), 30–40.
- Lomas J and Shashoua Y (1974) The dependence of wheat yields and grain weight in a semi-arid region of rainfall and on the number of hot, dry days. *Israel Journal of Agricultural Research* **23**, 113–121.
- Miller JM, Bohm M and Cleugh HA (1995) ‘Direct mechanical effect of wind on selected crops: a review’. CSIRO Centre for Environmental Mechanics. Technical Report no. 67, 1–68.
- Nuberg IK (1998) Effect of shelter on temperate crops: a review to define research for Australian conditions. *Agroforestry Systems* **41**, 3–34.
- Nuberg IK and Mylius SJ (2002) Effect of shelter on the yield and water use of wheat. *Australian Journal of Experimental Agriculture* **42**(6), 773–780.
- Ong CK, Corlett JE, Singh RP and Black CR (1991) Above and below ground interactions in agroforestry systems. In *Agroforestry: Principles and Practice*. (Ed. PG Jarvis) pp. 45–58. Elsevier, Amsterdam.
- Pitcairn CER, Jefree CE and Grace J (1986) Influence of polishing and abrasion on the diffusive conductance of leaf surface of *Festuca arundinacea* Schreb. *Plant Cell and Environment* **9**, 191–196.

- Stoddard FL (1993) Limits to retention of fertilized flowers in faba beans (*Vicia faba* L.). *Journal of Agronomy and Crop Science* **171**, 251–259.
- Sudmeyer RA, Adams MA, Eastham J, Scott PR, Hawkins W and Rowland IC (2002) Broadacre crop yield in the lee of windbreaks in the medium and low rainfall areas of south-western Australia. *Australian Journal of Experimental Agriculture* **42**(6), 739–750.
- Thornley JHM and Johnson IR (1990) *Plant and Crop Modelling: A Mathematical Approach to Plant and Crop Physiology*. Clarendon Press, Oxford.
- Wu YY and Dalmacio RV (1991) Energy balance, water use and wheat yield in a Paulownia-wheat intercropped field. In *Agroforestry Systems in China*. (Eds ZH Zhu *et al.*) pp. 54–65. CAF/IFDC.

6

Biodiversity and habitat enhancement

David Salt and David Freudenberger

This chapter aims to define the concepts of biodiversity and habitat, and discuss the role that agroforestry can have in enhancing biodiversity in agricultural landscapes. A set of principles is outlined that will help in planning and managing an agroforestry enterprise for biodiversity. Case studies are provided to illustrate the concepts.

Introduction

While there are no conclusive studies establishing the precise biodiversity benefits that agroforestry can provide, most of the evidence strongly suggests that tree plantations, even if they contain a mix of natives, are not a substitute for a native forest or a patch of remnant native vegetation. They simply do not have the structural complexity, the mix of ages nor the range of resources necessary to support a diverse assemblage of native animals and plants.

However, an agroforestry planting can provide several resources necessary for some of the wildlife and native plants present in a region. Agroforestry, if planned sympathetically with the retention of existing native vegetation, can have significant conservation benefits. Further, it is possible to modify a plantation and its management in many ways that do not cost too much in lost production or forgone opportunities.

An agroforestry planting may serve as an asset to biodiversity if it is appropriately established and maintained, but a poorly implemented plantation can prove the opposite – a damaging environmental

liability. Not only might it contain little of value for local native biota, but it could also have serious negative impacts on what is already present in the area. For example, if the plantation is established at the expense of remnant native vegetation it is unlikely that plantation will ever produce a net benefit for the native biodiversity of that area.

Defining biodiversity

The National Strategy for the Conservation of Australia's Biological Diversity (released in 1996) defined biodiversity as:

The variety of life forms: the different plants, animals and micro-organisms; the genes they contain; and the ecosystems they form. It is usually considered at three levels: genetic diversity, species diversity and ecosystem diversity.

This succinct and widely accepted definition does not make explicit the inherent and underpinning structural and functional aspects of biodiversity.

Noss (1990) recognised that biodiversity is not simply the number of genes, species or ecosystems in a defined area. Knowing that one area contains 500 species and another contains 50 species does not indicate how these species are arranged (structured) or what they do (function). Noss developed a simple conceptual framework for identifying specific and measurable indicators of compositional, structural and functional biodiversity (Figure 6.1). Biodiversity is much more than a list of species

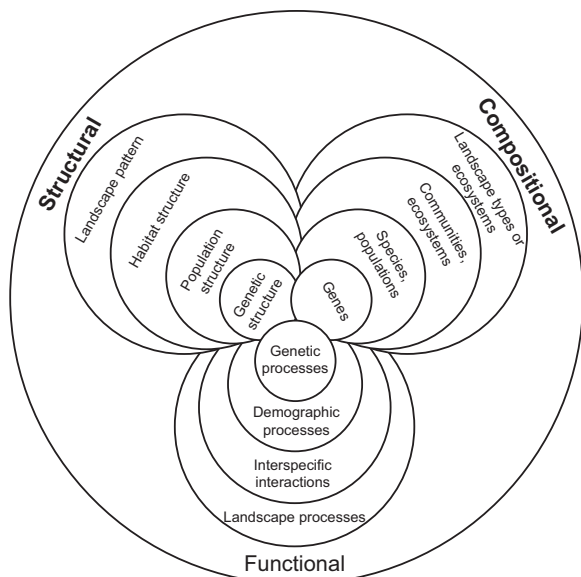


Figure 6.1: A simple conceptual framework for identifying specific and measurable attributes of biodiversity (adapted from Noss 1990).

found in a stand of trees. Rather, it is how these species are arranged or structured in space and how they interact with their environment that matters. So, for the following discussion we use a broader definition of biodiversity: it is the variety of life, what it is called (composition), how it is arranged (structure) and what it does (function) at a range of scales, from genetic to global (based on Noss 1990).

An example of composition, structure and function as distinct aspects of biodiversity can be seen in before-and-after surveys of forest plots in the Brindabella Mountains, to the west of the ACT, following the January 2003 bushfire (Doherty and Wright 2004) (Figures 6.2a, 6.2b). While the floristic composition of the forest is returning rapidly to pre-fire composition after an initial increase in species richness post-fire, the structure of the forest was greatly simplified to a few burnt stags with epicornic growth and a low understorey of regenerating plants, and this will take many years to re-establish a similar pre-fire structure. In the case of areas in the northern parts of the Brindabellas on acid volcanic soils, water quality was maintained after the fires. However, in areas on granitic geology in the Cotter catchment, the function of the forest was greatly altered by the fire. For six months after the fire, the forest in these areas no



Figure 6.2: (a) Before and (b) after photos of forests in the Brindabella Mountains, west of Canberra. The formerly forested landscape was converted into a mass of burnt spindles and resprouting shrubs. Floristically the ecosystem is the same but its structure and function have been dramatically modified (photos by Michael Doherty).

longer effectively filtered water runoff and the dams in the Cotter catchment became too full of suspended sediment to be used for Canberra's water supply.

This chapter will focus on how agroforestry can enhance the compositional and structural attributes of biodiversity. Chapters 2–4 have already discussed how biodiversity, particularly trees, can enhance the functionality of the landscape (e.g. water balance and nutrient cycling).

Enhancing habitat

Habitat refers to the environment in which individuals and populations of a species live. Habitat is a continuum across a landscape, and can also be thought of as the environmental niche that a species occupies.

There are two key features of habitat that must be kept in mind: irreplaceability and complementarity. Some habitats cannot be replaced. Old growth forests are unique. They are the result of millions of years of evolution in a given place and time. Once an old growth habitat, be it a wetland, grassland or woodland, has been cleared, it cannot be replaced in its entirety. The best we can do is mimic or replace some aspects of old growth habitat, but agroforestry can never fully replace the remarkable and ancient diversity of species and functions found in old growth forests. The irreplaceability of these forests has increased as they have become fragmented by clearing for agriculture, plantation forests and urbanisation.

Any patch of habitat occurs in a context of other habitat patches across any given landscape. Habitat patches are complementary, that is, they contribute to a greater whole. An agroforestry planting will complement other habitats depending on what else is around. A 1 ha planting of blue gums has little complementary habitat value if it is just another hectare in a 10 000 ha blue gum plantation. However, the same 1 ha planting may have high complementary value if it buffers a remnant patch of old growth woodland otherwise surrounded by a sea of wheat stubble.

When assessing the possible contribution an agroforestry planting (or design) might make to biodiversity, it ultimately comes back to these two key features: irreplaceability and complementa-

ry. That assessment can be simply phrased as two questions:

- **Irreplaceability:** does the planting involve the destruction or decline of existing habitat (such as remnant forest or native grassland)?
- **Complementarity:** does the planting offer additional resources that will complement or protect existing habitat?

Sometimes the answer is obvious. For example, if the establishment of a plantation involves the clearing of remnant vegetation then it will have a negative impact on an area's biodiversity. No matter what is done with the planting, it won't be able to fully replace the composition, structure and function of the remnant vegetation. For example, many of the features of a patch of mature native forest (e.g. tree hollows) often take more than 100 years to develop.

Sometimes the outcomes are less clear and are difficult to assess in advance. If a planting is done on land previously dominated by exotic pasture and involves growing a mix of local native trees, it might well have a positive impact on an area's biodiversity. The value of that impact, however, will depend on a range of factors relating to the location, configuration, composition, complexity and management of the planting. The following section presents a set of principles that will help maximise the benefit of a planting for biodiversity.

Modifying agroforestry to enhance biodiversity

When a landowner or farmer considers an agroforestry planting, they usually go through a series of steps. First they examine their land and consider where a planting might go. Next there might be consideration of the size and shape of the planting, then what types of trees might be put in. The process takes into account any special needs of the planting and ongoing management considerations.

At each step there are various factors to keep in mind: profitability, opportunity cost, accessibility and possible environmental outcomes. Enhancing biodiversity is one outcome that can be planned for and the following discussion outlines principles to consider when making

CASE STUDY 1

Agroforestry pays its way at Danengate

Danengate is a grazing property near Hamilton in Victoria. In 1947, Danengate had over 600 remnant eucalypts. By 1987, only 37 remained. In most respects Danengate was just like any other grazing property in the area: it was lacking in native cover, old trees were declining, there was heavy dependence on chemicals for pest control, and stock was vulnerable to cold weather events.

In 1987 Danengate was purchased by Don and Jann Jowett, whose vision for the property included a range of tree plantations integrated into other grazing activities. Paddocks were surrounded by fenced corridor/shelter belt plantings (two to three rows wide), with some small circular woodlots (0.4–1 ha) established within the paddocks (see Figures 6.3 and 6.4). The shelter belts and woodlots now provide timber, shelter and biodiversity, while pastures and stock provide annual cash flow. With small paddocks, shelter is always close at hand and birds feed on insects and seeds in the nearby pasture. Based on observation, Don and Jann now make shelter belts four rows wide to improve their biodiversity value.

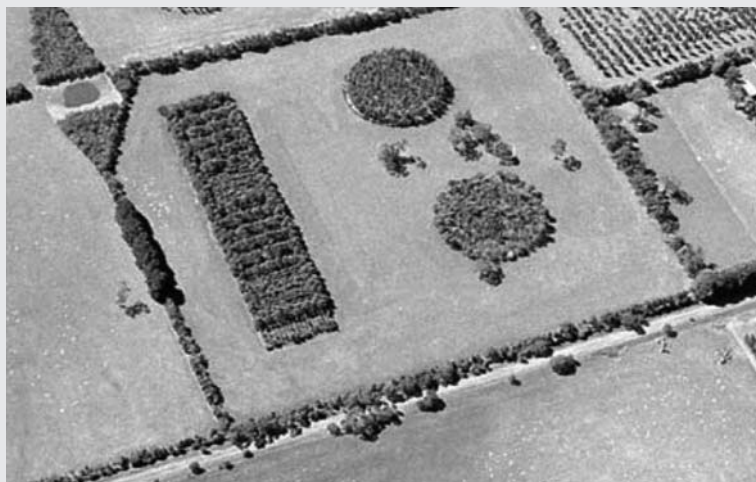


Figure 6.3: Aerial view of one of Danengate's paddocks. The upper circular planting is manna gum and the lower circle is a variety of sheoaks. The block planting is blackwood. Agroforestry at Danengate is providing a range of ecosystem services and will become an important part of the farm's income stream (photo by Don Jowett).

On average, 1–2 ha of timber trees have been planted each year since 1989. These include blackwood, black wattle, drooping sheoak, river sheoak, swamp sheoak, Monterey cypress, Mexican cypress, manna gum, mountain grey gum, Sydney blue gum, river red gum, spotted gum and radiata pine. The aim has been to plant 30% of the property to trees, with 5–10% permanently fenced off.

To some, the Jowetts are mavericks, but their new ways are paying dividends. In 1987–92, pastures required regular spraying for cockchafers and red-legged earthmite. Since 1992 no pasture has been sprayed or has needed spraying. In 1989–90, all plantations required spraying for spitfires, leaf blister and looper caterpillars. Since then, trees on Danengate have not been sprayed

for insects, nor have they required it. Don and Jann conclude that their revegetation activities have improved the biological control of pest insects of pastures and trees.

On 1 December 1987, an unusual weather event (snow, rain and wind) killed 50 000 sheep in the area surrounding the property. Today, sheep off-shears can be placed into any paddock on Danengate with safety. In the early 1990s, lamb losses were significant in the exposed western areas of the farm, which precluded the use of those paddocks for lambing. Today, ewes are lambed in all paddocks with few, if any, losses from the cold.

Blocks of agroforestry can be seen as ‘green insurance’. No one wants to make a profit from insurance; no one wants to have their house burnt or their car written off in a crash. Like insurance, trees can reduce risk of damage from severe storms and even reduce the rate of bushfire spread.

Overall, Don and Jann have no doubt that productivity is greater now than it was before areas of the farm were retired from grazing to grow trees. Their figures indicate a 320% increase in sheep numbers despite 33% of the original area of pasture being devoted to trees. On Danengate, ecosystem services are an important and nurtured source of farm income.



Figure 6.4: Well-fed, well-sheltered sheep feed under spotted gums at Danengate. In the distance is a shelter belt of mixed natives (photo by Rod Bird).

Source: Bird and Jowett, ‘Danengate’, case study 4 in Race and Freudenberger (2003).

decisions on location, configuration, composition, complexity and management. This framework of principles is based on Salt *et al.* (2004), which also provides detailed discussions of most of the research examples cited.

Location

The placement of agroforestry plantings greatly affects their habitat values. The most important consideration is avoiding the removal or decline of remnant native vegetation, including native grasslands.

The focus of most agroforestry is on the establishment of trees in agricultural landscapes where most of the original native vegetation has been cleared. Where trees are established on land previously used for farming, usually on exotic pastures, there is real potential for the planting to improve the biodiversity value of an area. When considering the location, it is vital to assess how the tree planting will relate to the remnant vegetation on or around the property. There are four principles to consider when discussing location: adjacency, connectivity, landscape context and the protection of waterways.

Adjacency

Agroforestry blocks will usually support a greater diversity of species if planted near existing remnants than if planted many kilometres from a sizeable remnant. Being close makes it easier for native animals and plants to access any resources offered by the tree planting. Surveys of blue gum plantations in Western Australia, for example, have shown that a range of birds, including some judged to be at risk, used plantations but that this mainly occurred where a plantation was close to patches of native vegetation (Hobbs *et al.* 2002).

Adjacent plantations also offer some degree of shelter to patches of remnant vegetation. Being too close, however, carries the risk that the tree plantation might place other pressures on the patch of remnant vegetation. These pressures include competition for available water by plantation trees, the invasion of the remnant patch by plantation tree seeds (Lindenmayer and McCarthy 2001), encroachment of pests (Hobbs *et al.* 2002) and hybridisation with remnant vegetation. The impact of management strategies such as pesticide and herbicide sprays drifting into the remnant patch are additional pressures.

Although there are no studies that indicate an optimal distance between a tree plantation and a patch of remnant vegetation (in terms of maximising its biodiversity value while minimising adverse impacts), a good precautionary approach would be to have the plantation separated from remnant vegetation by a buffer planting of a variety of local natives.

Connectivity

Agroforestry can also be used to reduce the isolation of remnant forest habitats by providing corridors and stepping stones to assist in the movement or dispersal of plant and animal species (Figure 6.5). Dispersal is often needed when a patch of habitat is burnt out and species must recolonise the burnt patch from an unburnt refuge. Dispersal is also essential for wildlife species that spend all or parts of their lives in more than one patch of habitat.

For example, a radio-tracking study of how greater gliders used remnant vegetation and pine plantations found that while the animals largely stayed within the patches of remnant vegetation (eucalypt forest), they occasionally used the pine forest to move from patch to patch (Lindenmayer



Figure 6.5: Shelter belts connecting patches of remnant vegetation add connectivity to a landscape (photo courtesy of Greening Australia ACT/SE NSW).

and Pope 2000). This finding suggests that the pine forest provided some value to the gliders in connecting the various patches of native vegetation.

Connectivity is about a species' ability to move through a landscape. Many studies have shown that some animals can move through trees but will not cross open paddocks; structures like logs may assist an animal moving through a plantation (Curry 1991).

Landscape context

The landscape context of a planting is also important. Attributes of the broader landscape, such as percentage cover of native vegetation, will have a bearing on the likelihood of the planting being used by native animals and plants. For example, there are generally many more bird species in landscapes with a 70% cover of native trees than in landscapes with only 10% tree cover. Hence there are likely to be many fewer birds in a plantation surrounded by only a 10% cover than in one surrounded by a high percentage cover of native vegetation.

A study in landscape size areas in the Northern Plains region of Victoria (Bennett and Ford 1997) found that the occurrence of woodland birds varied significantly between landscapes. The number of bird species was best predicted by total tree cover and the number of streams. The analysis indicated that woodland birds are sensitive to the total amount of native vegetation found in a landscape, and implied a substantial loss of species in landscapes that have been almost entirely cleared of woodland habitat (Radford *et al.* 2005).

Guidelines on location

Consider a map or plan of a property where agroforestry is being considered. Mark in areas of high biodiversity value. These include patches of remnant native vegetation, rocky outcrops, isolated native trees and watercourses. Locate plantations so that they complement these areas:

- site plantations to complement existing remnant vegetation (e.g. protect or connect patches of native vegetation, or site the plantation close to native vegetation);
- in the case of extensive plantations, incorporate patches of remnant vegetation within plantings;
- establish plantations around a riparian zone to protect this important area;
- join forces with your neighbours to control pests (e.g. foxes) and jointly create biodiverse plantings across property boundaries.

Protection of waterways

In terms of biodiversity value, the edges of creeks, streams and rivers (the riparian zone) should receive high priority for revegetation since they form an interconnected system of natural corridors throughout a catchment (Lindenmayer and Peakall 2000), they often provide rich habitats for wildlife, and revegetation along streams has many other benefits for water quality, aquatic environments and the reduction of soil erosion.

Farm forestry can play a role in protecting this valuable area by being used as a buffer zone around the edges of, but not within, riparian vegetation and corridors. High priority should be given to protecting and enhancing riparian zones before effort is put into other kinds of corridors.

Configuration

The size and shape of a patch of remnant vegetation or a nature reserve can have an important influence on what animals and plants will be found in that patch, and has relevance to the design of an agroforestry planting.

Size

Large blocks of remnant vegetation (and possibly agroforestry plantings) generally support more species than do small blocks or remnants. This is because more resources, such as insects for birds (Zanette *et al.* 2000), are available in 10 ha than in 1 ha. Large blocks are also likely to sample a greater variety of microhabitats including depressions,

ridges, drainages and slope aspects, than a small patch on just one north-facing slope.

Studies of wildlife in patches of remnant native vegetation have consistently shown that the bigger the patch the greater the range and number of animals it can support (Bennett *et al.* 2000; Lindenmayer 2000). While this has relevance to farm forests where bigger is better, size is not the only important factor. A large plantation of one species won't necessarily provide greater biodiversity value than a smaller mixed planting. This is especially the case if the plantation is managed as an agricultural crop with high chemical inputs. What is contained in a patch of vegetation, its mix of ages and structures, is just as critical as size. However, all other things being equal, if there is a diversity of plant species, ages and structures, then size becomes an important factor.

Large patches tend to be more diverse than small patches, but the habitat values of small patches and even of individual paddock trees should not be dismissed (Gibbons and Boak 2002). Research has documented a remarkable diversity and abundance of bats feeding on paddock trees in the Riverina of New South Wales and Victoria (Bennett and Lumsden 2003). Squirrel gliders have been found to feed in paddock trees as long as they are within the gliding distance (<70 m) of larger remnants. Even dead paddock trees can provide habitat if they have hollows. These stags should not be removed when establishing an agroforestry planting. In time their fallen branches provide the

Guidelines on configuration

- Consider establishing one larger plantation rather than several smaller separate plantations.
- Plan for shapes that minimise the edge to area ratio (i.e. circles and squares rather than thin rectangles).
- Think about arranging plantations so that they connect rivers to ridges, and include existing remnants wherever possible.

basis of a taxonomically and functionally diverse food web of fungi, beetles and spiders, and the reptiles and birds that feed on these prey.

Shape

Width affects the habitat value of a patch of vegetation. Long and narrow patches are mostly edge, which have little core for species that need protection from edge effects such as light, wind and the nutrients and weeds brought in by wind. However, there are many species that thrive on the resources presented in 'edge' situations, for example, food resources for birds and bats and increased light for shade-intolerant native herbs. A long linear remnant that runs from river bed to ridge is likely to be more biodiverse than one that sits in only one land class (e.g. upper slope). Not surprisingly, such river-to-remnant patches are rare in the landscape due to their interruption with productive agricultural land. Agroforestry has the opportunity to recreate, in part, such strips.

Shape also influences the ability of some organisms to collect food and find shelter from predators. Many possums and birds establish a circular or elliptical territory in which they forage and roam (Recher *et al.* 1987). Long thin patches of vegetation are not suitable for these species because they cannot gather sufficient food relative to the energy required to do so.

Composition

Currently, most tree plantations across Australia consist of a single species. In many cases that species is an exotic conifer, such as radiata pine. The composition of a planting can play an important role in what native animals and plants it will support. Composition can be split into two principles: mixed species and local species.

Mixed species

All trees, even pines and willows, provide habitat. Some species of bug or bat, native or feral, will find a home in a tree, either for a few hours or for a lifetime. There are simply a greater number of homes or niches available when various tree species are available than in a monoculture of trees.

A variety of plant species in a plantation provides resources needed by other plants and animals, so the greater the number of tree or shrub species included in a planting, the better the chances of other flora and fauna occurring there. A variety of plant species that produce fruits or flowers throughout the year will increase the range of animals that can be supported. If the commercial nature of a plantation means that only one species is being considered, a buffer of mixed native species adjoining the plantation should be considered.

Choosing a combination of species to include in an agroforestry planting involves more than selecting from a catalogue of species names. Factors include where the species comes from, and genetic variation within a species. For instance, a species like red gum is far more tolerant of salinity than other species are. Seeds from isolated trees may have less genetic variation than seeds from trees in large remnants, and seedlings from isolated trees may have high rates of hybridisation.

Local species

Plant species local to an area are more likely to provide food and shelter for local wildlife than are exotic plants. In general, native plants (especially those growing in the local area) will be of more value to a wider range of native animals than exotic species. The exotic radiata pine, for example, is Australia's most extensively used plantation tree. Being a conifer without flowers or fruit, it provides

Guidelines on species composition

Where possible:

- select native species rather than exotic species;
- select native species from the local area rather than native trees from different regions;
- use more than one tree species;
- establish understorey with native shrubs and/or native grasses.

no food for nectar or fruit-feeding animals. Its leaves are clusters of pine needles, quite different from the broad leaves of eucalypts which many of our insectivorous birds are adapted to forage on and around.

Local plants have features to which local animals are adapted. Local eucalypts, wattles and banksias, for example, produce nectar and fruiting structures, and support a variety of insects that serve as food to a wide range of birds naturally occurring in the local region. Plantings of local species may need to be tailored to suit local soil, landform and topographic conditions. For example, species that grow on ridgetops are different from those that grow along creeks and in low-lying areas. In some cases, local plants may no longer be appropriate if environmental conditions have become highly altered. For instance, salt-tolerant species of trees and shrubs may need to be imported from an arid zone to cope with saline discharge areas that did not exist in higher-rainfall zones 50 years ago.

Complexity

A major barrier preventing commercial tree plantations from providing habitat for native wildlife is their lack of complexity, since they often consist of one tree species of one age with no understorey. Three principles are discussed under this heading: structural complexity (layers of vegetation, ground cover, rocks, logs etc.); time and age of planting; and patchiness.

Structural complexity

Many species need particular structures such as logs, rocks, large trees and hollows in their habitat to survive. Structural complexity refers to the idea

that the greater the range of physical structures in an area, the greater the number of opportunities for animals and plants to find the resources they need to exist there.

When this concept is applied to a stand of trees, it incorporates layers of canopy – the more layers of vegetation there are, the more niches there are for animals to forage in and the greater the number of locations for plants such as mosses and lichens to become established. Ideally this would include understorey shrubs or native grasses, taller mid-storey shrubs or small trees, and an upper canopy of taller tree species. Understorey has been shown to be a vital element of habitat for many species of mammals, birds, reptiles and invertebrates (Catling and Burt 1995), but it doesn't have to be a layer of shrubs. It might consist of native grasses. The ideal situation for biodiversity would be a collection of plant communities and layers that resembles the vegetation that originally occupied the site.

Structural complexity also encompasses the idea of biological legacies – what structures and residues are passed on when a stand of trees is harvested or disturbed by a storm or fire. What's left in the newly regenerating stand strongly affects the recovery of plants and animals (Bonham *et al.* 2002).

Time and age

Habitat structure or complexity obviously changes over time. For instance, a tree seed provides a feeding habitat for a harvester ant or a home to a beetle larva. A seedling is a food source for a browsing wallaby. Seedlings that escape browsing and grow into trees provide a habitat for a remarkable diversity of insects that become food for a range of birds and bats (Majer *et al.* 1999). The few trees that



Figure 6.6: It is unlikely that the woodlot of blue gum in the background will ever generate the features such as tree hollows present in the old apple box in the foreground. This remnant tree is a vital component in protecting the local biodiversity (photo by David Salt).

survive long enough to become infested with fungi and termites then provide hollows for over 303 species of Australian vertebrates.

Hollows are important structures that only form in trees 120–180 years old. Clearly, hollows will not form in plantation trees because they are harvested before hollows can develop. Also, not all trees can develop the right kind of hollows for animals to utilise. Nest boxes may sometimes enhance biodiversity in plantations where the number of tree hollows are limited (Smith and Agnew 2002), but are an expensive and labour-intensive strategy that does not offer an effective long-term solution (Gibbons and Lindenmayer 2002). However, a good strategy to ensure that some tree hollows are available in the landscape is to retain old paddock trees in and around plantations, even if the trees are dead (Grabham *et al.* 2002). If plantations include a non-harvested buffer strip (e.g. adjacent to existing remnants) these trees will, over time, develop hollows.

The older a patch of vegetation or stand of trees, the longer it's had to generate the features and variety of structures that might provide suitable habitat for native plants and animals. For example, older trees may undergo heavy flowering and thus seeding peaks, or carry large accumulations of bark

that are not features on younger trees (Figure 6.6). These attract particular forms of wildlife.

Patchiness

Patchiness is an extension of the principle that animals and plants need resources that are found in different areas at different times. If a landscape contains a wide variety of patches that differ in terms of vegetation age, composition of plant and tree species present, degree of structural complexity or the proximity of other patches, it is more likely to meet the resource needs of different species.

Patchiness is about variety over distance. There are many more habitats, hence species and the processes they support, in a landscape with patches of forest, grassy woodland, grasslands, riparian woodlands and ephemeral wetlands, than in uniform landscapes without such diversity (e.g. hectares of cropland or pine forest).

In terms of tree plantations, patchiness can be achieved by planting clumps or strips of different tree species next to each other or, if a single species is being used, by having trees of different ages in adjacent patches. In extensive plantations, patchiness can be achieved by conserving patches of native forest, woodland or grassland within the boundaries of a plantation to produce a landscape mosaic rather than a plantation monoculture. Other features that can add to landscape heterogeneity and enhance biodiversity include dams, well-designed firebreaks and the retention of remnant paddock trees (Klomp *et al.* 2001).

Management

Enhancing the biodiversity values of landscapes with agroforestry plantings requires ongoing management. It is not a matter of plant-and-forget because plantings (and patches of remnant vegetation) change with time. Unfortunately, there are no instruction manuals on how to best manage for biodiversity. It generally needs to be worked out along the way, since every planting is unique. Each occurs at a unique point in time, on a particular soil and slope, adjacent to remnants of various ages, conditions and type (woodland, grassland or creek-line). Each situation has its own trajectory and its own set of problems. Managing for biodiversity is an adaptive process that requires learning by doing. It requires monitoring and evaluation. Four princi-

Guidelines on complexity

- Establish understorey with native shrubs.
- Retain existing physical structures (logs, stumps, boulders, windrows) in the area being planted.
- Include patches of remnant vegetation within a plantation.
- Retain remnant trees in or near the area being planted.
- Plant trees with variable spacings and leave gaps and spaces.
- Leave prunings on the ground.
- Add complexity to the stand by killing trees randomly.
- Add complexity to the stand by opening up irregular spaces when thinning.
- Add nest boxes and artificial substrates such as woodpiles.
- When harvesting, leave some trees standing to allow for the presence of older and larger trees through successive rotations (to form hollows and provide other structure that serve as habitat).
- When harvesting, leave debris, branches and some trunks to add structural complexity in successive rotations.

ples are discussed under this heading: monitoring biodiversity, adaptive management, simulating natural disturbances and controlling threats (weeds and pests).

Monitoring biodiversity

The more a land manager understands and appreciates the biodiversity on their land and how it changes over time, the greater their chances of effectively managing it. We do not have to be wildlife experts to monitor important attributes of biodiversity. Monitoring can be as simple as taking a few notes or a photograph of different areas in and around the tree plantation. The first priority is to make sure the agroforestry landscape is working properly. Are planted and remnant trees healthy? Is the canopy open enough to allow for at least a sparse understorey of grasses. Is the absence of ground cover causing erosion?

Monitoring depends on the enthusiasm, energy and objectives of the observer. If the objective is to grow one tree species as fast as possible, detailed wildlife surveys will be meaningless. However, if the objective is whole-of-landscape sustainability,

then monitoring compositional, structural and functional components of biodiversity is warranted. While monitoring can involve compiling extensive species lists and habitat descriptions including photo records from fixed points, one-off surveys can be a waste of resources. Monitoring takes commitment to documenting changes over time and space. The task is to regularly record what is around over a period of time in order to judge the effectiveness of different management strategies.

Adaptive management

Adaptive management is a form of ‘learning by doing’ and monitoring should inform ongoing management decisions. The rate at which species return to newly established plantations, and the interactions of soil fungi, soil and litter invertebrates, lichens and ground layer herbs in native woodlands, forests and plantations are poorly understood. What is known indicates that every situation is different. Agroforesters should devise their own management formulae for their situation. Ideally, monitoring should be done within a management ‘experiment’. For example, does a

Guidelines on ecological management

- Establish a routine that allows the periodic assessment of how management is enhancing biodiversity on and around a plantation. It is important to be realistic about what can be achieved and be consistent over time.
- Assess how effective each management approach is compared to another.
- Implement programs (where possible, as a group of farms) to control environmental weeds and pests.
- Think about innovative approaches to weed control, such as throwing handfuls of local native shrub seeds into the dying weed habitat.

mixed stand of acacias and eucalypts grow better and have fewer pests and more wildlife than a similar size planting of just one eucalypt species on a adjacent slope? Does thinning a stand at 10 years provide a better understorey cover than thinning an adjacent similar stand at 15 years? Agroforesters should try different variations, monitor what happens and be guided by the results.

Simulating natural disturbance

Native species are more likely to survive human disturbances such as prescribed fire, grazing and logging if the disturbances are similar to natural disturbances such as bushfires and storms in terms of type, intensity and frequency. By completely removing a stand of trees in one harvest operation, and removing understorey and all biological legacies, biodiversity values are greatly reduced (Lindenmayer and McCarthy 2001). Natural disturbances don't operate in this manner, and with a bit of planning a forest can be managed in ways that simulate natural processes. For instance, seasonal grazing may be useful in reducing weeds and creating space for native grasses, forbs and birds to colonise the understorey of a particular stand. Fire may be necessary to encourage regeneration of some species since, at best, patch harvesting or thinning is only a partial mimic of fire.

Controlling threats (weeds and pests)

Pine plantations have traditionally been seen as refuges for cats and foxes, and rich territory for weeds such as blackberry and lantana. If biodiversity outcomes are important, these threats must be managed effectively. Weeds cannot be controlled

simply by applying herbicides. Since exotic shrubs provide understorey structure and thus habitat for some native birds and mammals the challenge is to replace them with native species, rather than killing them and creating an empty niche in which they can regrow.

It may be necessary to control feral foxes and cats to encourage the colonisation of a plantation by native birds and small mammals. Predator control is only worth doing if the effort is coordinated with neighbours. Foxes and cats have large territories and will quickly expand these if a few individuals are removed from one property, rather than a large number from a dozen or so farms.

Applying theory to specific agroforestry situations

The principles and guidelines outlined above can be applied in a wide variety of situations. We can't provide an exact prescription on how tree plantings might be configured or composed to produce specific biodiversity outcomes. There are no equations that show how if X trees are planted in Y places, an outcome of Z biodiversity results. There are no absolute rules because every situation is different, and every action will produce a unique set of outcomes for a different suite of species. However, using the principles provided it is possible to construct a framework of understanding that helps assess available options.

First, the lay of the land needs to be considered on a regional scale. The Land and Water Resources Audit (www.nlwra.gov.au/) has an enormous amount of well-organised information that describes

the broad threats and biodiversity assets of all bioregions in Australia. The relevant catchment management authority or NRM board and its regional plans should also be consulted. Every catchment management authority has various biodiversity objectives that should be considered.

Once regional priorities are understood, we need to consider what is important at the landscape scale. For instance, where are the nearest large blocks of remnant vegetation? Where is the nearest riparian corridor with extensive tree cover? Is there a risk of dryland salinity or waterlogging in the local subcatchment? Detailed satellite images and a native vegetation map are handy tools. If nothing else, a recent topographic map at the most detailed scale is critical when considering the big picture, before focusing on the biodiversity values that can be enhanced by a particular planting design.

Second, we must negotiate clear objectives with all the stakeholders involved in designing, funding, establishing and managing an agroforestry planting. As explained earlier, there can be contentious trade-offs between maximising plantation productivity and maximising biodiversity. These tensions need to be addressed at the beginning so there are shared expectations. Most problems arise because stakeholders have conflicting expectations of what a particular agroforestry design can provide in terms of production and conservation values.

If the planting is primarily for commercial value, it must be managed accordingly in terms of thinning regimes, fertilisation, herbicides and pesticides (if necessary). If the management objectives for a particular stand involve maximising short-term commercial values, diverse habitat needs to be provided in other parts of the landscape, on a single property or a neighbourhood of properties. Below are some considerations that might apply to specific situations.

Shelter belts

Location, width and diversity of plantings are the key management variables. There are plenty of examples of shelter belt corridors to nowhere. Data from the central tablelands of New South Wales indicate that shelter belts wider than 25–30 m are occupied by a diversity of birds that are otherwise only found in large remnant woodlands with a high habitat complexity (Kinross 2004). Studies have



Figure 6.7: A nature-friendly shelter belt is more than three rows wide and consists of a diverse mix of local native plants (photo courtesy of Greening Australia ACT/SE NSW).

shown that single or two-row windbreaks are less beneficial to native birds than are windbreaks of three to five rows – the narrow belts expose them to higher levels of predation from other birds, such as currawongs and hawks. The species found in thinner belts are usually the most common birds, such as noisy miners and the introduced common starling. Noisy miners often actively exclude other species. Shelter belts of at least three to five rows of trees and shrubs give a higher level of protection to small bush birds, particularly during the nesting season. Noisy miners appear to stay away from a structurally complex windbreak that is being used by a healthy suite of other birds.

If a very wide shelter belt (>50 m wide) is being planned, it is recommended that a flight path should run through it. This should be about 4 m wide and oriented along the length of the belt, not the width. This will allow larger birds such as rosellas an access route through the dense vegetation to their food trees.

Where possible, local plants should be used and a variety provided in terms of height and structure, such as tall fast-growing eucalypts, bushy wattles, pine-leafed sheoaks and native callitris pines, and low-growing shrubs and tussock grasses. If the shorter plants are on the outside and the taller ones in the middle, this will enhance the effectiveness of the shelter belt for wind protection and ensure that the smaller plants are not excessively shaded by the larger ones. Prickly dense shrubs should be planted to give protection for

nesting birds; shrubs such as grevilleas, hakeas and blackthorn are ideal. These also give good protection from wind and discourage cats.

Introduced fruit-bearing plants such as hawthorn, cotoneaster and pyracantha should be avoided as they produce abundant fruit in winter, providing a feast for starlings and currawongs. Starlings are fierce competitors with native birds for nesting hollows, and currawongs are predators of small birds.

A shelter belt should be sited where it will complement and connect existing stands of remnant native vegetation. It should be located near water (rivers or farm dams). Any information on local hydrogeology should be considered. For instance, it may be useful to know whether a wide shelter belt can be used to intercept lateral flow of water coming off a bare hill.

Woodlots

A woodlot and a large-scale plantation are similar in that they are usually established with commercial outcomes in mind and often focus on growing a single species. The difference is mainly one of scale, with a woodlot ranging in size from 1–50 ha and usually contained on one farm, whereas a large-scale plantation is often measured in hundreds of hectares (or more) and frequently covers more than a single farm.

When it comes to biodiversity, the same suite of principles apply: where possible, local native species should be used, there should be structural complexity within the plantation and the plantation should be located to complement existing native vegetation. The application of these principles to woodlots and large-scale plantations differs from other plantings in that the commercial nature of the operation limits some of the choices, although planning for biodiversity is still possible. How this might be done in a large-scale plantation is discussed below.

Because woodlots are smaller in scale, the agroforester often has more options in respect of location and species composition. The woodlot should be sited in the context of the whole farm, starting with a map and aerial photo of the land. Areas of high biodiversity value should be identified: patches of remnant vegetation, clusters of remnant trees, watercourses, rock outcrops etc. Native vegetation on adjoining land or along adjacent road-



Figure 6.8: Dams can add a valuable element of complexity to a plantation (photo by Sylvia Leighton).

ways should also be identified, as should existing plantings.

Using a plastic overlay, possible plantation locations and configurations that augment these important elements to biodiversity should be mapped out. Plantations may protect, connect or enlarge existing blocks of native vegetation. In terms of connectivity, a plantation does not have to physically abut a patch of remnant vegetation to improve its connectivity, but it might serve as a stepping stone to other patches. Remember, isolation is a species-specific threat. For instance, sugar gliders cannot cross a treeless gap of greater than 70 m, but many different birds occupy patches of woodland separated by from other sizeable patches by 1 km. Some lizards and plants may need continuous habitat and multiple generations of dispersing offspring before they move into a new agroforestry planting.

Anything that increases the structural complexity and patchiness of the woodlot and its surrounds is likely to improve the habitat value of the area for a wider range of animals and plants. A strategy that adds considerable biodiversity value over time is the establishment of diverse habitat plantings close to the plantation, preferably between the plantation and patches of remnant vegetation. Habitat plantings add patchiness to the area, connectivity to the plantation and protection to remnant vegetation, and will be retained during and after harvesting of the plantation. Larger and more diverse habitat plantings should have greater biodiversity value in terms of adding connectivity,

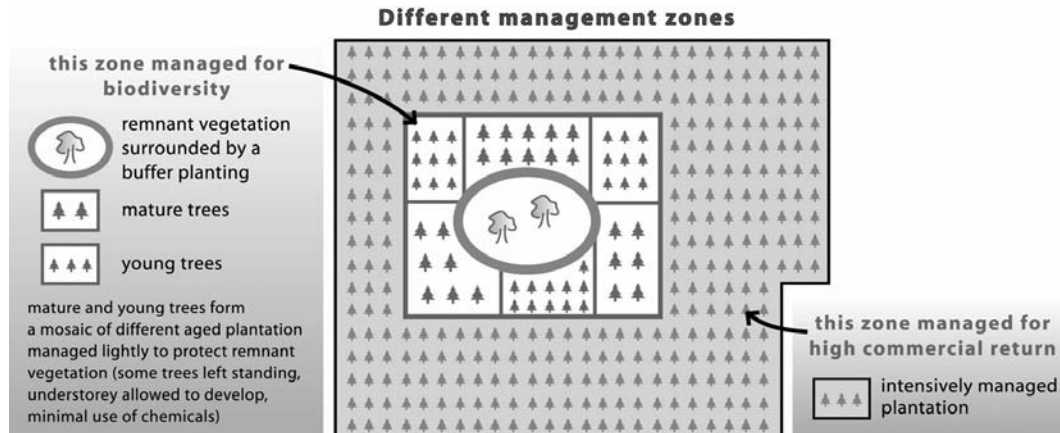


Figure 6.9: Zones of different management to suit areas of varying biodiversity value.

creating additional habitat and protecting remnant vegetation.

In terms of managing a woodlot, any action that makes it more like a native forest or woodland has the potential to enhance its biodiversity value. This includes leaving prunings and thinnings on the ground, adding refuges such as hollow logs and establishing an understorey of native vegetation. This also applies to harvesting. Consideration should be given as to whether it is possible to selectively harvest the woodlot, taking out single trees for specific timber needs such as furniture-making. It might be possible to progressively add to the ‘naturalness’ of the plantation by varying the age and spacing of the stand while allowing for the retention of ground cover and the build-up of leaf litter, branches and logs.

Large-scale plantations

As noted above, most large-scale plantations are established with commercial outcomes in mind, and this limits options in respect to biodiversity. It is better from a biodiversity standpoint to choose a mix of local native species planted with irregular spacings and long rotations, but this is rarely compatible with a commercial outcome. If biodiversity is a desirable outcome, a component of the plantation could be set aside and dedicated as an area for a habitat planting and the remainder of the plantation left for the commercial crop.

Habitat plantings might be in the form of a central block, corner plantings or perimeter rows, and should be left intact when the plantation is har-

vested. Another option would be to plant belts of local native species throughout the plantation, such as three rows in every 40. Again, these areas should be left intact during and after harvesting.

In a large-scale plantation, economies of scale dictate against selective harvesting practices but it might be possible to establish a harvesting regime that allows the creation of a patchwork of coupes of different ages. Areas around patches of remnant vegetation might be zoned for less-intensive harvesting, in which some mature trees might be left standing (see Figure 6.2). Harvesting could be planned so that some mature plantation is always present around parts of a remnant patch, as this improves connectivity between the remnant patch and the surrounding landscape. Harvesting practices that remove or destroy structures such as log piles reduce the biodiversity value of plantations, and harvesting practices that spread weeds from one area to another can have significant negative overall biodiversity conservation outcomes. Enhancing biodiversity values is about both thoughtful design at the beginning and responsive management over decades. Harvesting is a major disturbance that can be reduced by sensitive design implemented 30 years before harvesting.

Habitat plantings

At the other end of the plantation spectrum are habitat plantings designed specifically to encourage a diversity of species and ecosystem processes. All the principles outlined so far apply, with the aim of implementing them to the maximum in



Figure 6.10: Habitat plantings can add to the biodiversity value of a nearby commercial plantation. However, even with volunteer labour they can be expensive to establish (photo by David Salt).

order to enhance the existing elements of biodiversity in the landscape, restore a wide diversity of local plants established on appropriate sites, create large patches of quality nature plantings that are close to patches of remnant vegetation, connect various elements across the farm such as water points, old trees and watercourses, fence off native vegetation to protect it from stock, manage for weeds and feral pests, and coordinate efforts with others in the catchment to maximise the regional impact.

It is easy to make a list like this, but it is much harder to implement. There may be no great expectation of a commercial return on the plantings, the establishment of new vegetation still costs time and money, and even with the most economical form of restoration planting the costs quickly accumulate. For example, we need to ensure that the area being planted is protected from grazing stock with fencing, which can cost several thousand dollars per kilometre. The most basic site preparation requires the reduction of biomass (usually grass) with the application of herbicide laid down in strips along planting lines. Direct seeding behind a tractor costs around \$150/km or \$375/ha, and although it can lay down significant quantities of seed, survival can be variable. Tubestock usually provides greater certainty but is more expensive and takes more labour in the planting. Tubestock seedlings usually cost around \$2.50 each with an additional \$0.50 for tree guards to protect the seedlings from wind and rabbits. Fol-

low-up inspections are needed to ensure the plantings are not being dominated by just a few species, or serving as a refuge for pests or weeds.

These rough estimates demonstrate that even with volunteer labour and the best of intentions, the most basic restoration plantings still cost a lot of money. Indeed, this is why many state and Commonwealth government authorities are investing money in the search for native species that can be grown on a large scale with a commercial return. They are following this course because restoration and nature plantings simply cannot be undertaken on the scale necessary to address many of regional Australia's environmental problems.

Much research has been done on how to plan and manage effective revegetation, restoration and nature plantings (Bennett *et al.* 2000). There are a number of groups and organisations with expertise to help plan and possibly assist with restoration plantings. These include catchment management authorities, Greening Australia, Landcare and Land for Wildlife.

Agroforestry's role in protecting biodiversity

No matter what action is taken, land managers are always creating 'winners' and 'losers'. Some native species thrive in monoculture blocks of commercial plantings of blue gums – they are called insect pests. Other species cannot find a long-term home in short-rotation plantings because they depend tree hollows that take hundreds of years to form into the right size and shape.

The challenge of conserving biodiversity in production landscapes is to maintain or create patches of habitat for the species and processes that do not thrive in monocultures of annual crops, pastures or trees. Conservation of biodiversity is a whole-of-landscape challenge, not just a stand-level objective. Can agroforestry make a significant contribution to meeting this challenge? The answer is a qualified yes. Agroforestry can enhance elements of biodiversity if the patchiness or heterogeneity of landscapes is protected and enhanced. Patchiness applies to both space and time. Agroforestry can provide complementary habitat if diverse habitats are protected or rehabilitated, including patches of remnant forests, woodlands, grasslands,

CASE STUDY 2

Bringing the birds back to Lyndfield Park

Lyndfield Park is a farm near Canberra. Over the last two decades, the property has undergone a dramatic transformation as its owners, John and Jan Weatherstone, have changed from growing sheep to growing trees. In the process they've turned around many of the chronic environmental problems threatening the farm, significantly increased its resilience to the stresses of drought, improved its financial turnover, dramatically increased its capital value and created an attractive and pleasant place to work. On top of this, Lyndfield Park has more species of native birds than any other property in the area.

John and Jan changed the management direction of Lyndfield Park following a major episode of drought. At the height of the drought of 1982/83, they saw that despite applying what was considered best practice, they were working the land too hard and it had lost its resilience. The drought had exacerbated a host of problems such as poor soil, tree dieback, declining biodiversity and a loss of productivity. They believed that if Lyndfield Park were to have any future they needed to take greater care of the land (Figure 6.11).



Figure 6.11: Part of the 15 ha habitat planting at Lyndfield Park. It began as a planting around 20 remnant trees (photo by John Weatherstone).

In the years following the drought, John and Jan reduced grazing pressure (eventually they stopped grazing sheep altogether and went to grazing cattle), minimised soil cultivation, cut back the application of farm chemicals and established more than 80 000 trees and shrubs. Indeed, selling native trees, shrubs and seeds has become the main enterprise of Lyndfield Park. Cattle are still grazed but at higher (equivalent) stocking rates than prior to the 1982/83 drought and with significantly less impact on the land.

Farm forestry, with a range of native trees for timber products, is also being developed, and John and Jan are running a number of trials of natives to test their growth and marketability. These include plantings of sheoak, red box, yellow box, red stringybark, red ironbark and black oak.

The Weatherstones' efforts to create habitat for local wildlife reflect several of the principles discussed in this chapter. They knew that the larger the area they could revegetate with native plants, the greater the chance of providing adequate areas of habitat to support some species of wildlife. They also knew that an area containing existing trees and native shrubs was a good place to begin. Consequently, in 1988 they set aside 15 ha in the middle of the farm in which to

undertake a long-term habitat restoration project. This area was on light shale country and did not support many sheep, so they were not losing much income by setting aside the land. Also, the site contained 20 natural trees, some native grasses and a few native shrubs. Not much, but better than nothing.

Over several years, John and Jan enhanced this area by planting a wide mix of native trees and shrubs. Diversity was the key: variety in plant species and variety in plant shapes and sizes – variety in what is available through the year. One of the ways they encouraged birds and other animals to use the farm was to have a variety of plants flowering at all times of the year. They now have at least one or two species of wattle flowering every month, as well as a range of other flowering trees and shrubs. Another important factor was establishing prickly shrubs in many areas, as these plants provide secure nesting sites for birds and a safe haven from predators.

The results have been spectacular. Since 1996 just on 120 species of native birds have been identified on Lyndfield Park. Many of these species have not been recorded in the area before, and many others had disappeared during the previous few decades.

For all this success, John and Jan acknowledge that there is one component of habitat that they cannot easily recreate. 'Probably our greatest habitat deficiency is the lack of trees with hollows', says John. 'Regretfully, we removed most of the old trees long before we recognised their value. Now there's little we can do in the short term to rectify that.'

Source: Weatherstone (2003).

riparian strips and wetlands. The habitat values of agroforestry can be enhanced if there are different kinds of plantings established in different parts of the landscapes at different times, with a wide range of harvesting rotations.

Commercial values of agroforestry do not have to be sacrificed to enhance landscape patchiness. No landscape of any size, from a few hectares to hundreds of square kilometres, is uniformly productive or uniformly profitable in either space or time. Dry stony ridges will never be as productive as more fertile lower slopes. There is no guarantee that any one agroforestry species will be profitable and tolerant of climate change 20–50 years from now, when ready to harvest. Well-planned agroforestry that recognises the inherent variation in landscape productivity and aims to reduce long-term risk due to climatic variation should enhance the biodiversity of landscapes that may otherwise be dominated by a few land uses such as crops and pastures.

References and further reading

Abel N, Baxter J, Campbell A, Cleugh H, Fargher J, Lambeck R, Prinsley R, Prosser M, Reid R,

Revell G, Schmidt C, Stirzaker R and Thorburn P (1997) *Design Principles for Farm Forestry*. Rural Industries Research and Development Corporation, Canberra.

Barrett G (2000) Birds on farms: ecological management for agricultural sustainability. *Wingspan* 10(4), Supplement. Birds Australia, Melbourne.

Bennett A and Ford LA (1997) Land use, habitat change and the conservation of birds in fragmented rural environments: a landscape perspective from the Northern Plains, Victoria, Australia. *Pacific Conservation Biology* 3, 244–261.

Bennett A and Lumsden L (2003) *Bats and Paddock Trees: Insights from Current Research*. Department of Sustainability and Environment, Vic.

Bennett A, Kimber S and Ryan P (2000) 'Revegetation and wildlife'. Environment Australia, Bushcare Research Report 2/00.

Binning C, Baker B, Meharg S, Cork S and Kearns K (2002) 'Making farm forestry pay: markets for ecosystem services'. Rural Industries Research and Development Corporation, Canberra. RIRDC Publication no. 02/005.

- Bird R (2000) *Farm Forestry in Southern Australia*. Pastoral and Veterinary Institute, Department of Sustainability & Environment, Vic.
- Bonham K, Mesibov R and Bashford R (2002) Diversity and abundance of some ground-dwelling invertebrates in plantation vs native forests in Tasmania. *Forest Ecology and Management* **158**, 237–247.
- Borsboom A, Wang J, Lees N, Mathieson M and Hogan L (2002) ‘Measurement and integration of fauna biodiversity values in Queensland agroforestry systems’. Rural Industries Research and Development Corporation, Canberra. RIRDC Publication no. 02/044.
- Catling P and Burt R (1995) Studies of the ground-dwelling mammals of Eucalypt forests in south-eastern NSW: the effect of habitat variables on distribution and abundance. *Wildlife Research* **22**, 271–288.
- Curry G (1991) The influence of proximity to plantation edge on diversity and abundance of bird species in an exotic pine plantation in north-eastern New South Wales. *Wildlife Research* **18**, 299–314.
- Dames and Moore NRM/FOR TECH (1999) ‘Integrating farm forestry and biodiversity’. Rural Industries Research and Development Corporation, Canberra. RIRDC Report no. 99/166.
- Doherty MD and Wright G (2004) ‘Preliminary assessment of the impact of the 2003 wild fires on the flora and vegetation of Brindabella National Park, Bimberi Nature Reserve and Burrinjuck Nature Reserve’. A report prepared for the Reserve Conservation Unit, New South Wales National Parks and Wildlife Service, Queanbeyan. CSIRO Sustainable Ecosystems, Canberra.
- Freudenberger D and Stol J (2002) *SAND Farm-scapes Project Report: Integrating Production and Biodiversity*. CSIRO Sustainable Ecosystems, Canberra.
- Gibbons P and Boak M (2002) The value of paddock trees for regional conservation in an agricultural landscape. *Ecological Management and Restoration* **3**, 205–210.
- Gibbons P and Lindenmayer D (2002) *Tree Hollows and Wildlife Conservation in Australia*. CSIRO Publishing, Melbourne.
- Goldney D and Wakefield S (1997) *Save the Bush Toolkit*. Charles Sturt University, Bathurst, NSW.
- Grabham C, Klomp N and Robinson W (2002) *The Influence of Remnant Trees Retained within Native Hardwood Plantations on the Diversity and Abundance of Birds*. Department of Natural Resources and Environment, Wangaratta, Vic.
- Guijt I and Race D (1998) *Growing Successfully: Australian Experiences with Farm Forestry*. Greening Australia, Canberra.
- Grant J (1997) *The Nestbox Book*. Gould League, Melbourne.
- Hobbs R, Floyd R, Cunningham S, Catling P and Ive J (2002) ‘Hardwood plantations: quantifying conservation and environmental service benefits’. Rural Industries Research and Development Corporation, Canberra. RIRDC Publication no. 02/083.
- Kinross C (2004) Avian use of farm habitats, including windbreaks, on the New South Wales Tablelands. *Pacific Conservation Biology* **10**, 180–192.
- Klomp N and Grabham C (2002) ‘A comparison of the avifaunal diversity on native hardwood plantations and pastureland in north-east Victoria’. Johnstone Centre, Charles Sturt University. Report no. 164.
- Klomp N, Grabham C and Herring M (2001) ‘Fauna study of Ettamogah Forest’. Johnstone Centre, Charles Sturt University. Report no. 154.
- Lindenmayer D (2000) ‘Islands of bush in a sea of pines’. Land and Water Resources Research and Development Corporation. Research Report 6/00.
- Lindenmayer DB and McCarthy MA (2001) The spatial distribution of non-native plant invaders in a pine-eucalypt mosaic in south-eastern Australia. *Biological Conservation* **102**, 77–87.
- Lindenmayer D and McCarthy M (2002) Congruence between natural and human forest disturbance: a case study from Australian montane ash forests. *Journal of Forest Ecology and Management* **155**, 319–335.
- Lindenmayer D and Peakall R (2000) The Tumut experiment: integrating demographic and genetic studies to unravel fragmentation effects. In *Genetics, Demography and Viability*

- of *Fragmented Populations*. (Eds A Young and G Clarke) pp. 173–201. Cambridge University Press, Cambridge.
- Lindenmayer D and Pope M (2000) The design of exotic softwood plantations to enhance wildlife conservation: preliminary lessons from the Tumut fragmentation experiment, southeastern Australia. In *Nature Conservation 5: Nature Conservation in Production Environments: Managing the Matrix*. (Eds J Craig, N Mitchell and D Saunders) pp. 44–49. Surrey Beatty & Sons, Sydney.
- Lindenmayer D, Claridge A, Hazell D, Michael D, Crane M, MacGregor C and Cunningham R (2003) *Wildlife on Farms: How to Conserve Native Animals*. CSIRO Publishing, Melbourne.
- Majer J, Recher H and Keals N (1999) Canopy arthropod faunas in fragmented agricultural landscapes. In *Conservation of Australia's Temperate Woodlands*. (Eds RJ Hobbs and C Yates) pp. 235–247. Surrey Beatty & Sons, Sydney.
- McIntyre S, McIvor J and Heard K (2002) *Managing and Conserving Grassy Woodlands*. CSIRO Publishing, Melbourne.
- New B and England M (2002) *Farm Forestry: Designing for Increased Biodiversity*. Department for Environment and Heritage, Adelaide.
- Noss R (1990) Indicators for monitoring biodiversity: a hierarchical approach. *Conservation Biology* **4**, 355–364.
- O'Neill G (1999) Renaissance on Lanark. *Wingspan* **9**(1), Supplement. Birds Australia, Melbourne.
- Platt S (2002) *How to Plan Wildlife Landscapes*. Department of Natural Resources and Environment, Melbourne.
- Race D and Freudenberger D (2003) *Farm Forestry for Green and Gold: Australian Experiences of Linking Biodiversity to Business Solutions*. Australian National University, Canberra.
- Radford J, Bennett A and Cheers G (2005) Landscape-level thresholds of habitat cover for woodland-dependent birds. *Biological Conservation* **124**, 317–337.
- Recher H, Shields J, Kavanagh R and Webb G (1987) Retaining remnant mature forest for nature conservation at Eden, NSW: a review of theory and practice. In *Nature Conservation: The Role of Remnants of Native Vegetation*. (Eds D Saunders, G Arnold, A Burbidge and A Hopkins) pp. 177–194. Surrey Beatty & Sons, Sydney.
- Salt D, Lindenmayer D and Hobbs R (2004) *Trees and Biodiversity: A Guide for Australian Farm Forestry*. RIRDC, Canberra.
- Smith G and Agnew G (2002) The value of 'bat boxes' for attracting hollow-dependent fauna to farm forestry plantations in southeast Queensland. *Ecological Management & Restoration* **3**, 37–46.
- Taws N and Streatfield S (2001) *Bringing Birds Back*. Greening Australia, ACT and SE NSW.
- Weatherstone J (2003) *Lyndfield Park: Looking Back, Moving Forward*. Land and Water Australia, Canberra.
- Zanette L, Doyle P and Tremont S (2000) Food shortage in small fragments: evidence from an area-sensitive passerine. *Ecology* **81**, 1654–1666.

Environmental risk in agroforestry

Margaret Byrne, Lynley Stone and Melissa Millar

Introduction

The development of agroforestry systems promises significant environmental and economic benefits, particularly in the management of dryland salinity. Large-scale planting of woody crops also poses some risks to existing natural biodiversity. These risks include the establishment of new plant species as environmental weeds, hybridisation with native species and gene flow from cultivated populations into natural populations.

Agriculture and agroforestry don't occur in isolation. They are dominant parts of many rural landscapes, having replaced native communities over large areas of southern Australia. Local and regional biodiversity are strongly influenced by human land use and its alteration in many landscapes. Chapter 6 discussed the biodiversity benefits agroforestry can provide. These benefits are most advantageous when agroforestry is integrated into the landscape. This integration also requires the recognition of any negative impacts agroforestry may have on biodiversity in the landscape. As pointed out in Chapter 5, biodiversity is complex and has both structural and functional aspects, essential for the integrity of complex self-sustaining natural ecosystems. Biodiversity integrates biotic variability at all levels of organisation including genes, organisms, populations, communities and ecosystems. One community is not the same as any other even though on a superficial level the same species composition may be present. Organisms have differentiated their functional traits and

niche occupation during speciation. Their co-existence is a reflection of functional speciation and niche complementarity (Beierkuhnlein and Jentsch 2005), particularly in southern Australia where current landscapes have been continuously occupied for millions of years due to lack of major glaciation events (Hopper *et al.* 1996).

It is extremely difficult to put a value on native biodiversity, particularly in a world driven by economics. In agricultural regions in Australia, the value of biodiversity in maintaining functional landscapes is readily seen in the extent of hydrological imbalance leading to dryland salinity as a consequence of land clearing. However, biodiversity contributes to the human experience in many ways – consumptive use, productive use, opportunity use, ecosystem services, amenity values, scientific and educational experience, recreational opportunity and spiritual/philosophical experience (Wallace *et al.* 2003). Apart from the cultural, economic and ecosystem values that influence human experience, biodiversity has an intrinsic value (SEAC 2001). The first priority for biodiversity conservation is to protect existing biodiversity assets from further threat, the second is to enhance their condition and the third is to restore their former extent (Anderson *et al.* 2001).

Biotic variability is fundamental for adaptation to the challenging environment of southern Australia, which in turn is critical to long-term survival. The ability to change allows functional stability and redundancy, and ensures persistence

of ecosystems under changing environmental conditions and resilience in response to disturbance (Beierkuhnlein and Jentsch 2005).

Two primary components of biotic variability are species diversity and genetic diversity. Plant species diversity plays a significant role in the control of ecosystem processes and overall functioning, and there is a close relationship between particular ecosystem processes and species diversity (Beierkuhnlein and Jentsch 2005). In some cases the effects will be related to complementarity of functional traits of species, in others just to the occurrence of key species. Species are not similar; the historical and evolutionary background of each species may have a strong influence on the performance of entire ecosystems (Beierkuhnlein and Jentsch 2005). There are various hypotheses on the role of species in ecosystem function: one end of the spectrum views each species as uniquely contributing to the integrity of communities (Ehrlich and Wilson 1981) and the other expounds that species diversity includes redundancy, in that ecological processes can be maintained by a subset of species (Lawton and Brown 1993). Regardless of which view is held, biological diversity is threatened by loss of species since there is no obvious way to identify keystone species *a priori*, redundancy is not easily recognised and there is no guarantee that species lost will have co-occurring analogues (Frankel *et al.* 1995). Genetic diversity is closely linked to adaptive potential, and the long-term survival of functional ecosystems depends on the genetic integrity of species and populations. Natural vegetation is a complex and finely tuned system. Disturbance of genetic and species diversity in communities impacts on a wide range of ecosystem functions (Frankel *et al.* 1995), affecting not only native vegetation but all elements of rural landscapes.

Agroforestry provides major ecosystem benefits and, when integrated into landscapes, enhances the biodiversity values of the region. Are there any negative aspects from the agroforestry enterprise? Two factors that impact on the structural and compositional features of biodiversity include weed invasion and genetic contamination. Invasion by weeds changes the structural and compositional aspects of natural vegetation. Invasive species have been identified as the second-greatest threat to biodiversity, after habitat destruction (Walker and Steffan 1997).

Each year Australia faces a cost of over \$4 billion from weeds and their impacts on agriculture, natural environments, public and indigenous land (Sinden *et al.* 2004). The fundamental basis of species composition is genetic diversity, and genetic contamination or hybridisation disrupts genetic integrity of species. This chapter discusses these factors of weed invasion and genetic contamination, their potential to negatively impact on remnant vegetation, and the opportunities to manage these impacts. There are also environmental risks from agroforestry in relation to sources of disease and habitat for pests. Although those aspects are not considered here, the principles of risk assessment and management discussed would apply to the evaluation of pest and disease impacts. Environmental risks can be managed; the critical aspect is to have sufficient information to assess and evaluate the risk, and to design management guidelines.

Weed invasion

What is a weed?

Auld *et al.* (1987) summarised the definition of a weed as something that is both time- and location-specific. It is a non-scientific term that centres on a human value judgement (Sindel 2000). That is, many weeds are also considered useful plants and are highly valuable in particular land use systems. For example, in forestry *Pinus* species are valued as a source of fast-growing softwood, but in natural ecosystems are invasive and are considered environmental weeds. Weed species are often pioneer species, meaning they are the first to colonise disturbed soil. In their native environment, other factors such as competition for resources, climate, presence of insects and disease would have controlled their spread and abundance (Sindel 2000). In a new environment, without these elements, these species can colonise new areas and invade native vegetation.

Source of weeds

The majority of weeds in Australia are exotic, and many were purposefully introduced for horticulture, agriculture or garden/amenity use. There are more exotic taxa in Australia (approx. 27 000) (Virtue *et al.* 2004) than native species (15 638)

Table 7.1: Impact of naturalised flora on agricultural and natural ecosystems

Category	No. of species affecting agricultural systems	No. of species affecting natural ecosystems	No. of species affecting both systems
Naturalised in Australia	~2700	~2700	~2700
Considered a major problem	426	798	276
Considered a minor problem	840	1388	533
Species harbour pests/diseases or are toxic or are having direct impact on threatened flora	295	49	7
Recommended for eradication and/or under eradication	25	34	7

Source: Data from Groves *et al.* (2003)

(Hnatiuk 1990). Of course not all introduced plants become weeds. In fact, the majority do not impact negatively on biodiversity and provide many benefits to society through agriculture, horticulture, forestry, landscaping etc. However, a study of Australia's naturalised flora published in 2003 revealed that of the 27 000 introductions approximately 2750 have naturalised (formed self-sustaining populations) and are having an impact on natural ecosystems or agricultural systems (Table 7.1) (Groves *et al.* 2003).

Weediness is not restricted to exotic species, and there are an increasing number of examples of indigenous flora becoming environmental weeds outside their native range. For example, *Acacia pycnantha* from eastern Australia has become a weed in Western Australia, Tasmania and New South Wales, and overseas in South Africa. *Acacia saligna* is invasive in areas outside its native range in Western Australia and is known as an invasive weed in Chile, Spain, Portugal, Cyprus and South Africa (Maslin and McDonald 2004). Other native genera used in agroforestry that have been identified as having weed potential are *Melaleuca* and *Casuarina* (Marcar and Crawford 2004).

Weed impacts in Australia

The increasingly fragmented landscape of Australia means that our ecosystems are at higher risk of invasion. In the wheatbelt region of Western Australia less than 10% of the native vegetation remains (Hobbs *et al.* 1993), with as little as 2–3% in some areas (Hobbs 2001). Australia-wide, environmental weeds are the presumed cause of the extinction of at least four taxa, with a further 57

species under threat from competition with weeds (Leigh and Briggs 1992). Many threatened flora exist in fragmented populations, and have a greater risk of invasion due to large edge:area ratios (Hobbs 2001). Ecosystems are more likely to be invaded by weed species if they have a low level of plant cover. In Western Australia, woodland communities are more susceptible to invasion than shrub communities, as they have little understorey and have higher soil nutrient levels (Hobbs *et al.* 1993). Soil disturbance, human or machinery disturbance and even frequent fires provide opportunities for invasion. Hobbs and Atkins (1988) found that seeds from annual weeds were able to penetrate large patches of remnant vegetation, but did not necessarily germinate and survive without some form of disturbance. If disturbance was accompanied by the addition of nutrients, weed survival increased. Remnant vegetation often occurs in close proximity to areas of agricultural production, which contributes to two of these factors – they provide a large source of immigrant plants and the addition of nutrients to the soil is commonplace.

The impact of weed species on ecosystems varies, but major impacts include (Williams and West 2000):

- competition for light, nutrients, moisture and pollinators;
- replacement of indigenous plant communities;
- prevention of natural regeneration;
- change in movement of water in soil and watercourses;
- increased soil erosion;
- provision of food and shelter for pest animals;

- reduced water quality;
- introduction of foreign genes into local plant populations;
- altered fire behaviour and fuel loads;
- altered disturbance regimes.

Invasion by weeds does not affect only plant species in an ecosystem. Changes in the structure and composition of an ecological community may also have an impact on the vertebrate and invertebrate fauna of that area. For example, *Mimosa pigra* forms impenetrable thickets in tropical Australia, replacing riverine and floodplain vegetation, including sedgeland, paperbark forest, monsoon forest and riparian woodland. This invasion has reduced the abundance of birds and reptiles in the area and is predicted to cause a decline in mammal populations as food sources disappear (Braithwaite *et al.* 1989).

Weed threats in agroforestry

A review of agroforestry species planted worldwide suggested that approximately 1% were considered weedy in more than half the records surveyed and a further 7% were weedy under certain conditions (Richardson 1999). Characteristics desirable in an agroforestry species, such as rapid growth and establishment, and adaptability to soil and climate, also enable a species to become invasive. *Pinus* spp. are particularly weedy in both the northern and southern hemispheres, and there has been much research to assess the impacts on native ecosystems where wildlings have invaded (Richardson 1998). In his review, Richardson (1999) noted that 19 *Pinus* species are invaders of native ecosystems in the southern hemisphere. A large study conducted in New South Wales (the Tumut fragmentation experiment), revealed *Pinus radiata* wildling occurrence increased in eucalypt forest where there was limited ground cover and where remnant forests had been surrounded by pine stands for a prolonged period (Lindenmayer 2000b; Lindenmayer and McCarthy 2001). In South Australia, *Pinus brutia*, *P. halepensis* and *P. radiata* have been identified as species with high to very high weed risk (Virtue and Melland 2003). High seedling densities resulting in dense thickets under parent trees and a build-up of pine needles in the ground litter affect native vegetation by inhibiting native seed-

ling establishment and reducing the growth of shade-tolerant native species.

Acacia species are also notorious worldwide for their invasive characteristics and appear, with *Pinus*, on a large number of weed lists (Richardson 1999). *Acacia saligna* is a species with high potential for agroforestry in southern Australia but has been identified as having high weed risk (see case study). However, there is variation in *A. saligna* for suckering, a characteristic favourable for weediness. Use of non-suckering variants or selection of non-suckering lines may overcome the weed risk in use of *A. saligna*. This highlights the importance of knowledge of species biology in utilisation.

There are other examples of agroforestry species becoming invasive, such as the olive (*Olea europaea* subsp. *europaea*) and *Leucaena leucocephala*. Olives can spread prolifically through the wide dispersal of seeds by birds that eat the fleshy fruits. Dense stands form a permanent crown under which native plant species cannot survive or regenerate, resulting in displacement of native species and dramatic changes in biodiversity (Spennemann and Allen 2000). The invasibility of these species has been recognised by industry and a proactive approach to management has been taken. Olive trees, other than those actively cultivated, are proclaimed as weeds in South Australia and there is a code of practice that growers must follow when cultivating olives (Anon 1999). A code of practice has also been adopted in Tasmania to prevent the naturalisation of the species in habitat that would provide ideal growing conditions. *Leucaena leucocephala* is extensively used in Queensland as a highly valued palatable forage tree for beef production. It is a prolific seeder and is highly invasive, and has potential to become a serious weed of riparian zones in Queensland. Growers in Queensland have adopted a code of practice and the Queensland government has developed a policy for reducing the weed threat of *Leucaena* (Anon 2004b).

Genetic contamination

Genetic contamination describes the movement of foreign genes from domesticated or other non-local populations into native populations via pollen (Arnold 1992). This may occur when non-local species have been introduced or the habitat

CASE STUDY 1

Acacia saligna

The species

Acacia saligna is highly variable in morphology and is being reclassified into a number of subspecies (Maslin and McDonald 2004).

- Subspecies *lindleyi* is widespread and occurs predominantly in the wheatbelt region of Western Australia. It grows as a shrub or small tree with usually stout, straight to substraight stems, smooth bark and green phyllodes. This subspecies suckers, but the predominant mode of spread appears to be by seed.
- Subspecies *saligna* is found along the Swan coastal plain near Perth and on the south coast near Esperance. It grows as a tall erect shrub or tree with robust straight to substraight stems, grey-green to subglaucous phyllodes and smooth bark, although the bark becomes longitudinally fissured in older plants. Suckering is infrequent.
- Subspecies *stolonifera* occurs in the southern forest region and grows as a tall shrub or tree with substraight to crooked stems and friable bark. It appears to sucker aggressively.
- Subspecies *pruinescens* is geographically restricted and largely occurs within the range of subspecies *stolonifera*. It grows as a tree with straight stems and friable bark, tends to have white pruinose branchlets and relatively short glaucous phyllodes. It suckers strongly.

The status of a possible fifth subspecies of limited distribution is being assessed.

Analysis of the genetic diversity within *A. saligna* showed significant differentiation into three genetic groups, which corresponded with subspecies *lindleyi*, *stolonifera* and *saligna/pruinescens* (George *et al.* 2006; Millar *et al.* 2008).

Uses

A. saligna was ranked as the species with the best potential for utilisation as a crop species in southern Australia by the AcaciaSearch assessment of 35 species of Australian acacia (Maslin and McDonald 2004). *A. saligna* is a versatile plant, and efforts are underway to improve its value as a fodder species by selecting for low tannin content and increased digestibility for stock. As a timber it is used for fuelwood and charcoal, and it shows promise for particle board (Bartle *et al.* 2004). It has been used to provide screening, windbreaks and shade for stock and wildlife, and has gained attention for its use in mitigating salinity (Maslin and McDonald 2004). Fast growth and survival has been recorded in saline and waterlogged clay soils (Bennett and George 1993).

The risk to biodiversity

The weed potential of *A. saligna* outside its native range is well-documented. Naturalised populations can be found in Victoria, South Australia, New South Wales and Queensland. It has also become invasive in South Africa, Chile, Spain, Portugal and Cyprus (Maslin and McDonald 2004). In South Australia, *A. saligna* is classed as a medium- to high-risk species (Virtue and Melland 2003) due to its rapid growth, difficulty in distinguishing it from indigenous *Acacia* spp. (particularly as seedlings), and long-lived soil seedbank. Trees readily sucker and resprout from cut stumps, and repeated herbicide application is required for eradication.

Overlap in flowering times between *A. saligna* subspecies means that there is high risk of genetic contamination if one subspecies is planted within the natural range of another subspecies in Western Australia. The high level of genetic differentiation in *A. saligna* also means that the impacts of genetic contamination may be significant for natural populations. Gene flow studies have confirmed hybridisation in 14% of subspecies *saligna* progeny via genetic contamination from trees of subspecies *lindleyi* (Millar and Byrne 2007). Genetic contamination in subspecies *lindleyi* from subspecies *saligna* was detected at over twice that rate (32%) at the same site (Millar *et al.* 2007). While the majority of genetic contamination occurred at short distances of <450 m, significant levels of gene flow between the two subspecies were detected at distances of over 1.5 km.

Managing the risk

Management guidelines need to be developed for plantings of *A. saligna*, and the principles explained in the main text apply. Virtue and Melland (2003) suggest the development of cultivars with reduced reproductive output (e.g. reduced seed production, low hard-seededness, reduced suckering capacity) and improvement in control techniques. They also suggest discouraging landscape and revegetation plantings, and the development of specific management guidelines. There is variation in the suckering propensity of the *A. saligna* variants, with subspecies *saligna* rarely observed to sucker. Investigation of the identity of variants that are invasive in South Australia is being undertaken to determine weediness of specific variants.

Management guidelines for the species utilisation in Western Australia, where there is risk of genetic contamination in natural populations, may include the harvesting of crops before they reach reproductive maturity or the isolation of crops by distance. Results of gene flow studies indicate that isolation distances between agroforestry crops and natural populations of >1.5 km may be required in certain circumstances (Millar *et al.* 2007; Millar and Byrne 2007).



Figure 7.1: *A. saligna*.



Figure 7.2: Phyllodes of *A. saligna*.

modified, bringing previously isolated species or populations into geographic contact.

Gene flow is an important factor in natural population and ecosystem processes and is usually considered beneficial to plant conservation (Ellstrand and Elam 1993). It shapes gene pools and the population genetic structure of species, acting as a force to maintain genetic continuity between populations and preventing the loss of genetic diversity through inbreeding. However, gene flow can be negative when it occurs between divergent populations, as it may result in hybridisation. Hybridisation is typically defined as interbreeding of individuals from genetically distinct populations, regardless of their taxonomic status. While hybridisation is readily recognised as a result of gene flow between species or subspecies, gene flow between differentiated gene pools within species can be thought of as intraspecific or interprovenance hybridisation. Concerns about the impacts of hybridisation in conservation management are increasing (Ellstrand *et al.* 1999; Potts *et al.* 2003; Rhymer and Simberloff 1996; Strauss 2001).

Hybridisation can result in one of two outcomes for hybrid progeny – heterosis, or outbreeding depression (Ellstrand and Elam 1993). Heterosis, also known as hybrid vigour, occurs when hybrid fitness is enhanced relative to the parental populations. The vigour of an initial hybrid generation may result in the establishment of hybrid populations between domesticated and natural populations. If the hybrids maintain increased fitness relative to the parental populations through successive generations, the typically smaller native population is at risk from a loss of genetic integrity. This may eventually result in total genetic assimilation via introgression.

Introgression is the transfer of genes from one population to another by the repeated backcrossing of hybrids to one or both parental populations. It may result in a small component of the donor genome being transferred to the native gene pool or may extend to virtually complete introgressive displacement of the native population. Such displacement, or genetic assimilation, may result in extinction of native populations in the absence of selection against hybrids. Native populations are likely to suffer from direct competition and reduction in size and be subject to the impact of small

population processes. If the growth rate of native populations declines below that required for replacement, they may become extinct due to hybrid swamping.

An alternative outcome from hybridisation is outbreeding depression, which occurs when hybrid fitness is reduced relative to the parental population. The extreme case of this is when all hybrids produced are sterile. In this case the reproductive output of a native population may be lowered such that it leads to extinction (Rhymer and Simberloff 1996). This effect will be exacerbated when pollen swamping is extreme, the reproductive output of the population is low or the population is already subject to the impacts of small population processes such as inbreeding.

Impacts of genetic contamination

The impacts that genetic contamination or hybridisation from agroforestry species may have on native populations are difficult to predict but are related to:

- the scale of genetic divergence between the domesticated and native populations;
- the nature of the evolutionary process generating the divergence;
- the size of the pollen source and sink populations;
- the functionality of the ecosystem.

Scale of genetic divergence

Native agroforestry species have undergone little selective breeding for domestication to date (Adams and Burczyk 2000), particularly if a broad base of genetic diversity has been captured, as is generally the case in tree breeding programs (Moran *et al.* 2000). Breeding itself is not a significant factor leading to differentiation of planted populations. However, native species under utilisation are generally widespread species that occur across broad environmental gradients, as these are characteristics that increase their utility. It is now recognised that many of these species are species complexes where the morphological and genetic variation has not been resolved taxonomically, particularly in south-west Australia, where a long evolutionary history in a stable landscape has led to a high degree of morphological variation that contributes to a

certain degree of taxonomic ambiguity (Coates 2000). Combined genetic and taxonomic studies of key species identified as having potential for crop development are being undertaken to provide more detailed understanding of taxonomic entities and their genetic relationships. Most studies of native species have revealed some genetic divergence but there are exceptions, for example there was little genetic differentiation in the oil mallee *Eucalyptus kochii* (Byrne 1999). A high level of divergence was observed between the variants of *A. microbotrya* (Byrne unpub.) and *A. saligna* (George *et al.* 2006) and a phylogenetic study of populations of *Melaleuca uncinata* confirmed the presence of genetic divergence between groups that have since been recognised as new species (Broadhurst *et al.* 2004). Differentiation has also been identified between eastern and western regions of widespread species in northern Australia, e.g. *E. camaldulensis* (Butcher *et al.* 2002), *A. auriculiformis* (Wickneswari and Norwati 1993) and *A. tumida* (McDonald *et al.* 2003). The identification of significant levels of divergence and presence of unrecognised taxa within such species indicates that their use as agroforestry crops involves some risk of genetic contamination via hybridisation with native populations. A clear definition of the taxa in key agroforestry species complexes is required for more certain identification and characterisation of native populations. This will enable agroforestry management practices to ensure that divergent populations are not planted in close proximity to each other.

Evolutionary processes that generate divergence

The impacts of crossing between differentiated populations depend on the nature of the genetic processes underlying the divergence between source and sink populations. If divergence is due to selection and adaptation, outbreeding depression can occur, depending on the nature of the population adaptation (Templeton 1986). If population fitness has occurred through selection for locally adapted genotypes then hybridisation will result in the dilution of these genotypes, as hybrids show heterozygosity and underdominance at loci formerly fixed for adapted alleles. If the population fitness occurs through the development of co-adapted gene complexes (distinct combinations of epistatically interacting loci), hybridisation may

expose these complexes to disruption through recombination. The effects of disruption to co-adapted gene complexes are not expressed until the F2 generation and are often seen as advanced generation breakdown (Fenster and Dudash 1994; Hufford and Mazer 2003; Templeton 1986).

Size of pollen source and sink populations

The risk of genetic contamination from planted populations depends greatly on the relative size and distribution of native and domesticated populations. In Australia's disturbed agricultural landscapes, broad-scale revegetation for agroforestry may generate large amounts of contaminant pollen (source) in comparison to small natural pollen pools (sink). As native population sizes decrease, the relative fraction of immigrant pollen increases (Ellstrand and Elam 1993) and the impacts of genetic contamination are greater. For example, small populations of the rare *E. aggregata* that are outnumbered by the common *E. viminalis* and *E. rubida* show high levels of hybrid seed production compared to large populations (Field *et al.* 2004). The effects of large-scale changes in gene flow are likely to have negative consequences for the long-term persistence of small native populations, especially as remnants may already be suffering from the effects of small population size.

Ecosystem functionality

The fragmented agricultural landscapes of southern Australia are examples of disturbed landscapes where ecosystem processes have been highly disrupted. Such disturbed landscapes are typically composed of small remnant populations, where gene flow is especially important in shaping genetic structure. In small, genetically or geographically isolated populations, effective population sizes may become limited so that the effects of inbreeding depression (loss of fitness due to increasing homozygosity) produce a significant decrease in reproductive performance (Ellstrand and Elam 1993). This is especially relevant to predominantly outbreeding species, such as most trees, where significant increases in inbreeding can lead to depleted genetic variation within populations and increased differentiation among populations.

Decreased genetic variation has negative effects on population responses to selection pressures

caused by changing environments, and ultimately on population persistence. The impact of gene flow between planted and natural populations would be less in functional ecosystems with large native populations. Ecological instability brought about by disturbance also tends to create heterogeneous habitats which provide greater opportunity for hybrid establishment (Stebbins 1959). The risk of hybridisation through pollen dispersal increases with fragmentation and reduction in population size. Investigation of the mating system in *E. benthamii*, a rare species in the Camden area of New South Wales, showed that small populations had 25–35% hybridity in their seed crops arising from hybridisation with nearby *E. viminalis* trees, compared to larger populations where there was no evidence of hybridisation (Butcher *et al.* 2005).

Hybrid zones may lead to increased herbivore and pathogen pressure in native vegetation. Hybrids are often more vulnerable to pests and may support considerable and diverse pest assemblages in close proximity to the parental species (Dungey and Potts 2001; Whitham *et al.* 1999). These may serve as staging areas for pest establishment on parental species.

Assessing the risk

Risk assessment is the combination of determining how likely an event is to happen, and the consequences of that event. In the context of this discussion, the question to ask is: ‘What risk does agroforestry pose to biodiversity?’

The answer will include an evaluation of:

- the risk of agroforestry species invading and impacting on native ecosystems;
- the risk of gene flow from cultivated plants to indigenous plants of the same or related species.

Assessing weed risk

Predicting invasiveness of a species

The ability of a species to become invasive depends on a number of variables. One philosophy of predicting invasive characteristics is that all species have the traits necessary to invade, as they must have the ability to persist (even if at low numbers) or they would become extinct. However, weed spe-

cies vary widely in their invasive capacity and impact on ecosystem processes (Heywood 1989). All introduced species affect the communities in which they occur, but invasive and aggressive species have significant impacts on communities. If habitat and environmental conditions are ideal – an ‘invasion window’ presents itself (Johnson 1986) – then any plant species has the potential to become invasive. For some species, called ‘sleepers weeds’, this window may not occur for many years. In Florida, the native Australian species *Melaleuca quinquenervia* was introduced in the early 1900s as an ornamental and erosion control tree, but it wasn’t until decades later that it was recognised as a serious environmental weed infesting over 200 000 ha of wetlands (Turner *et al.* 1998). In Germany, the average time from the planting of an exotic shrub or tree to recognition as an invasive species was 131 years for woody shrubs and 170 years for trees (Kowarik 1995). An Australian example of a woody sleeper weed is *Tamarix aphylla*, also known as Athel pine or tamarisk. Athel pine was introduced to Australia in 1930 and was extensively planted for shelter, shade and erosion control in South Australia. It wasn’t until the 1970s and 1980s, when extensive flooding occurred, that its distribution greatly increased along waterways throughout inland Australia and by the late 1980s it was formally recognised as a weed (Anon 2003; Griffin *et al.* 1989). In 1999, *T. aphylla* was declared as an Australian Weed of National Significance (WONS), one of 20 species identified as posing the greatest threat to socioeconomic and environmental values (Thorp and Lynch 2000).

The biological attributes of invasive species vary so widely that many believe that biological attributes alone are a poor indicator of invasiveness. There are particular characteristics that assist a species to become invasive (Table 7.2), and many of these attributes have been incorporated into weed risk assessment protocols to try to predict whether a species will become weedy. Table 7.3 shows some of the biological attributes of woody species identified as WONS, and woody species that are on the environmental weed alert list. A comparison of the characters in Tables 7.2 and 7.3 shows many of the key characters associated with invasiveness are present in Australia’s worst woody

Table 7.2: Ecological attributes that increase weed potential in native ecosystems

High input of viable propagules
Short (<2 yr) development time to reproductive maturity
Seed or other reproductive units with prolonged (>5 yr) periods of dormancy
High rate of aerial or subterranean biomass production, particularly under conditions of low light, water or nutrient availability
Dense and spreading foliar canopy
Efficient long-distance (>1 km) dispersal capabilities
Presence of interspecific allelopathic properties or absence of intraspecific allelopathic properties
Successful colonisation of disturbed or bare ground
Reproductive strategies that facilitate survival in fire-prone environments
Broad distribution over a range of distinct climatic types
Low susceptibility to attack by phytophagous organisms

Source: Adair (1995)

weeds. For example, for the 18 species listed most use water to disperse seed, enabling long-distance dispersal, the maximum time to flowering in the species is only three years, most of the species produce many thousands of seed annually and only two species do not have dormant seed.

Environmental weeds are not specific to a few plant families and examples can be found in most families of plants. In North America the Rosaceae (16%) have the most weed species (Reichard 2001), in New Zealand, the families with the most weed species are Poaceae (13%) and Fabaceae (8%) (Williams & West 2000), and in temperate Southern Australia, Asteraceae is the family with most weed species (Groves & Burdon 1986).

The single best predictor of invasive ability is knowledge of species behaviour in other areas where it has been introduced (Daehler *et al.* 2004; Reichard 2001; Rejmanek 2000). In North America for example, 54% of invasive species invade elsewhere, and in Hawai'i, 76% of invasive species are invaders elsewhere (Reichard 2001).

Weed risk assessment protocols

The ability to assess the risk of a plant becoming a weed is important for weed management. Weed risk

assessment is 'the use of standard, technical criteria to determine the relative weed threats posed by different plant species' (Virtue *et al.* in press). Over the years, several efforts have been made to produce an effective weed risk assessment protocol to enable a scientific assessment of a plant's capacity to become a weed. Two types of assessment protocols have emerged – predictive and prioritising. A predictive weed risk assessment aims to predict the risk of a plant becoming a weed *a priori*, i.e. before it happens. A prioritising assessment aims to identify the impacts of weed species and potential for containment, to prioritise species for management.

Biosecurity Australia is the national government agency charged with developing policy to control entry of species into Australia, which is then implemented by the Australian Quarantine Inspection Service (AQIS). AQIS uses a predictive weed risk assessment protocol to assess whether plants species being imported into Australia could become environmental or agricultural weeds. Any plant species deemed to be of high risk is not permitted entry to Australia. This system has been adapted for use in New Zealand (Pheloung *et al.* 1999) and Hawaii (Daehler *et al.* 2004), and is internationally recognised as the most accurate and effective system available.

The weed risk assessment protocol consists of 49 questions divided into eight sections:

- 1 domestication/cultivation;
- 2 climate and distribution;
- 3 weed elsewhere;
- 4 undesirable traits;
- 5 plant type;
- 6 reproduction;
- 7 dispersal mechanisms;
- 8 persistence attributes.

The answers to the questions generate a score (usually +1 for a weedy attribute and -1 for a non-weedy attribute) which is converted into a recommendation of 'accept' (total score ≤ 0), 'evaluate' (total score 1–6) or 'reject' (total score > 6). Species classed as 'evaluate' require a wider literature search or collection of further data from glasshouse or field trials to determine the potential weed risk.

Other weed risk assessment systems in use by state agencies in Australia aim to prioritise weeds for cost-effective control or eradication. These protocols use questions similar to the Biosecurity

Australia model, but the outcome enables species to be prioritised using local data. This type of assessment usually assesses the invasiveness of a species, its impacts and potential distribution. There is no uniform process used by all Australian states, but a national post-border weed risk management protocol published by Standards Australia aims to harmonise post-border models (Standards Australia 2006). The South Australian weed risk assessment protocol (based on an earlier draft of the national protocol) was used by Virtue and Mel-land (2003) to evaluate the environmental weed risk of revegetation and forestry species in South Australia. Similarly, in Victoria, a Pest Plant Prioritisation Process, also based on an earlier draft of the national protocol, has been used to review the Victorian noxious weeds list (Weiss *et al.* 2004).

Assessing genetic risk

No predictive framework exists to assess the likelihood that hybridisation will lead to extinction, the rate with which it may occur or the quantitative assessment of the relative importance of risk factors. Considerable genetic and ecological information is required to predict the likely outcome of hybridisation between species. Effective risk assessment and the development of management guidelines for the use of native species in agroforestry requires key research in the following areas:

- crossability of key species;
- spatial patterns of genetic diversity;
- distances and levels of gene flow;
- long-term monitoring of introgression;
- impacts on local biodiversity.

Crossability of key species

While the natural distributions of key agroforestry species and their relatives are generally well-known, further information is required regarding the likelihood of hybridisation. Studies of natural and manipulated hybrids and knowledge of barriers to hybridisation, including pre-zygotic and post-zygotic barriers, will provide further information on the potential of hybridisation with related species in intended planting areas (Potts *et al.* 2001). This information must be associated with ongoing changes in taxonomy.

Knowledge of flowering phenology of closely related species in different environments is crucial

as this is often the first barrier to hybridisation. Flowering phenology is readily assessed, although flowering time is influenced by environment and can vary markedly across different environments. Potential for crop–wild hybridisation, including forestry crops, has recently been assessed at a national level in New Zealand (Armstrong *et al.* 2005) and potential for hybridisation between exotic *E. nitens* and native eucalypts in Tasmania has also been assessed (Barbour *et al.* 2005).

Spatial patterns of genetic diversity

Many of the native species identified as having potential for agroforestry are species complexes where morphological and genetic variation has not been fully resolved. Combined genetic and taxonomic studies of these species are required for a more detailed understanding of taxonomic entities and their genetic relationships. This will allow for more efficient processes of identification and characterisation of germplasm resources for use in domestication programs. It will also help to ensure that the environmental and economic impacts of agroforestry can be achieved without creating additional risks to existing natural biodiversity.

Distances and levels of gene flow

Pollen dispersal patterns should be investigated for key agroforestry species likely to be in contact with vulnerable populations capable of hybridisation. This will allow for the description of recommended safe isolation distances and buffer zones. Pollen-mediated gene flow in plants is nearly always described by a leptokurtic distribution of pollen from its source, with the majority of pollen travelling a short distance and a low-level tail of long-distance distribution (Ellstrand 1992). The extent of the tail of the dispersal curve is important as long-distance pollen dispersal is often underestimated. Hybridisation between the native *E. ovata* and planted *E. nitens* in Tasmania has been documented on several occasions (Barbour *et al.* 2003, 2002). In a recent study the pollen dispersal curve was investigated; it showed an average of 7% hybrid seed within 100 m of the plantation boundary, dropping to 0.7% by 200–300 m. Hybrids were still detected 1.6 km from the boundary (Barbour *et al.* 2005).

Pollen dispersal is directly related to the method of pollination dispersal, pollinator behaviour and

Table 7.3: Biological attributes of the woody species identified as Australian Weeds of National Significance or as environmental alert weeds

Common name	Species name	Reason for introduction to Australia	Seeds per plant	Seed size (mm)	Dispersal	Vegetative dispersal	Time to flower	Dormant	Pollinator
Athel pine	<i>Tamarix aphylla</i>	Shade, windbreak, erosion control	500 000 ^a	1	Wind, water	Yes	3 years	No	Insect, wind
Prickly acacia	<i>Acacia nilotica</i>	Shade, fodder, ornamental	175 000	7–9 ^b	Stock, water	No	2–3 years	Yes	Insect ^c
Mimosa	<i>Mimosa pigra</i>	Escaped from botanic gardens	220 000	4–6	Water, animals, people		4–12 months	Yes	Insect, wind, self ^d
Parkinsonia	<i>Parkinsonia aculeata</i>	Shade, ornamental, hedge	5000–13 000	10	Water, mud	No	2–3 years	Yes	
Mesquite	<i>Prosopis</i> spp.	Shade, fodder, ornamental	>100 000	9–12 ^b	Stock, water	Yes ^d		Yes	Insect
Willows	<i>Salix</i> spp.	Shade, erosion control, ornamental	Prolific	<1	Wind, water	Yes	2–3 years	No	Insect
Boneseed	<i>Chrysanthemoides monilifera</i> ssp. <i>monilifera</i>	Dune stabiliser, ornamental	50 000	6–7	Birds, pest animals, stock	No	1–3 years	Yes	Insect, self
Bitou bush	<i>Chrysanthemoides monilifera</i> ssp. <i>rotundata</i>	Dune stabiliser, revegetation	50 000	5–7	Wind, water, pest animals	No	1–3 years	Yes	Insect
Lantana	<i>Lantana camara</i>	Escapee, ornamental	12 000	1.5	Birds, foxes	Yes	1 year	Yes	Insect, self ^d
Gorse	<i>Ulex europaeus</i>	Ornamental	6 million/ha	3 ^e	Water, soil, ants, birds	Yes	18 months	Yes	Insect
Blackberry	<i>Rubus fruticosus</i>	Fruit	80/fruit	2–3	Birds, pest animals	Yes	2 years	Yes ^f	Insect
Pond apple	<i>Annona glabra</i>	Rootstock for custard apple	140/fruit	15	Water, feral pigs, cassowaries	No	2 years	Yes	Insect
Rosewood	<i>Tipuana tipu</i>	Shade, stock feed, timber, ornamental	10 000		Wind, water	No			Insect
White Spanish broom	<i>Cytisus multiflorus</i>	Ornamental		2.5–3	Explosive pods, water, animals, mud	Yes	3 years	Yes	Insect ^g

Common name	Species name	Reason for introduction to Australia	Seeds per plant	Seed size (mm)	Dispersal	Vegetative dispersal	Time to flower	Dormant	Pollinator
White weeping broom	<i>Retama raetam</i>	Ornamental	>1000	6.5		No		Yes	
Karoo thorn	<i>Acacia karroo</i>	Ornamental, escaped from botanic gardens	19 000	5–8 ^b	Wind, water, animals	No		Yes	
Cutch tree	<i>Acacia catechu</i>	Escaped from botanic gardens		5–8	Water, mud, animals	No		Yes	
Chinese rain tree*	<i>Koeleruteria elegans</i> ssp. <i>formosana</i>	Ornamental		5	Water, birds	No		Yes	

Information cited is from weed management guides (Anon 2003) unless specified otherwise.

a: Frost (2005)

b: Anon (2004a) Flora Zambesica <www.kew.org/efloras>

c: Stone *et al.* (1998)

d: Anon (2005b) Global invasive species database. <www.issg.org/database>

e: Anon (2005a) <www.cdffa.ca.gov/phppps/ipc/weedinfo/ulex.htm>

f: Faithfull (2005)

g: Rodriguez-Riano *et al.* (2004)

factors affecting pollinator movement. In general, wind-pollinated species show greater pollen dispersal distances than animal- or insect-pollinated species, but dispersal is highly idiosyncratic and can vary greatly in different environments at different times and even for different individual plants. Research is required on the major pollinators and factors affecting their foraging behaviour. Recent studies overseas have shown that fragmentation has led to increased gene flow among scattered trees and populations (Bacles *et al.* 2005; White *et al.* 2002). This is likely to be a factor in Australia: recent analysis of gene flow in fragmented populations of *E. wandoo* in the Western Australia wheatbelt revealed that 50% of the pollen load of some trees came from >1 km away (Byrne *et al.* 2008). In contrast to the *E. nitens*–*E. ovata* studies (Barbour *et al.* 2003, 2005, 2002) noted above, the *E. wandoo* data indicate a fat-tailed pollen dispersal curve with substantial levels of long-distance pollen dispersal.

Long-term monitoring of introgression

Data is required on the long-term level and impact of hybridisation and introgression in populations where hybridisation is known to occur. Research should determine whether introgression is more likely to confer neutral, advantageous or disadvantageous genes to native genotypes. Long-term introgression of crop genes into wild relatives has a history of producing or enhancing weediness traits in native populations, creating new weeds or enhancing the effects of existing weeds (Ellstrand *et al.* 1999). This may occur if key traits influencing weediness are transferred, such as the ability to propagate vegetatively, herbicide resistance or insect resistance. In order to judge the ecological impact of hybridisation or repeated introgression for given taxa, it is probably necessary to perform controlled crosses and test the hybrids under closely controlled field conditions (Tiedje *et al.* 1989). This is extremely difficult and time-consuming in agroforestry due to the long generation time of most tree species.

Impacts on local biodiversity

To assess risks posed to native populations, it is important to have an understanding of the occurrence, size and distributions of remnant native

populations as well as their genetic diversity. Placing a conservation value upon individual populations makes it possible to evaluate acceptable levels of genetic contamination. If a population has low conservation value (e.g. its representative species and genetic diversity is captured in several other populations and conservation reserves) and the likelihood and impact of genetic contamination are both low, the benefits from agroforestry planting may be considered greater than the risk.

Managing the risk

Risk management framework

Risk management is a common and essential aspect of many industries, businesses and organisations. Agroforestry is no different. Environmental risk is one aspect that requires evaluation in a risk management framework. The first steps in risk management are to identify and evaluate the risks through use of assessment protocols. Once the risks are identified and evaluated, decisions can be made about the level of risk that is acceptable, in association with the level of management that is feasible. Where there is a high feasibility of managing risk, the information from the risk assessment is used to develop strategies for minimising the impacts and for design of management practices. Some general guidelines for the management of weed and genetic risk in agroforestry are presented here, although they will need to be assessed in specific situations for specific species.

Weed risk management

Guidelines were developed for biodiversity conservation in softwood plantations (*Pinus radiata*) in 2000, incorporating the results of an extensive research project at Tumut, New South Wales (Lindenmayer 2000a). Some of the key recommendations in relation to weed and genetic risk include:

- further develop and use reproductively sterile cultivars for plantation establishment;
- remove existing wildlings from remnant vegetation patches;
- develop hygiene protocols for machinery to reduce the spread of other weeds, e.g. blackberry.

Virtue and Melland (2003) provide options for managing species that have a high weed risk and a high utility, such as *Pinus* and *Acacia* species, though further research into many of the options is required. The options include:

- setting minimum planting distances from native vegetation;
- introducing measures to limit seed production and dispersal;
- ensuring routine monitoring and control of escapees;
- choosing less weedy species/cultivars.

Some agricultural industries are including management options similar to those suggested above, in voluntary codes of practice. An example is the code of practice adopted by olive growers in South Australia. Some of the code's requirements include:

- a buffer zone of 200 m within property boundaries between orchards and the nearest significant native vegetation;
- if there are no trees in the buffer zone, a bird perch must be provided every 100 m around the perimeter, as birds are major dispersers of the seed;
- removal of fruit from the trees each year, including spilt fruit on the ground;
- active fox control and netting or scaring of birds to reduce seed dispersal;
- an olive-free zone around commercial orchards of 20–50 m to allow monitoring and access in case of fire.

Genetic risk management

Managing genetic risk through cultural management practices, including processes such as planting so that flowering times do not coincide, or harvesting before flowering, are virtually impossible to implement effectively with the long lifecycles of agroforestry species. The most reliable practices to limit gene flow include keeping the agroforestry crop isolated from native populations by distance or the use of barriers.

Isolation distances

Paternity studies have enabled estimates of gene flow distances to be made for a number of species. In crop plants, specific minimal isolation distances

have been suggested at 300 m for self-fertilising species and 800 m for primary outcrossing species to maintain varietal purity, despite these distances allowing for contamination of up to 10% (Raybould and Gray 1994). However, levels of pollen-mediated gene flow in natural populations and crop/weed complexes has proven to be much more extensive than initially predicted (Ellstrand 2003; Raybould and Gray 1994) and these recommendations may be inadequate.

Direct studies of gene flow in agroforestry species in Australia are limited. In eucalypts, a low level of long-distance pollen dispersal has been inferred from isolated mature hybrids found in native stands up to 1 km from a boundary (Potts *et al.* 2001) and long-distance pollen dispersal of around 5 km has been reported although not verified (Potts 1990). Pollen dispersal from a planted stand of *E. loxophleba* ssp. *lissophloia* into remnant populations of ssp. *supralaervis* occurred over 2 km (Sampson and Byrne 2008). Similarly, in *A. saligna* pollen dispersal from planted stands into remnant populations over distances of 1.5 km has also been documented (Miller *et al.* 2007; Millar and Byrne 2007).

Until we have greater knowledge of what influences pollen dispersal curves in native species, general guidelines include:

- isolation distances should be greater for wind- and bird-pollinated species than for insect-pollinated species;
- isolation distances should be greater for a patchy than for a spatially continuous flowering resource;
- at least 1 km is required for pollen immigration to be effectively reduced in a continuous native forest abutting a plantation with synchronous flowering (Potts *et al.* 2001);
- estimates of gene flow are a guide and specific estimates will always be imprecise due to sensitivity to environmental conditions and the spatial distribution of source and sink populations.

Border rows

Barrier rows, or guard rows, of different non-interbreeding species of the same species may be incorporated around agroforestry plantations to intercept a portion of pollen entering or leaving the crop. For insect-pollinated eucalypts, 100–200 m

buffer zones of non-interbreeding trees have been suggested to protect seed orchards from contamination by pollen from natural populations (Potts *et al.* 2001). In crop species, models have predicted that buffer zones will substantially reduce pollen leakage from plantings (Manasse and Kareiva 1991). The effectiveness of this strategy and the distances involved need to be investigated in agroforestry systems.

Conclusion

There are weed and genetic risks associated with the use of native species for large-scale revegetation for agroforestry, even within their natural range. This does not mean that the use of native species should be abandoned – they still have considerable advantages over exotic species. It does indicate that the use of native species should be developed within a risk management framework (Potts *et al.* 2003). Risks must be identified, adequate information obtained to assess the level of risk and evaluations of management options made. Weed risk assessment is relatively advanced and readily evaluated. Many genetic and ecological factors interact, making it difficult to assess the impacts of genetic contamination from hybridisation. However, a greater understanding of the dynamics of gene flow will allow some assessment of the risks involved in using particular taxa in large-scale revegetation for agroforestry. Risk assessment should be an integral part of environmental impact assessments of agroforestry plantations. These risk assessments will contribute to the development of informed decision-making processes in the implementation of agroforestry revegetation systems and ultimately aid in the development of land uses that protect and enhance biodiversity in the agricultural landscapes of southern Australia.

References

- Adair RJ (1995) The threat of environmental weeds to biodiversity in Australia: a search for solutions. In *Conserving Biodiversity: Threats and Solutions*. (Eds RA Bradstock, TD Auld, DA Keith, RT Kingsford, D Lunney and DP Sivertsen) pp. 184–201. Surrey Beatty & Sons, Sydney.
- Adams W and Burczyk J (2000) Magnitude and implications of gene flow in gene conservation reserves. In *Forest Conservation Genetics: Principles and Practice*. (Ed. T Boyle) pp. 215–226. CSIRO Publishing, Melbourne.
- Anderson S, Lowe K, Preece K and Crouch A (2001) *Incorporating Biodiversity into Environmental Management Systems for Victorian Agriculture*. Department of Natural Resources and Environment, Vic.
- Anon (1999) ‘Olive policy’. South Australian Animal and Plant Control Commission, Adelaide.
- Anon (2003) ‘Weed management guide’. CRC for Australian Weed Management, Adelaide.
- Anon (2004a) *Flora Zambesiaca*. Board of Trustees of the Royal Botanic Gardens, Kew. <<http://www.rbgb.org.uk/efloras/search.do>>.
- Anon (2004b) ‘Policy to reduce the weed threat of *Leucaena*’. Queensland Department of Natural Resources and Mines/Environmental Protection Agency/Department of Primary Industries, Brisbane.
- Anon (2005a) *Gorse (Ulex europaeus L.)*. Californian Department of Food and Agriculture. <www.cdffa.gov/phpps/ipc/weedinfo/ulex.htm>.
- Anon (2005b) *ISSG Global invasive species database*. Invasive Species Specialist Group. <<http://www.issg.org/database>>.
- Armstrong TT, Fitzjohn RG, Newstrom LE, Wilton AD and Lee WG (2005) Transgene escape: what potential for crop-wild hybridisation? *Molecular Ecology* **14**, 2111–2132.
- Arnold M (1992) Natural hybridisation as an evolutionary process. *Annual Review of Ecology and Systematics* **23**, 237–261.
- Auld BA, Menz KM and Tisdell CA (Eds) (1987) *Weed Control Economics*. Academic Press, London.
- Bacles CFE, Burczyk J, Lowe AJ and Ennos RA (2005) Historical and contemporary mating patterns in remnant populations of forest tree, *Fraxinus excelsior* L. *Evolution* **59**, 979–990.
- Barbour RC, Potts BM, Vaillancourt RE, Tibbits WN and Wiltshire RJE (2002) Gene flow between introduced and native *Eucalyptus* species. *New Forests* **23**, 177–191.
- Barbour RC, Potts BM and Vaillancourt RE (2003) Gene flow between introduced and native *Eucalyptus* species: exotic hybrids are estab-

- lishing in the wild. *Australian Journal of Botany* **51**, 429–439.
- Barbour RC, Potts BM and Vaillancourt RE (2005) Gene flow between introduced and native eucalyptus species: crossability of native Tasmanian species with exotic *E. nitens*. *Australian Journal of Botany* **53**, 465–477.
- Bartle J, Olsen G, Cooper D and Huxtable D (2004) Domestication of native woody germplasm for large-scale woody crops: a component of sustainable agriculture in southern Australia. In *Proceedings of the Conference: Salinity Solutions: Working with Science and Society*. 2–5 August, Bendigo, Vic. (Eds A Ridley, P Feikema, S Bennett, MJ Rogers, R Wilkinson and J Hirth). CRC for Plant-based Management of Dryland Salinity.
- Beierkuhnlein C and Jentsch A (2005) Ecological importance of species diversity. In *Plant Diversity and Evolution: Genotypic and Phenotypic Variation in Higher Plants*. (Ed RJ Henry) pp. 249–285. CAB International.
- Bennett D and George R (1993) *Performance of Tree Species on the Coastal Plain*. Department of Agriculture, Bunbury, WA.
- Braithwaite RW, Lonsdale WM and Estbergs JA (1989) Alien vegetation and native biota in tropical Australia: the impact of *Mimosa pigra*. *Biological Conservation* **48**, 189–210.
- Broadhurst L, Byrne M, Craven L and Lepschi B (2004) Genetic congruence with new species boundaries in the *Melaleuca uncinata* complex (Myrtaceae). *Australian Journal of Botany* **52**, 729–737.
- Butcher PA, Otero A, McDonald MW and Moran GF (2002) Nuclear RFLP variation in *Eucalyptus camaldulensis* Denh. from northern Australia. *Heredity* **88**, 402–412.
- Butcher PA, Skinner AK and Gardiner CA (2005) Increased inbreeding and inter-species gene flow in remnant populations of the rare *Eucalyptus benthamii*. *Conservation Genetics* **6**, 213–226.
- Byrne M (1999) High genetic identities between three oil mallee taxa, *Eucalyptus kochii* subsp *kochii*, subsp *plenissima* and *E. horistes*, based on nuclear RFLP analysis. *Heredity* **82**, 205–211.
- Byrne M, Elliott C, Yates C and Coates D (2008) Extensive pollen dispersal in *Eucalyptus wandoo*, a dominant tree of the fragmented agricultural region in Western Australia. *Conservation Genetics* **9**, 97–105.
- Coates DJ (2000) Defining conservation units in a rich and fragmented flora: implications for the management of genetic resources and evolutionary processes in south-west Australian plants. *Australian Journal of Botany* **48**, 329–339.
- Daehler CC, Denslow JS, Ansari S and Kuo H (2004) A risk-assessment system for screening out invasive pest plants from Hawaii and other Pacific islands. *Conservation Biology* **18**, 360–368.
- Dungey HS and Potts BM (2001) Possum damage to *Eucalyptus* species and hybrids in Tasmania. *Australian Forestry* **64**, 446–452.
- Ehrlich PR and Wilson EO (Eds) (1981) *Extinction: The Causes and Consequences of the Disappearance of Species*. Random House, New York.
- Ellstrand N (1992) Gene flow by pollen: implications for plant conservation genetics. *Oikos* **63**, 77–86.
- Ellstrand N (Ed.) (2003) *Dangerous Liaisons: When Cultivated Plants Mate with their Wild Relatives*. Johns Hopkins University Press.
- Ellstrand N and Elam D (1993) Population genetic consequences of small population size: implications for plant conservation. *Annual Review of Ecology and Systematics* **24**, 217–242.
- Ellstrand NC, Prentice HC and Hancock JF (1999) Gene flow and introgression from domesticated plants into their wild relatives. *Annual Review of Ecology and Systematics* **30**, 539–563.
- Faithfull I (2004) *Blackberry Identification*. Department of Primary Industries, Frankston, Vic.
- Fenster C and Dudash M (1994) Genetic considerations for plant population restoration and conservation. In *Restoration of Endangered Species: Conceptual Issues, Planning, and Implementation*. (Ed. C Whelan) pp. 34–62. Cambridge University Press, Cambridge.
- Field D, Young A, Whelan R and Ayre D (2004) Swamping the swamp gum: habitat fragmentation and disturbance promotes hybridisation in *Eucalyptus aggregata*. In *Proceedings of 51st Annual Meeting of Genetics Society of Australia*. p. 18. Genetics Society of Australia, Melbourne.

- Frankel OH, Brown AHD and Burdon JJ (Eds) (1995) *The Conservation of Plant Biodiversity*. Cambridge University Press, Cambridge.
- Frost R (2003) *Saltcedar (Tamarix spp.)*. University of Idaho. <www.cnr.uidaho.edu/range454/2003%20Pet%20weeds/saltcedar.html>.
- Frost R (2005) Weed management guidelines. <www.cnr.uidaho.edu>.
- George N, Byrne M, Maslin B and Yan G (2006) Genetic differentiation in *Acacia saligna* and its implications for domestication of the species as a fodder crop. *Tree Genetics and Genomes* **2**, 109–119.
- Griffin GE, Stafford Smith DM, Morton SR, Allan GF and Masters KA (1989) Status and implications of the invasion of Tamarisk (*T. aphylla*) on the Finke River, Northern Territory. *Journal of Environmental Management* **29**, 297–315.
- Groves RH and Burdon JJ (Eds) (1986) *Ecology of Biological Invasions: An Australian Perspective*. Cambridge University Press, Cambridge.
- Groves RH, Hosking JR, Batianoff GN, Cooke DA, Cowie ID, Johnson RW, Keighery GJ, Lepschi BJ, Mitchell AA, Moerkerk M, Randall RP, Rozefelds AC, Walsh NG and Waterhouse BM (Eds) (2003) *Weed Categories for Natural and Agricultural Ecosystem Management*. Bureau of Rural Sciences, Canberra.
- Heywood VH (1989) Patterns, extents and modes of invasions by terrestrial plants. In *Biological Invasions: A Global Perspective*. (Eds JA Drake, HA Mooney, F di Castri, RH Groves, FJ Kruger, M Rejmanek and M Williamson) pp. 31–60. John Wiley, Chichester.
- Hnatiuk RJ (Ed.) (1990) *Census of Australian Vascular Plants*. Australian Government Publishing Service, Canberra.
- Hobbs RJ (2001) Synergisms among habitat fragmentation, livestock grazing and biotic invasions in southwestern Australia. *Conservation Biology* **15**, 1522–1528.
- Hobbs RJ and Atkins L (1988) Effect of disturbance and nutrient addition on native and introduced annuals in plant communities in the Western Australian wheatbelt. *Australian Journal of Ecology* **13**, 171–179.
- Hobbs RJ, Saunders DA, Lobry de Bruyn LA and Main AR (1993) Changes in biota. In *Reintegrating Fragmented Landscapes: Towards Sustainable Production and Nature Conservation*. (Eds RJ Hobbs and DA Saunders) pp. 65–106. Springer-Verlag, New York.
- Hopper SD, Harvey MS, Chappill JA, Main AR and Main BY (1996) The Western Australian biota as Gondwanan heritage. In *Gondwanan Heritage: Past, Present and Future of the Western Australian Biota*. (Eds SD Hopper, JA Chappill, MS Harvey and AS George) pp. 1–16. Surrey Beatty & Sons, Sydney.
- Hufford KM and Mazer SJ (2003) Plant ecotypes: genetic differentiation in the age of ecological restoration. *Trends in Ecology and Evolution* **18**, 147–155.
- Johnson IM (1986) Plant invasion windows: a time-based classification of invasion potential. *Biological Reviews* **61**, 369–394.
- Kowarik I (1995) Time lags in biological invasions with regard to the success and failure of alien species. in *Plant Invasions: General Aspects and Special Problems*. (Eds P Pysek, K Prach, M Rejmanek and M Wade) pp. 15–38. SPB Academic Publishing, Amsterdam.
- Lawton JH and Brown VK (1993) Redundancy in ecosystems. In *Biodiversity and Ecosystem Function*. (Eds ED Schulze and HA Mooney) pp. 255–270. Springer, Berlin.
- Leigh JH and Briggs JD (1992) *Threatened Australian Plants. Overview and Case Studies*. Australian National Parks and Wildlife Service, Canberra.
- Lindenmayer D (2000a) 'Guidelines for biodiversity conservation in new and existing softwood plantations'. Rural Industries Research and Development Corporation, Canberra. Report no. 77.
- Lindenmayer D (2000b) *Islands of Bush in a Sea of Pines: A Summary of Studies from the Tumut Fragmentation Experiment*. Land and Water Resources Research and Development Corporation, Canberra.
- Lindenmayer DB and McCarthy MA (2001) The spatial distribution of non-native plant invaders in a pine-eucalypt landscape mosaic in south-eastern Australia. *Biological Conservation* **102**, 77–87.
- Manasse R and Kareiva P (1991) Quantifying the spread of recombinant genes and organisms. In *Assessing the Ecological Risks of Biotechnol-*

- ogy. (Ed. L Ginzburg) pp. 215–231. Butterworth-Heinemann, Boston.
- Marcar NE and Crawford DF (Eds) (2004) *Trees for Saline Landscapes*. Rural Industries Research and Development Corporation, Canberra.
- Maslin B (Ed.) (2001) *Flora of Australia, Mimosaceae, Acacia Part 1*, CSIRO Publishing Australian Biological Resources Study, Canberra.
- Maslin BR and McDonald MW (eds) (2004) *Acacia Search. Evaluation of Acacia as a Woody Crop Option for Southern Australia*. Rural Industries Research and Development Corporation, Canberra.
- McDonald MW, Butcher PA, Bell JC and Nguyen CV (2003) Clonal variation and genetic divergence in *Acacia tumida* (Mimosaceae). *Australian Systematic Botany* **16**, 57–68.
- Millar MA and Byrne M (2007) Pollen contamination in *Acacia saligna*: assessing the risks for sustainable agroforestry. In *Ecosystems and Sustainable Development VI*. (Eds E Tiezzi, JC Marques and CA Brebbia) pp. 101–110. WIT Press, UK.
- Millar MA, Byrne M, Nuberg I and Sedgley M (2007) High outcrossing and random pollen dispersal in a planted stand of *Acacia saligna* subsp. *saligna* revealed by paternity analysis using microsatellites. *Tree Genetics and Genomes* **4**, 367–377.
- Millar MA, Byrne M, Nuberg I and Sedgley M (2008) A rapid PCR-based diagnostic test for the identification of subspecies of *Acacia saligna*. *Tree Genetics and Genomes* **4**, 625–635.
- Moran GF, Butcher PA and Glaubitz J (2000) Application of genetic markers in the domestication, conservation and utilisation of genetic resources of Australian tree species. *Australian Journal of Botany* **48**, 313–320.
- Pheloung PC, Williams PA and Halloy SR (1999) A weed risk assessment model for use as a biosecurity tool evaluating plant introductions. *Journal of Environmental Management* **57**, 239–251.
- Potts BM (1990) The response of eucalypt populations to a changing environment. *Tasforests* **2**, 179–793.
- Potts B, Barbour R and Hingston A (2001) ‘Genetic pollution from farm forestry using eucalypt species and hybrids’. Rural Industries Research and Development Corporation, Canberra. RIRDC Publication no. 01/114.
- Potts BM, Barbour RC, Hingston A and Vaillancourt RE (2003) Genetic pollution of native eucalypt gene pools: identifying the risks. *Australian Journal of Botany* **51**, 1–25.
- Raybould AF and Gray AJ (1994) Will hybrids of genetically modified crops invade natural communities? *Trends in Ecology and Evolution* **9**, 85–89.
- Reichard S (2001) The search for patterns that enable prediction of invasion. In *Weed Risk Assessment* (Eds RH Groves, FD Panetta and JG Virtue) pp. 10–19. CSIRO Publishing, Melbourne.
- Rejmanek M (2000) Invasive plants: approaches and predictions. *Austral Ecology* **25**, 497–506.
- Rhymer JM and Simberloff D (1996) Extinction by hybridisation and introgression. *Annual Review of Ecology and Systematics* **27**, 83–109.
- Richardson DM (Ed.) (1998) *Ecology and Biogeography of Pinus*. Cambridge University Press, Cambridge.
- Richardson DM (1999) Commercial forestry and agroforestry as sources of invasive alien trees and shrubs. In *Invasive Species and Biodiversity Management*. (Eds OT Sandlund, PJ Schei and A Viken) pp. 237–257. Kluwer Academic, Netherlands.
- Rodriguez-Riano T, Ortego-Olivencia A and Devesa JA (2004) Reproductive biology in *Cytisus multiflorus* (Fabaceae). *Annals of Botany Fennici* **41**, 179–188.
- Sampson JF and Byrne M (2008) Outcrossing between an agroforestry plantation and remnant native population of *Eucalyptus loxophleba*. *Molecular Ecology* **17**, 2769–2781.
- SEAC (2001) ‘Australia: State of the Environment 1996’. State of the Environment Advisory Council. CSIRO Publishing, Melbourne.
- Sindel BM (2000) Weeds and their impact. In *Australian Weed Management Systems*. (Ed. BM Sindel) pp. 3–16. RG & FJ Richardson, Melbourne.
- Sinden J, Jones R, Hester S, Odom D, Kalisch C, James R and Cacho O (Eds) (2004) *The Economic Impact of Weeds in Australia*. CRC for Australian Weed Management Systems, Adelaide.

- Spennemann DHR and Allen LR (2000) Feral olives (*Olea europaea*) as future woody weeds in Australia: a review. *Australian Journal of Experimental Agriculture* **40**, 889–901.
- Standards Australia (2006) *HB 294-2006 National Post-Border Weed Risk Management Protocol*. CRC Australian Weed Management, Adelaide, and Standards Australia and New Zealand.
- Stebbins GL (1959) The role of hybridisation in evolution. *American Philosophical Society* **103**, 231–251.
- Stone GN, Willmer P and Rowe JA (1998) Partitioning of pollinators during flowering in an African *Acacia* community. *Ecology* **79**, 2808–2827.
- Strauss SY (2001) Benefits and risks of biotic exchange between *Eucalyptus* plantations and native Australian forests. *Austral Ecology* **226**, 447–457.
- Templeton A (1986) Coadaptation and outbreeding depression. In *Conservation Biology: The Science of Scarcity and Diversity*. (Ed. M Soule) pp. 105–116. Sinauer, Sunderland MA.
- Thorp JR and Lynch R (2000) *The Determination of Weeds of National Significance*. Commonwealth of Australia and National Weeds Strategy Executive Committee. <<http://www.weeds.org.au/docs/WONS/>>.
- Tiedje JM, Colwell RK, Grossman YL, Hodson RE, Lenski RE, Mack RN and Regal PJ (1989) The planned introduction of genetically engineered organisms: ecological considerations and recommendations. *Ecology* **70**, 298–315.
- Turner CE, Center TD, Burrows DW and Buckingham GR (1998) Ecology and management of *Melaleuca quinquenervia*, an invader of wetlands in Florida, USA. *Wetlands Ecology and Management* **5**, 165–178.
- Virtue JG and Melland RL (2003) 'The environmental weed risk of revegetation and forestry plants'. Department of Water, Land and Biodiversity Conservation, DWLBC 2003–02, Adelaide.
- Virtue JG, Bennett SJ and Randall RP (2004) Plant introductions in Australia: how can we resolve 'weedy' conflicts of interest?' In *Proceedings of 14th Australian Weeds Conference*. Wagga Wagga, NSW. (Eds BM Sindel and SB Johnson) pp. 42–48. Weed Society of New South Wales.
- Walker B and Steffan W (1997) An overview of the implications of global change for natural and managed terrestrial ecosystems. *Ecology and Society* (formerly *Conservation Ecology*) online **1**, 2.
- Wallace KJ, Beecham BC and Bone BH (2003) *Managing Natural Biodiversity in the Western Australian Wheatbelt. A Conceptual Framework*. Department of Conservation and Land Management, Perth.
- Weiss J, Edgar B, Hunt T and Morfe T (2004) Victoria's noxious weed review: roll out not fall out. In *Proceedings of 14th Australian Weeds Conference*. Wagga Wagga, NSW. (Eds BM Sindel and SB Johnson) pp. 707–710. Weed Society of New South Wales.
- White GM, Boshier DH and Powell W (2002) Increased pollen flow counteracts fragmentation in a tropical dry forest. An example from *Swietenia humilis* Zuccarini. *Proceedings of the National Academy of Sciences* **99**, 2038–2042.
- Whitham TG, Martinson GD, Floate KD, Dungey HS, Potts BM and Keim P (1999) Plant hybrid zones affect biodiversity: tools for a genetic based understanding of community structure. *Ecology* **80**, 416–428.
- Wickneswari R and Norwati M (1993) Genetic diversity of natural populations of *Acacia auriculiformis*. *Australian Journal of Botany* **41**, 65–77.
- Williams JA and West CJ (2000) Environmental weeds in Australia and New Zealand: issues and approaches to management. *Austral Ecology* **25**, 425–444.

Landscape aesthetics and agroforestry

Grant Revell

Introduction

All landscapes are essentially social constructs – they are sensed environments that tell us a lot about how we see ourselves as casual observers, concerned environmentalists or active land managers in the Australian setting. Landscapes help us understand where we have come from and where we are heading as individuals or as communities, sometimes with (or without) any detailed knowledge of the natural or cultural environment. Greider and Garkovich (1994) suggest that:

'Landscapes' are the symbolic environments created by human acts of conferring meaning to nature and the environment, of giving the environment definition and form from a particular angle of vision and through a special filter of values and beliefs. Every landscape is a symbolic environment. These landscapes reflect our self definitions that are grounded in culture (Greider and Garkovich 1994, p. 1).

Landscapes consequently not only conceptualise and represent our lives, they actually *become* our lives.

As natural resource managers, we have begun to open up our eyes, hearts and minds to the ideas that such environmental resources have deeper social values attached to them – from very small private localised holdings to very large industrial or regionally based landscapes and their communities. Knowing the cultural meanings attached to these social landscape values can often help land managers realise the complexities of environmen-

tal management practices. In turn, this shift in thinking necessitates a more innovative and creative response to agroforestry land management that embodies the integration of a range of social and physical sciences and arts disciplines and professions, their knowledge sets and associated practices (Winchcombe and Revell 2004).

Today, the natural resource management of agrarian landscapes has every opportunity to value-add, as the cultural products of custodial care and stewardship of land and community are very much process-driven. It is this rich integrated management process that can support and set up the creative abilities for scientists and artists to collaborate, ensuring that agroforestry decision-making considers the potentially negative impacts on social, biophysical and economic landscapes, while optimising the positive. Indeed, the aesthetic values placed on agroforestry landscapes can be read as complex cultural outcomes or as barometers of good or bad integrated land management through the processes of land design. Consequently, natural resource managers are fast becoming the new aesthetic facilitators for holistic cultural resource management of our environments; as Greider and Garkovich (1994) might infer, 'the creative managers of cultural symbols'.

This chapter provides a detailed background to the relevant theories and practices of landscape aesthetic assessment and an outline of the typically integrated landscape design requirements of agroforestry systems. From the outset, it should be

noted that this study of agroforestry systems is not well-established in Australia. The body of related literature is small, is often too generic and is historically represented from research and practice undertaken primarily in the UK and North America. This chapter complements the locally documented work of Van Pelt (1980), Ramsay and Paraskevopoulos (1993), Revell (1997), Cleary (1999), Cowan and Revell (2000) and Winchcombe and Revell (2004). It provides a useful beginning for all students and practitioners interested in developing stronger design sensibilities for the agroforestry management of specific and meaningful places in Australia. It asks questions. How do we make environmental features important for biological reasons, and economic values important for landscape aesthetic reasons? Is this new integration of values through the creative thinking and practices of agroforestry simply a new land aesthetic?

Key terms defined

The following key terms are used (adapted from Winchcombe and Revell 2004).

- *Aesthetic landscape values* are the experiential responses derived from an appreciation of a complex mosaic of environmental elements. They include natural and cultural attributes with visual and non-visual aspects such as sound, smell, sense of place, emotional response and all factors having an influence on human attitude (O'Brien and Ramsay 1992). These aesthetic values are derived from a structural inquiry into any act of representation and how it is constituted by ideologies of nature and culture, as opposed to connoisseurship, taste or style (Weller 1997).
- *Analysis* is the process by which the landscape is broken down into components and understood in terms of its particular compositional elements and behaviours (Revell and Cleary 1998).
- *Assessment* is a process of synthesis. It is the expression of composite value based on the value of individual landscape components (Revell and Cleary 1998).
- *Evaluation* is the process where landscape assessment results are examined and used to make decisions about alternative landscape futures (Revell and Cleary 1998).
- *Inventory* refers to the identification and collection of landscape data. Inventory is without value judgements (Revell and Cleary 1998).
- *Landscape* refers to a place or defined area of land exhibiting aesthetic, historic, scientific and social values (Stuart-Street and Revell 1994).
- *Landscape architecture* is the development of a harmonious, sustainable and enriching fit between human systems and natural systems. Landscape architecture is art and science, both analysis and intervention (Riley 1998).
- *Landscape design* (as a verb) refers to the creative processes that prepares strategies or plans for the spatial and meaningful fit or intervention between these biophysical and social systems.
- *Landscape character* is the combination of natural and cultural landscape characteristics which allow people to differentiate between one place and another.
- *Landscape value* is generally derived from a process of valuation and can be expressed numerically (Litton 1979).
- *Participatory design* typically involves a close working relationship between the designer, the client and other members of a community interested in a project, including other scientists. Joint contributions are often made by all parties throughout the design process. It is very different from design consultation, which often reinforces the designer as the expert and ignores the design interests and talents of the landowner, manager and wider community. The educational and learning outcomes for all parties is often restricted in design consultation models.
- *Scenic quality* is the relative visual character of a landscape, expressed as an overall visual impression or value held by society after perceiving a segment of land/water (Stuart-Street and Revell 1994).
- *Sense of place* describes a holistic experience which defines a person's perception of place and their relationship with it.
- *Visual landscape* is that portion of the landscape within a person's view (Stuart-Street and Revell 1994).

- *Visual landscape management* is the act of managing the visual landscape, its environmental values, resources and attributes.

Landscape assessment models for agroforestry

As discussed and taken from Winchcombe and Revell (2004), the actual assessment of landscape aesthetic values is often carried out as part of the site inventory and analysis procedures typically employed by landscape planners and landscape architects in land design or management projects. There are few agroforestry planning and design projects in Australia that have consciously and systematically employed these environmental assessment procedures or techniques (Winchcombe 2000). The work of Daniel and Vinning (1983) and Lamb (1993) describes a number of key theoretical models or conceptual approaches employed in assessing landscape aesthetic values, as follows:

- component model;
- formal aesthetic model;
- ecological model;
- psychophysical model;
- psychological model;
- phenomenological/experiential model.

The component model and the formal aesthetic model assume that aesthetic value is intrinsic to the physical attributes of the landscape. These approaches are considered to be descriptive inventory approaches. The formal aesthetic model is influenced by picturesque perceptions of the landscape, not unlike those that influenced the development of the landscape painting schools of the 18th and 19th centuries. Visual qualities such as form, line, colour, texture and scale are factors contributing to landscape quality.

The ecological model recognises that much of the concern for landscape quality or amenity value stems from a more general concern for the satisfactory management of the natural environment, where the ideas of naturalness are the significant evaluative factors. Natural resource managers and landscape architects work closely with expert biologists and ecologists to determine the relationships between ecological and aesthetic values of the environment. Ecological units, classes or functions (e.g.

riparian zones, edges, open woodlands, closed forests) are often classified for their significance and disturbance, and corresponding aesthetic evaluations are made. Rare and endangered landscapes are often given high aesthetic values, and human-influenced or modified environments are judged as low. The closer a development (or agroforestry system) simulates or mimics a natural environment, the more aesthetically acceptable it becomes (Daniel and Vinning 1983).

The psychophysical model assumes that the physical attributes of the landscape determine the psychological response of the viewer. When developing management guidelines and management strategies for forests and agroforestry systems under their control, the Forests Commission of Victoria and the Department of Conservation and Land Management in Western Australia employ this approach. The psychological model is more concerned with people's experience of the landscape. It explores the reasons behind a viewer's response and includes things such as memory, past experience, interests and cultural background. Ultimately it gives more weight to landscape user preferences than do the other approaches. It has been criticised from a problem-solving point of view for lacking an applied orientation or clear practical outcomes. It is considered as a hypothesis builder rather than an analysis type model. Nonetheless, it can give explicit knowledge about how certain landscapes are valued and how they are managed, with or without agroforestry systems.

The phenomenological/experiential model approaches landscape from the viewer's deeper experiences, feelings about and expectations of the environments that surround them. Through a systematic content analysis, common experiences are identified and used as a basis for a deeper understanding of the perceived landscape. Landscape quality is considered a very intimate interaction between the observer and the environment. It is influenced by a whole set of complex cultural factors, including the histories of the environments as well as the observers themselves – their cultural backgrounds, education, intentions and motivations. An understanding of landscape quality is derived from the meanings and significance of its environmental attributes and associations (Daniel and Vinning 1983). When landscape architects and

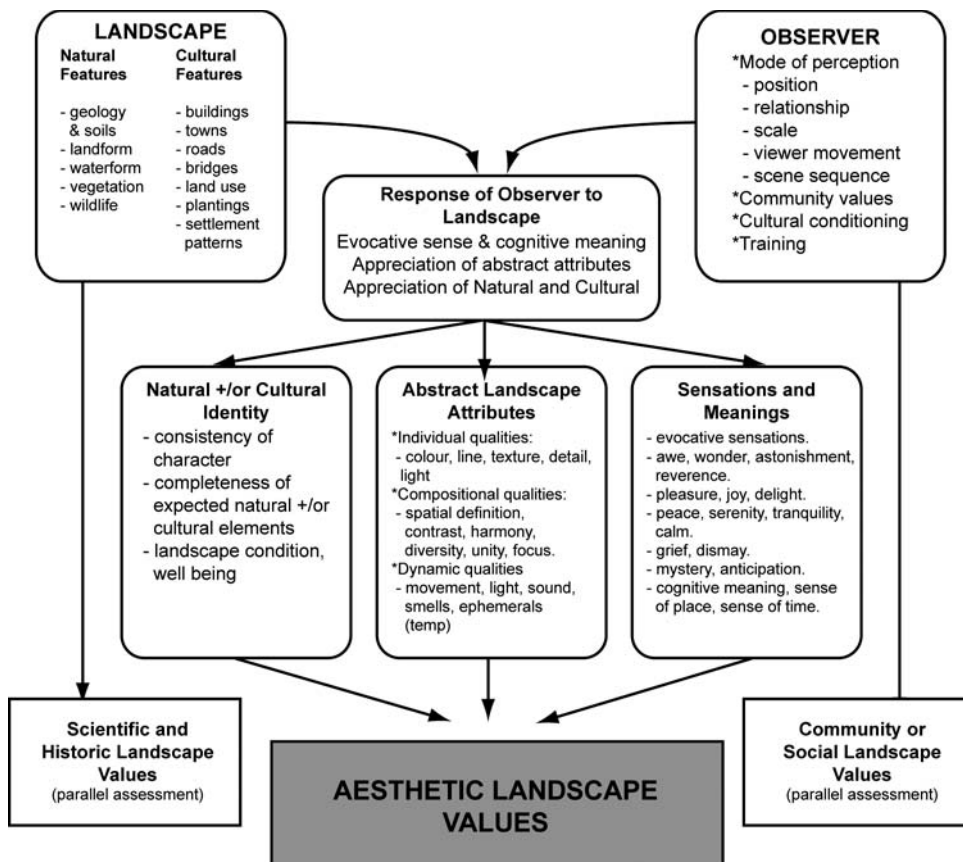


Figure 8.1: Landscape aesthetic value assessment process (adapted from O’Brien and Ramsay 1992).

natural resource managers attempt to define or describe the sense of a place, they often look at the potential reawakening of innate senses and abilities to understand the aesthetic phenomena of human behaviour and environment relations.

Each model has strengths and weaknesses arising from the critical elements used to describe a landscape’s quality, the objectivity of the evaluator and the repeatability of the result. They are included to illustrate the typical methods employed in assessing landscape attributes for their qualities and values, and to provide the background for a potential approach for agroforestry management systems (Winchcombe and Revell 2004). The realities of choosing the ‘best’ landscape assessment model largely depend on the type of the agroforestry project, in particular the brief set by the land manager or property owner. Design expectations are also influenced by various legislative requirements and/or government codes that require inter-

pretation in the greater property planning and design process.

An example of a best practice landscape assessment model is the methodology developed by the Australian Heritage Commission (Figure 8.1). It is used to assess the aesthetic value of landscapes for inclusion into the National Register, according to certain criteria. It is a highly complex and comprehensive model for assessing landscape aesthetic values, developed as an amalgamation of the models previously described by Daniel and Vining, and Lamb. One of its key features is acknowledging the inclusion and integration of other environmental assessment methodologies, e.g. for the determination of social, historical or scientific values associated with particular environments. In applying this type of assessment model, the extra knowledge and understanding of what influences the construction of landscapes from environments and their attributes can be significant when shared

among land managers and other specialists involved in the planning and design of agroforestry systems (Winchcombe and Revell 2004).

Landscape management planning and design guidelines

This section discusses the major visual landscape design principles and guidelines applicable to agroforestry systems (Revell 1997, pp. 74–79). Admittedly, designing agroforestry systems predominantly on scenic or visual quality grounds is essentially a reductionist approach to managing landscape values, as explained above. However, it offers a point of departure for the landscape architect or land designer working with other pragmatic specialists in the arena of agroforestry. In that 1997 study I asked (and attempted to answer) two significant questions regarding the actual landscape planning and design of agroforestry systems.

- 1 What are the major visual design principles and guidelines to consider in the layout of agroforestry landscapes?
- 2 What are the essential steps in the scenic quality?

In response to the first question, the following major visual design principles and guidelines were proposed.

Design principles and guidelines for background-scale landscapes

- Agroforestry plantation scale should reflect the scale of the surrounding landscape. For example, large open valley landscapes can accommodate a greater area of plantation establishment and harvest area than can smaller ones. Impacts can be minimised by separating plantation areas with existing vegetation or by creating cells of varying age classes.
- Patterns of the plantation areas should reflect or imitate surrounding land use patterns.
- Plantation design should, where possible, follow existing landscape lines such as tree line, road line, fence line, creek line and ridge line. The delineation of the plantation establishment or harvest area should respect these. Avoid reinforcing lines if they are incongruous with the surrounding landscape. For example, in a land-

scape setting which predominantly exhibits free-flowing lines, avoid breaking skylines and reinforcing property and fence lines that are geometric in nature.

- Plantation access roads and firebreaks should be of low visual impact, preferably screened, with alignments following contours, existing road patterns, vegetation lines etc. rather than artificial property boundaries.
- In visually sensitive areas, potential plantation impacts can be reduced by enhancing and extending existing vegetation areas with similar species plantings. These plantings could be protected from future harvesting, thus optimising wildlife, soil, water and recreation values. If harvested, the sequence and timing of cut should be separate from the main plantation harvest schedule.

Design principles and guidelines for middleground-scale landscapes

- At this scale middleground areas dominate the landscape. The local appreciation of ridges, valleys and plains is offered. Unlike background-scale plantation areas, the whole plantation is unlikely to be viewed at one time. Perception of detail increases, colour and texture replaces shape, and pattern and line become the major visual or scenic elements.
- The outline of the plantation area should be defined by gullies, spurs and ridges, and should borrow from the lines offered by the surrounding landscape. Plantation areas should be defined as individual units broken up by ridges, drainage lines and dominant land use patterns.
- Avoid over-reinforcing areas of maximum visual contrast such as tree lines, skylines, vegetation changes etc. Ensure that such contrasts reflect other contrasts (if present) in the surrounding landscape. For example, in natural settings, edges of vegetation change can be softened by sympathetic boundary lines, gradual change in density or age class across the interface, or the use of species of different form, colour and texture.
- For skyline edges, maintain ridges with species typically dominant within the surrounding landscape. For example, avoid pines in a hardwood forest setting. If pines are necessary

then locate them below the skyline and vary age class and planting density where possible. The harvesting of ridge or skyline plantation areas should be sequenced to reduce the extent of clearing disturbance visible at any one time, or to enable adjoining areas to be successfully regenerated.

- The upper margins of any planted area are prominent components of the planting design. In settings of a strong natural character these margins should rise or point up in the valleys and depressions, and fall or point down on the spurs. The upper margin should be located so that any open ground above the planting area is of sufficient size to reflect the scale of the hill cap, knoll or ridge.
- The visual impacts of power lines, transmission towers and corridors can be reduced by creating a series of irregular planting spaces. Trees can be planted closer to power lines opposite pylons or towers than in mid-span, and smaller trees and shrubs can be grown closer still.

Design principles and guidelines for foreground-scale landscapes

- At this scale foreground areas dominate the landscape. All perception of the background and middleground landscapes is lost. The microscale dominates, with occasional glimpses extending to the middle and background areas. The observer is virtually in the plantation or revegetated landscape. There is total perception of details of individual trees, their colours and textures, their diversity or uniformity. Visual change to the plantation is most easily detected at this scale. These plantation landscapes require a high degree of scenic quality management throughout all stages of the plantation program.
- Follow the visual expression of the surrounding foreground landscape. Avoid contrasts to these details. For example, in a uniform, patchwork, geometric, foreground agricultural landscape setting, the visual character of an exotic, regimented-looking blue gum or pine tree belt could enhance the local landscape.
- In natural non-uniform settings encourage diversity through the physical separation of plantation sections or compartments. These

areas may differ in age, species mix, planting density, thinning regime etc.

- Maintaining visual penetration through the plantation can enhance visual quality of the plantation landscape. This can be achieved by an open or clumped planting density or through thinning techniques. In natural-appearing landscape settings, thinning regimes should be non-uniform. Conversely, in geometric or culturally dominated landscapes thinning regimes should be regular and uniform.
- Access tracks and firebreaks should be designed and constructed with low visual impact.
- In sensitive areas, avoid visual impacts created by plantation debris, slashed material etc. Reduce impacts by screening, burning, mulching or scattering debris away from seen areas.
- In visually sensitive areas, harvest areas should be of minimal size in relation to the overall plantation landscape. Felled areas should not dominate over unfelled areas.
- In visually sensitive areas, employ harvest sequencing techniques. Near-roadside vegetation, for example, can reduce the visual impacts of adjoining harvest areas. Final harvesting of near-roadside vegetation should take place after surrounding coupe areas have been regenerated or replanted, and grown to become a strong enough visual element. Near-roadside vegetation could also be treated as multi-aged stands, and harvested sequentially within themselves.

In response to the second question, the essential steps in the scenic quality design of agroforestry landscapes, there are important steps in the scenic quality design process.

- Observe the agroforestry landscape setting. Take time to see and appreciate the visual character of the surrounding landscape. What are the local, district or regional scenic attributes or features of these landscapes? Map these features on suitably scaled topographic maps and aerial photographs. Try to identify any patterns in land use, land form, hydrography or vegetation cover.
- Consider whether the proposed tree planting will maintain, enhance or have a negative visual impact on natural or cultural landscape features?

Table 8.1: Comparative analysis of integrating landscape aesthetic quality management objectives with other agroforestry system objectives

Other agroforestry objective	Impact of other objective on landscape aesthetic quality management	Impact of landscape aesthetic quality management on other objective
Nature conservation	Positive impact of conserving or reconstructing a natural aesthetic on the farm and in the catchment. Maintaining remnant vegetation cover will substantially benefit landscape quality.	Ensure landscape aesthetic quality revegetation objectives increase nature conservation benefits to farm and catchment.
Soil conservation	General increase in landscape quality, especially with vegetation along valleys, ridge lines and stream lines and around water bodies and discharge areas. Impacts of poor soil conservation management often result in low scenic quality. Avoid stock access to stream lines and dams where possible.	Design landscape quality management to increase all conservation benefits. Use local plant species where possible.
Salinity control	Revegetation for salinity control generally increases landscape quality depending on species type and planting layout. Poor tree growth and potential death will reduce scenic quality.	Design salinity control revegetation measures to enhance the visual character of the farm and catchment landscapes.
Shelter	Positive impact if vegetation shelter layout follows natural and/or cultural landscape characteristics. Species diversity (grasses, shrubs and trees) will often increase landscape aesthetic quality.	Shelter may be compromised depending on wind direction and land form patterns. Ensure remnant vegetation is retained, protected and managed for additional stock shelter where required.
Fodder	Positive impact on landscape aesthetic quality depending on species type and design layout. For example, geometric shaped, exotic and/or heavily grazed vegetation plots can be visually obtrusive in the landscape, especially in foreground areas.	Minimising visual impacts from grazing and species type may be unacceptable, depending on visual landscape character of the farm and surrounding areas.
Windbreaks	General benefit to landscape aesthetic quality depending on scale, shape, orientation and species type of the windbreak.	Notwithstanding soil conservation requirements, orientation of revegetation layout may compromise windbreak benefits. Maximise use of remnant vegetation.
Timber production	General benefit depending on species type and plot layout. Visual impacts of conventional silvicultural prescriptions and harvest operations usually lower landscape aesthetic quality.	Landscape quality management may require alternative and creative silvicultural and harvesting practices. Need not affect economic output.
Agroforestry tourism	General benefit to landscape aesthetic quality and environmental education experience.	Landscape aesthetic quality management should enhance the agroforestry-based tourism experience. Should increase economic output.
Sense of place	Agroforestry systems encouraging a greater sense of place and perceived belonging to the farm locality usually increase landscape aesthetic quality.	Scenic quality improvements through agroforestry systems can be designed to enhance local and regional landscape character and identity, general sense of place, and liveability within the agrarian environment and surrounding community.

How will the planting area look in five, 15, or 30 years? What impacts will the plantation have on major private or public views and vistas of the landscape, during all establishment and harvest periods?

- Are there local community landscape design ideas and aspirations that should be respected?
- How can the planting area be planned and designed to accommodate such scenic quality considerations? Refer to the guidelines and principles above.
- Prepare preliminary planting design plans, visual simulations and prescriptions to suit integrated agroforestry management objectives and share these with neighbouring property owners/residents.
- In scenically sensitive areas, maintain a landscape evaluation and monitoring program. Take periodic photographs and monitor public and private feedback.

Further guidelines for landscape quality management

New guidelines will need to be developed, as greater resources for integrated agroforestry landscape perception research become available. Research specialists should collaborate on studies that seek to understand potential connections between aesthetics (landscape quality), economics and ecology, then develop their own hybrid landscape assessment approaches to assist agroforestry-related projects (Winchcombe and Revell 2004). Table 8.1 considers the value of landscape quality management (simple integrated landscape planning and design initiatives) in an attempt to quantify the potential relationships and impacts on other land management objectives applicable to integrated agroforestry systems. For some, it should dismiss the negative connotations concerning the worth of landscape aesthetic management if treated as a non-integrated resource management tool. As noted, further integrated research is required to test these potential management impacts and interrelationships across the greater agroforestry landscape. This challenge should be taken up by agroforestry-related scientists and artists whether or not they are directly affected; there are multiple benefits on offer from these new designed landscapes.

New projects for integrated agroforestry lead land management

In recent years the Western Australian Department of Land Management and the University of Western Australia, along with a number of noted private projects, have embarked upon a series of experimental integrated agroforestry land management projects (Winchcombe 2000). These projects have brought together a range of land management specialists representing particular scientific fields and associated practices. The landscape architects, natural resource managers and property owners have represented many of the arts-related disciplines and have essentially become the designer-integrators or design-facilitators of the more holistic land management practices demanded in these innovative projects. There is much to say about these projects; they have successfully achieved a set of integrated and pragmatic working plans that have delivered an agreed resource management consen-



Figure 8.2: Specialists gather to develop an integrated and participatory agroforestry property plan (photos by Grant Revell).

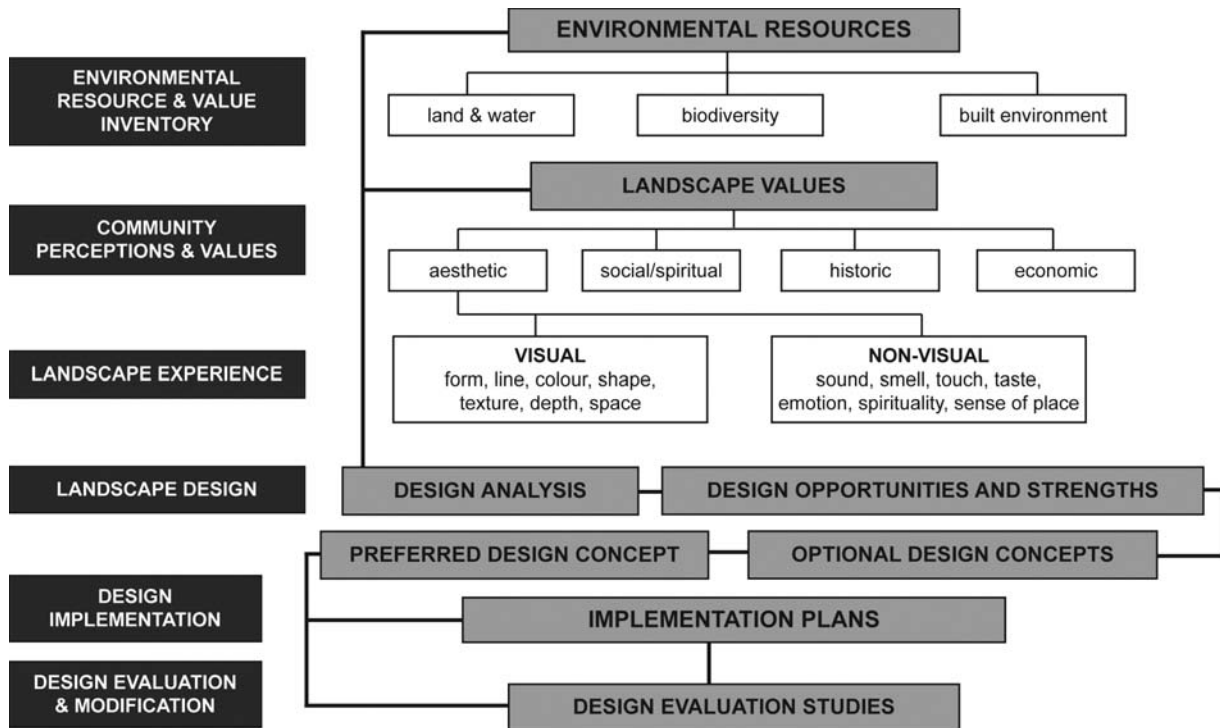


Figure 8.3: The agroforestry landscape design process (adapted from Winchcombe and Revell 2004).

sus from all those around the planning and design table (Figure 8.2).

From a landscape management point of view, in these projects the landscape architects and natural resource managers have guided a rich design process that attempted to quantify and represent, on scaled site plans and aerial photographs, a series of conventional planning and design tasks, namely resource and value inventories, spatial analyses of that data, site design opportunities and constraints, optional agroforestry design concepts, preferred concepts, agroforestry design implementation plans and design evaluation methods. Figure 8.3 illustrates this integrated landscape design process.


Figures 8.4a and 8.4b show innovative yet simple computer-generated digital terrain modelling exercises used to quantify, evaluate and redesign a significant view-shed in an agroforestry property. The landowner wanted to protect and enhance the visual character of the paddock sky lines where the older tree species of marri (*Eucalyptus calophylla*) dominated. The proposed pine and eucalyptus tree belts were designed and located so as to avoid any major interruption to these important endemic

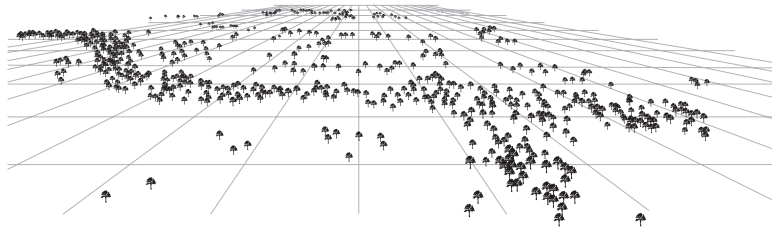
views and associated landscape amenity. Where possible, the imposed lines created by the new tree belts visually complement the remnant vegetation lines and patterns. Proposed gaps between tree belts were designed to mimic the scale of gaps found in surrounding healthy remnant vegetation patches.

Figure 8.5 shows a hand-drawn sketch plan developed for another key view-shed, on a separate project. The design process is assisted by realistic site photography and design intentions are annotated on the sketch for communication with the planning team. The visual landscape attributes of scale, pattern, form, line and contrast within the paddock's composition and setting, for example, are simply manipulated in the design process – trees are used to mimic the local landscape character or to enhance it, not unlike composing an aesthetically pleasing landscape painting. This time, the design process also aimed to improve the paddock's ecological well-being.




Both these design techniques are relatively quick, easy and cheap to employ on-site. Most importantly, they are iterative design devices and

NOTLEY'S "WESTERN NODES" FARM - DANDARAGAN EXISTING VIEW OF WESTERN RIDGE

 Remnant vegetation



NOTLEY'S "WESTERN NODES" FARM - DANDARAGAN PROPOSED VIEW OF WESTERN RIDGELINE

 Remnant vegetation
 Eucalypt shelterbelts
 Pine shelterbelts

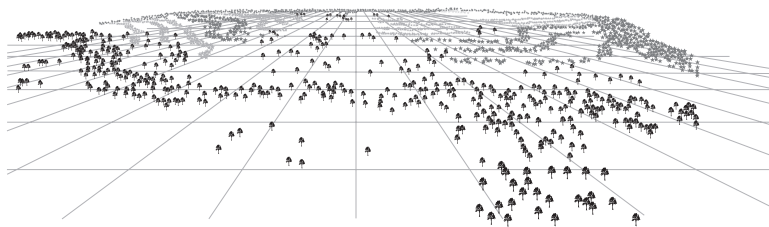


Figure 8.4: Computer simulations of (a) existing and (b) proposed design conditions in the protection and enhancement of a significant property view-shed. (c) Tree rip-lines prepared and located in accordance with the plan in Figure 8.4b. (Images by Grant Revell and Phil Durrell).

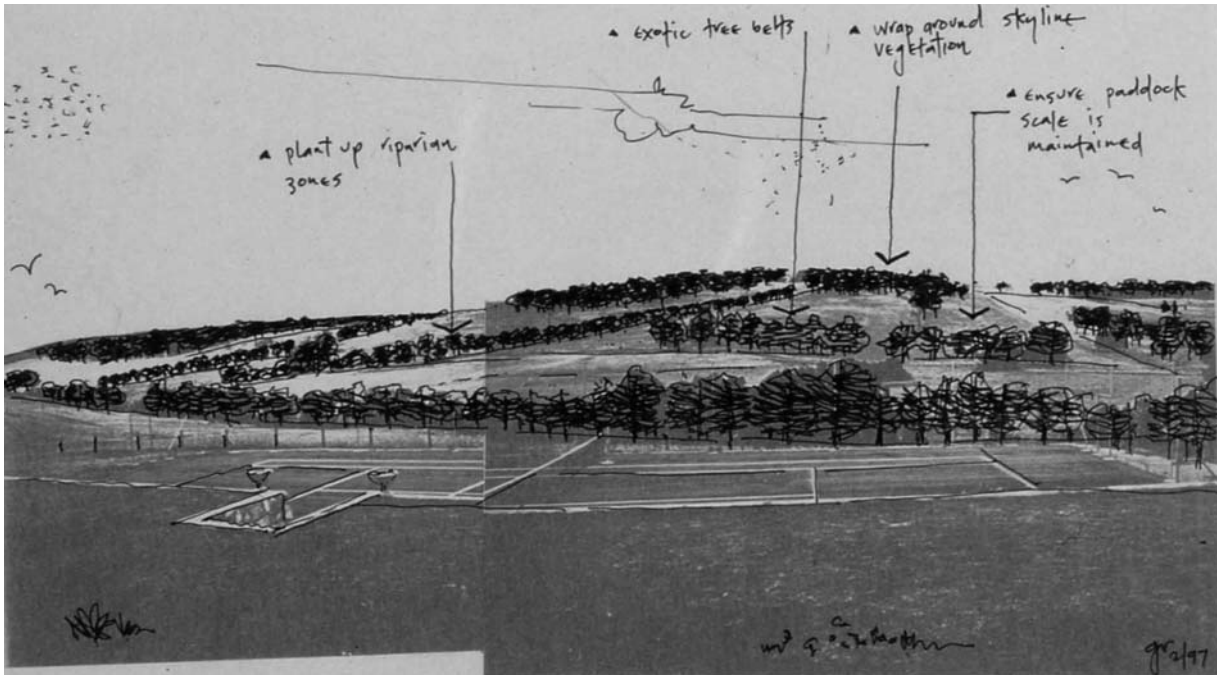


Figure 8.5: Hand-drawn sketch of proposed agroforestry modifications to a key property view-shed (image by Grant Revell).

allow the agroforestry planning team to evaluate the proposed results and make quick decisive modifications to the concept and implementation plans.

Figure 8.6 illustrates a final agroforestry master plan for a property named Brooklyn, in the township of Bridgetown, south-west Western Australia (Cowan and Revell 2000). Its development employed the design process indicated in Figure 8.3, and gives the land manager a strong visual outcome of the integrated planning work. A formal aesthetic and ecological landscape assessment model was used to identify the aesthetic landscape qualities of the property. The master plan represents a spatial approach to systematically undertaking resource and value inventories, identifying clear design opportunities and constraints, optional and preferred design concepts and implementation measures. Most importantly, it remains a flexible document – a strong conversation piece in the further evaluation of its likely performance in the landscape. It adapts itself as a decision-making tool to a staged implementation schedule, influenced by the availability of other resources and knowledge sets.

The land design criteria developed by the Brooklyn farming family and the project landscape architects are set out below.

Landscape character

The aims were to:

- preserve and strengthen the existing 19th-century picturesque nature of the property's open space and parkland character. Where possible, different tree species were used to reflect the ecological and cultural landscape diversity across the property;
- maintain and enhance vegetated ridge and skyline characteristics of the Bridgetown district landscapes;
- ensure key private and public views are maintained, enhancing visual prospect and visual refuge;
- shape, taper and/or feather agroforestry plantation edges to complement strong land forms. Where possible, the aesthetic principles of shaping the belts according to the contours are followed, with tapering belts up valleys and down spurs;

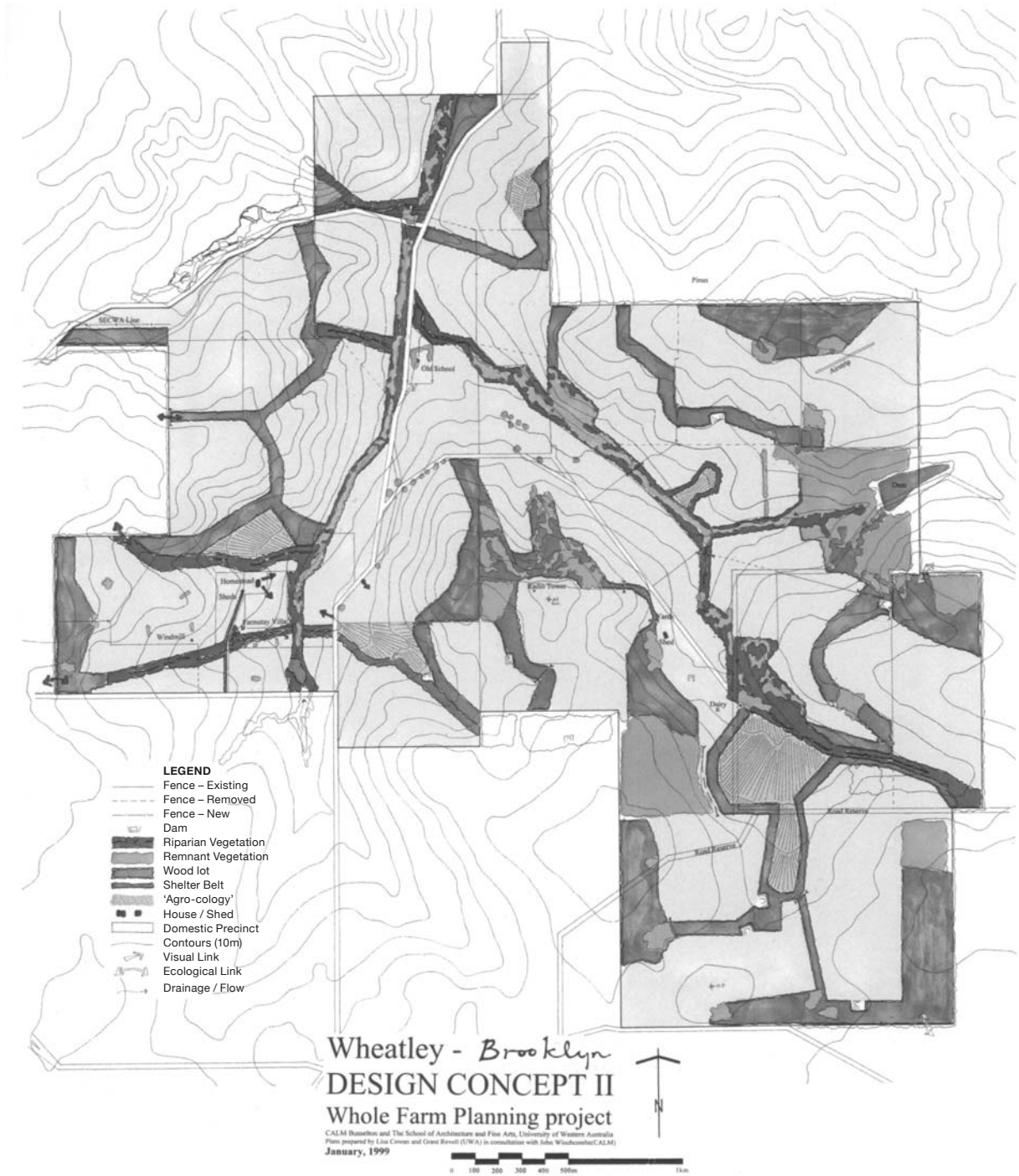


Figure 8.6: Integrated agroforestry design master plan (Cowan and Revell 2000).

- focus on and strengthen the strong cultural character of the homestead, its formal gardens and the nearby old school area;
- where possible, enhance the farm-stay facility views and associated landscape experiences.

Landscape ecology

The aims were to:

- fence and revegetate riparian zones;
- maximise water uptake in discharge areas and mitigate further salinity expression by revegetating ridges and midslopes identified by the project hydrogeographer;
- fence and link remnant vegetation, and connect to surrounding plantation areas to create continuous wildlife corridors;
- interpret the property's ecological health to help benefit farm-stay objectives.

Stock management

The aims were to:

- ensure visual access across and into paddocks for ease of stock management;
- orient agroforestry layouts as windbreaks to minimise wind exposure;
- where possible, fence to soil types for the purpose of controlled grazing.

The master plan (Figure 8.6) illustrates the potential for the whole farm landscape to be envisaged as a rural garden or utilitarian arboretum. Landscape rooms were identified according to their preferred agrarian character and use, and designed accordingly. Integrated agroforestry systems have a design potential, albeit in a less formal manner, similar to the traditions of 17th- and 18th-century English estates and French chateaus where integrated agricultural, horticultural, forestry, recreational, artistic and residential pursuits within the designed landscape were commonplace. These traditions followed the idea that the countryside, with all its appeal of nature, should be laid out for greater public view and enjoyment. The shared sense of place and the formal aesthetic qualities of landscape were based on a public ideal not unlike the values promoted by the picturesque landscape painting schools of the time. Prolific English designer and writer Stephen Switzer's publication

in 1715, for example, entitled *The Nobleman, Gentleman, and Gardener's Recreation* (reissued in 1718 as *Ichnographia Rustica*), gave explicit advice on the design of large-scale forest and rural garden landscapes (Jellicoe *et al.* 1986). Switzer's agroforestry design expertise is shown in Figure 8.7, where the forest garden is laid out on a massive scale incorporating a carefully planned framework of tree belts, avenues and plantations defining other agrarian rooms, smaller gardens and open-space areas, all laced together with a series of hierarchical walkways, carriageways and vistas. This may well be one of England's earliest attempts at designing public agroforestry as an aesthetic and utilitarian practice of rural gardening.

Conclusion

If natural resource managers are to become the new creative managers of meaningful cultural symbols in our environments, then as a discipline and profession we need to develop innovative ways to collaboratively design agroforestry systems to suit a complex array of societal values. Custodial relationships with the land need to embrace a diversity of economic, biophysical, social, spiritual and religious attachments to the great environmental nexus of nature and culture. The ecological management of rural and urban lands, for example, may develop a nature and human relationship, aesthetic or amenity that mimics natural systems that existed in some historical context. More importantly, it could encourage a whole range of additional and exciting cultural expressions and understandings of nature. It is these designed, contemporary narratives of integrated land management that offer so much in the appreciation and definition of who we were, who we are, and who we hope to be. We have vast opportunities to learn about Australian nature and culture through an honest and genuine design and management of its environment. This is the practice of both scientific and artistic intelligence.

Economics will probably dictate these greater agroforestry design opportunities, and the more visible or public lands will embrace stronger aesthetic design care, stewardship and return – not unlike those designed forests and rural gardens of the 18th century. The desirable character of the land

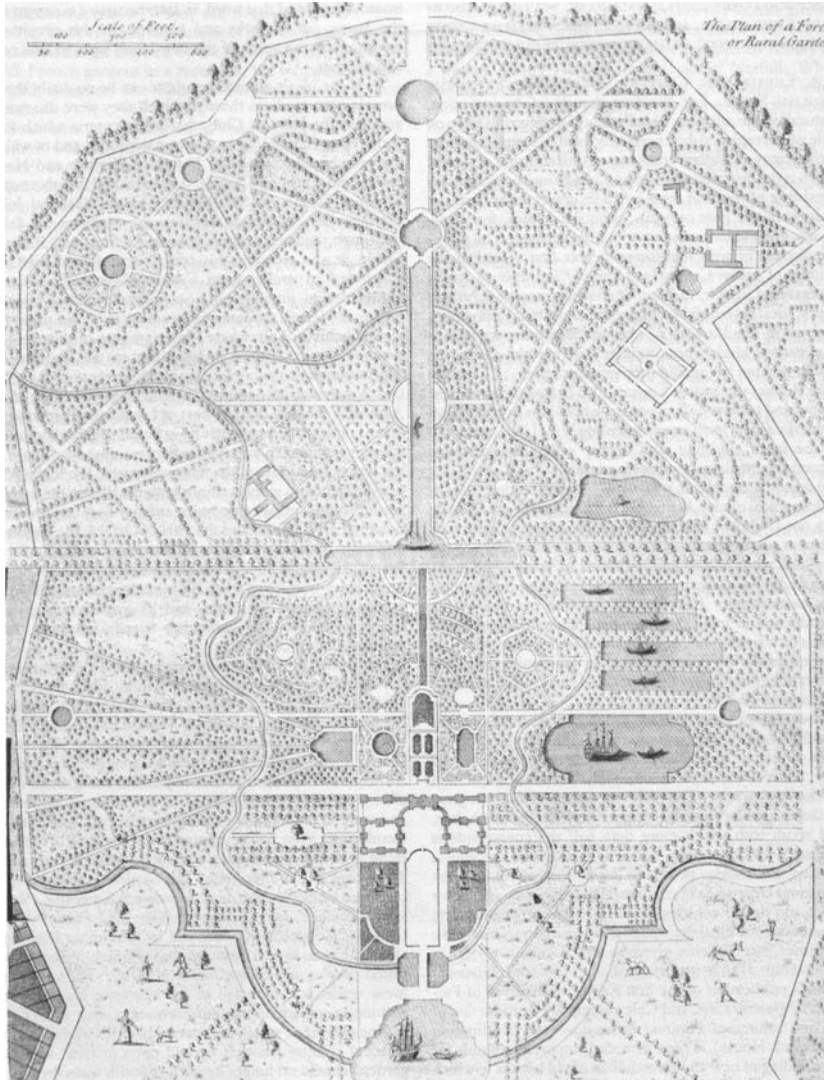


Figure 8.7: Stephen Switzer's agroforestry plan of a forest or rural garden, from *Ichnographia Rustica* (1742 edn, vol. 3, reproduced in Jellicoe *et al.* 1986) (image courtesy of Oxford University Press).

will be protected or enhanced, land prices may rise and other new economies like tourism, forestry or housing may benefit. For other custodians, it will require a careful balance of limited resources. Land design must be based on economics so that they can stay in place on the land, to maintain their deeper ties and healthy relationships to their specific environments and interconnected communities.

Much has been discussed in recent landscape literature about the importance of cultures developing peaceful ecological aesthetics to land and its management (Nassauer 1997; Johnson and Hill 2002; Judith Wright in Tredinnick 2004). Some cultures

always had a strong alignment between aesthetics and ecology – somewhere along the way it just needed additional nurturing or resuscitation. Others have learnt not to see – and for the time being they may remain that way. Most importantly, as a discipline of land managers we are now realising that the ecological health of our environments, good or bad, demand revitalised aesthetic appreciation – a stronger alignment between an ecology of place and its corresponding aesthetics of landscape.

The 'beautiful' picturesque aesthetic of land should perhaps no longer dominate our environmental values and landscape management. Open

parkland and tidy rural landscapes may start to disappear in favour of more truthful, designed, boggy and intermittent wetlands, biologically rich scrappy bushlands or brutally honest, industrial-scale watertable pumping agroforestry plantations. We have begun to demand landscapes and economies that are both scenically and ecologically beautiful and perhaps, for the time being, ugly. Our aesthetic senses are changing, and their abilities to experience a deeper *genius loci* of specific environments will encourage a temporal appreciation of this strange ugliness. In time, a richer ecological aesthetic of landscape beauty or appreciation will arise, encouraged by the development or resuscitation of stronger senses for the qualities and systems of vernacular place.

Finally, agroforestry systems and their designers need to play a vital role in the further research and application of some of the creative ideas discussed here. The experimentation, representation and interpretation of such ideas may help contribute to the cultural transformation of a healthier, more meaningful and sustainable Australian landscape. At the very least, we may see some more interesting integrated agroforestry systems.

References

- Abel N, Baxter J, Campbell A, Cleugh H, Fargher J, Lambeck R, Prinsley R, Prosser M, Reid R, Revell G, Schmidt C, Stirzaker R and Thornburn P (1997) *Design Principles for Farm Forestry: A Guide to Assist Farmers to Decide Where to Plant Trees*. Joint Venture Agroforestry Program, Rural Industries Research and Development Corporation, Canberra.
- Cleary J (1999a) Landscape and visual resource analysis. In *Coastal Planning and Management*. (Eds R Kay and J Alder) pp. 213–225. E & FN Spon, London.
- Cleary J (1999b) *Shark Bay World Heritage Landscape Study*. Department of Conservation and Land Management, Perth, WA.
- Cobham Resource Consultants (1993) *Landscape Assessment Guidance*. Prepared for the Countryside Commission, UK.
- Cowan L and Revell G (2000) ‘South-west farm land planning and design projects’. Unpublished report prepared for the Department of Conservation and Land Management, Busselton Farm Forestry Unit. University of Western Australia.
- Curtis A and Race D (1996) *A Review of Socio-economic Factors Affecting Regional Farm Forestry Development in Australia*. Johnstone Centre, Charles Sturt University, Albury, NSW.
- Daniel TC and Vinning J (1983) Methodological issues in the assessment of landscape quality. In *Behaviour and the Natural Environment. Advances in Theory and Research*. (Eds I Altman and JF Wohlwill) vol. 6, pp. 39–84. Plenum Press, New York.
- Forestry Commission Tasmania (nd) *A Manual for Forest Landscape Management*. Government of Tasmania, Hobart.
- Greider T and Garkovich L (1994) Landscapes: the social construction of nature and the environment. *Rural Sociology* 59(1), 1–24.
- Itami RM (1993) Characteristics of landscape aesthetic value and implications for assessment methodology. In *More Than Meets the Eye. Identifying and Assessing Aesthetic Value*. (Eds J Ramsay and J Paraskevopoulos) pp. 13–21. Australian Heritage Commission, Technical Workshop Series no. 7.
- Jellicoe J, Jellicoe S, Goode P and Lancaster M (Eds) (1986) *The Oxford Companion to Gardens*. Oxford University Press, New York.
- Johnson BR and Hill K (Eds) (2002) *Ecology and Design: Frameworks for Learning*. Island Press, Washington DC.
- Kay R and Alder J (1999) *Coastal Planning and Management*. E & FN Spon, London.
- Lamb R (1993) Advancing arguments for the conservation of valued landscapes. In *More Than Meets the Eye. Identifying and Assessing Aesthetic Value*. (Eds J Ramsay and J Paraskevopoulos) pp. 23–36. Australian Heritage Commission, Technical Workshop Series no. 7.
- Leonard M and Hammond R (1984) *Landscape Character Types of Victoria, with Frames of Reference for Scenic Quality Assessment*. Forests Commission of Victoria.
- Leonard L, Delaney J and Revell G (2000) ‘Adaptation of computer software to evaluate the visual impact of farm forestry layouts’. Joint Venture Agroforestry Program, Rural Industries Research and Development Corporation, Canberra. Project no. CAL-2A.

- Litton RB (1979) Descriptive approaches to landscape analysis. In *Proceedings of Our National Landscape, a Conference on Applied Techniques for Analysis and Management of the Visual Resource*. PSW Forest and Range Experiment Station, USDA Forest Service, Berkeley, California.
- Lucas OWRL (1991) *The Design of Forest Landscapes*. Oxford University Press.
- Nassauer JI (Ed.) (1997) *Placing Nature: Culture and Landscape Ecology*. Island Press, Washington DC.
- O'Brien M and Ramsay J (1992) 'Assessing aesthetic values of landscapes for the Register of the National Estate'. Australian Heritage Commission, Canberra. Discussion Paper.
- Ramsay J and Paraskevopoulos J (Eds) (1993) *More than Meets the Eye: Identifying and Assessing Aesthetic Value*. Australian Heritage Commission. Technical Workshop Series no. 7.
- Revell G (1994) *Guidelines for Managing Plantation Landscapes*. Department of Conservation and Land Management, Perth, WA.
- Revell G (1997) Trees for scenic quality management. In *Design Principles for Farm Forestry: A Guide to Assist Farmers to Decide Where to Plant Trees*. (Eds N Abel *et al.*). Joint Venture Agroforestry Program, Rural Industries Research and Development Corporation, Canberra.
- Revell G (2000) South-west farm land planning and design project. School of Architecture and Fine Arts, University of Western Australia.
- Revell G and Cleary J (1998) *Landscape Planning Guidelines*. Prepared for Department of Conservation and Land Management WA.
- Revell G, McAuliffe T and Winchcombe J (Eds) (1999) A boree store. School of Architecture and Fine Arts, University of Western Australia, Perth.
- Riley R (1998) Landscape architecture and education. *Landscape Architecture Journal*, Spring, University of Wisconsin.
- Stirzaker R, Vertessy R and Sarre A (2002) 'Trees, water and salt: an Australian guide to using trees for healthy catchments and productive farms'. Joint Venture Agroforestry Program, Rural Industries Research and Development Corporation, Canberra. Publication no. 01/086.
- Stuart-Street A and Revell G (1994) *Reading the Remote: Landscape Characters of Western Australia*. Department of Conservation and Land Management, Perth, WA.
- Tonts M, Campbell C and Black A (2001) 'Socio-economic impacts of farm forestry'. Joint Venture Agroforestry Program, Rural Industries Research and Development Corporation, Canberra. Publication no. 01/45.
- Tredinnick M (2004) The genius of the place: an introductory essay. In *Sense of Place: A Response to the Environment*. (G Seddon). Limited facsimile edition. Bloomings Books, Melbourne.
- Lamb R (1993) Advancing arguments for the conservation of valued landscapes. In *More than Meets the Eye: Identifying and Assessing Aesthetic Value*. (Eds J Ramsay and J Paraskevopoulos) pp. 23–36. Australian Heritage Commission, Technical Workshop Series no. 7.
- Van Pelt JW (1980) Landscape analysis and design for conifer plantations. *Journal of Australian Forestry* 43(3), 178–188.
- Weller R (1997) Design with the lot: a takeaway. Unpublished keynote paper presented to *W-Edge Conference: National Student Conference in Landscape Architecture*. September 23–27, Rottneest Island, WA.
- Winchcombe J (1999) (Ed.) 'Southwest farm forestry project. Subproject 3. Farm forestry integration packaging'. National Heritage Trust Farm Forestry Project, Department of CALM Report to DAFF.
- Winchcombe J (2000) 'Investigation of the economic and social opportunities for farm forestry in the Dandaragan Shire'. Dandaragan Shire Land Conservation District Committee. NHT Project no. 983017.
- Winchcombe J and Revell G (2004) 'Farm forestry and landscape architecture: a feasibility study'. Joint Venture Agroforestry Program, Rural Industries Research and Development Corporation, Canberra. Project no. UWA-68A. Publication no. 04/187.
- Zube EH, Sell JL and Taylor JG (1982) *Landscape perception: research application and theory*. Department of Geography, University of Arizona, Tucson, Arizona.

PART II

Productive function of trees in the landscape

Wood as a farm product

Rowan Reid

Introduction

There are thousands of different wood products that farmers may be able to produce, ranging from fine furniture timbers to firewood. Wood is also the basis of many chemically derived products including cellophane, charcoal, dyestuffs, explosives, lacquers, turpentine and yeast. It is possible to identify both virtues and defects for any wood product market and processing method that will affect the value of a tree or forest as a source of raw material. All trees grow wood, but not all wood is worth growing.

Although cellulose and lignin are the main constituents of all woods the quality of wood for a particular purpose may be influenced by its colour, density, cell structure, presence of resins, oils or other compounds, distribution of growth rings, grain pattern, natural durability, ease of working or any number of other properties. These vary between species and may also vary with location in the tree, growth rate, tree age, site characteristics and management. The value of a particular tree or log as a source of wood may depend on other factors such as log diameter, straightness, length, knot size or presence of internal growth stresses.

Like most other commercial farm products, the forest grower generally receives what's left after their product has been harvested and transported to the point of sale. Wood is a bulky product so, if the product is of low value or demand is low, harvesting and transport costs can easily amount to more than the sale price, making it unviable to harvest. To increase returns, growers might explore ways of

reducing the costs associated with the production, harvesting and marketing of their timber. Alternatively, there may be ways in which they can increase or add value to their product as it is growing. Distance to market, ease of access, harvest volume, uniformity of growth, tree species, log size and shape, the availability of appropriate skills and equipment, the ability to value-add on site and direct marketing are all important.

Every management decision a tree grower makes, from the time of planting through to the final harvest, can influence wood quality, log quality and forest value. It is in every grower's interest to know what defines quality and value in the wood markets they are interested in supplying. Working backwards from the market specifications to the paddock, growers can balance their views about future market opportunities and prices, non-wood values they'd like their forest to provide, personal preferences and risk, to develop a clear vision of their target forest. Only then can they select the most appropriate species, planting arrangement and management plan for their site.

This chapter reviews the nature of wood and how trees and forest grow. Based on market specifications, the following chapters explore the production options for particular timber products including firewood, pulpwood and sawlogs.

Hardwoods and softwoods

Trees are classified into two groups – hardwoods and softwoods. Confusingly, the wood of a

hardwood is not necessarily hard. Balsa wood, for example, is actually a hardwood, while some of Australia's toughest timbers, such as callitris pine, are actually softwoods. The easiest way to distinguish the two is to remember that flowering trees are all hardwoods (eucalypts, wattles, oaks and others) and that cone-bearing trees or conifers are all softwoods (pines, cypresses, spruces etc.).

The important difference between hardwoods and softwoods is the cellular structure of the wood. Hardwood timber is made up of four types of cells: small fibres that make up the bulk of the wood structure, large cells called pores or vessels that act as pipes for moving water and nutrients up the tree through the mass of fibres, ray cells that run from the centre of the stem to the bark rather than up and down the stem, which play a role in storing and distributing carbohydrates, and a last cell type that is largely used to store food. With experience, it is possible to distinguish individual hardwood timbers on the basis of the number, size and location of the pores and ray cells.

Softwoods have a simpler cell structure. The bulk of the wood is made up of long open fibres which provide strength and transport all the water and nutrients up the stem from the roots. They have ray cells but rarely are these visible to the eye. Although they do not have pores, most softwoods do have large resin canals or ducts. The resin provides an important defence against decay in the living tree.

Tree growth and wood production

How trees grow wood

The above-ground part of a tree grows in two ways. Elongation or height growth of the main stem and branches occurs as a result of cell division by the apical meristems (dividing cells) located in the growing tips. Leaf, stem and flower buds arise from the apical meristem and may develop immediately or remain dormant below the bark at that point on the stem. The corky remnant of apical growth is called the pith and can often be seen at the centre of a log. This growth gives the tree height but is not responsible for producing the true wood found in the trunk or branches of a tree.

True wood is the result of growth derived from the cambium, a thin layer of cells hidden just below

the bark. The cambium produces both wood and bark and is sandwiched between these two parts of the tree. As a stem thickens the cambium moves out away from the pith and expands to cover the greater surface area of wood. In the living tree, newly created bark cells on the outside of the cambium form the phloem through which the carbohydrates and hormones generated in the leaves flow down the trunk to the root system (Figure 9.1). As new phloem cells are formed older ones dry out, adding to the protective bark. On the inside of the cambium newly fashioned wood cells add to the band of sapwood through which the water and nutrients flow up the tree.

The type and number of wood cells produced by the cambium is determined by the concentrations of carbohydrates and growth hormones in the phloem. During favourable conditions for growth high concentrations of carbohydrate and hormones flowing down the phloem result in the formation of the large earlywood cells in the stem. As photosynthetic activity slows during dry or cool conditions (or as the tree enters a dormant phase) the concentration of hormones falls, resulting in small thick-walled latewood cells. These dense latewood cells give rise to the growth rings. In well-watered temperate regions trees generally produce one growth ring per year. In dry or tropical areas, where growth responds to rainfall rather than temperature, there may be a number of growth rings produced each year, or even none at all.

As new sapwood is formed, the inner rings of older sapwood, no longer required for water flow, are retired (the cells being filled with crystals or resins) and become heartwood. The absence of starch and the presence of phenolic compounds often give the heartwood a darker colour and greater natural durability against fungi, insects and other decay agents. Although the process of transition of sapwood to heartwood is not well-understood we do know that there is a relationship between the water needs of the canopy (leaf area) and the width of the sapwood band in most species (Vertessy *et al.* 1995; Teskey and Sheriff 1996). A large open grown tree with a large canopy is therefore likely to have a wider sapwood band than a tree of similar size growing in a dense forest. Because of the relationship between canopy size and growth rate, fast-growing trees generally have

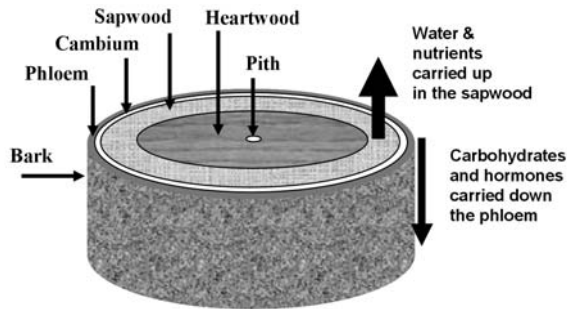


Figure 9.1: Cross-section of the stem showing the different wood types and their function.

a wider sapwood band than slow-growing trees of the same species.

Tree growth and wood properties

How a tree grows can affect wood properties. It is important that forest growers understand these relationships and the potential to use silvicultural management to control wood quality. This section reviews some important relationships between tree growth and a range of important wood properties.

Wood density

Wood density affects the strength of timber, pulp yields, fuel value and many other important properties. Although the wood of some species is naturally heavier than others it is important to appreciate how density varies within the tree and in response to growth.

First, in all species wood density varies across the growth ring depending on the location and density of the latewood and earlywood, the transition between them and the distribution of pores (in hardwoods). If the variation in density between the earlywood and latewood is great then the distance between growth rings may be critical for some applications. Variations in strength, appearance or acoustical qualities across the growth ring may make some fast-grown trees (with wide growth rings) of otherwise valuable species unsuitable for products such as flooring, furniture or musical instruments.

It is common to think of fast growth resulting in lower wood density but this is generally not the case. In some hardwood species the large open pores form a ring in the early wood (ring-porous species) at the start of the growing season, accentuating the appearance of the growth ring (Figure 9.2). Because

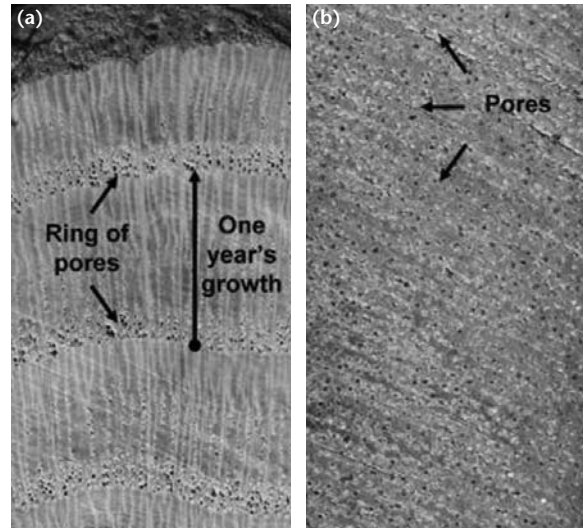


Figure 9.2: (a) Ring-porous oak (*Quercus robur*). (b) Diffuse-porous merbau (*Intsia* spp.).

the bands of pores have the same width, irrespective of growth rate, the densest timber actually comes from the fastest-growing trees because there are fewer rings of open pores (Haygreen and Bowyer 1989). This is the case for many of the oak species (*Quercus* spp.), with the heaviest and most durable timber produced from the fastest-growing trees on the most fertile sites. For barrels, coopers may prefer the lighter slow-grown Oak because it is easier to bend and imparts more flavour to the wine.

Australian hardwoods, such as eucalypts and acacias, are usually diffuse-porous. The distribution of pores stays relatively uniform across the growth ring, meaning that growth rate does not directly influence wood density (DeBell *et al.* 2001). However, research suggests that the average wood density of each successive growth ring in young eucalypts increases as the trees grow and that the highest wood density is found just below the bark (Wilkes 1984; DeBell *et al.* 2001). This phenomenon is related to the concept of juvenile wood or crown wood rather than growth rate (see below).

Wood density may also vary with site location. Many pine species, for example, produce more latewood, and therefore have higher density, when grown closer to the equator. In New Zealand the wood density of radiata pine is classified in some markets by the region in which it was grown: high density (Northland, Auckland), medium density

(central North Island) and low density (South Island) (Cown *et al.* 1991). Similarly, in Australia the wood density of subtropical exotic pines of the same age can increase by as much as 10% between northern New South Wales and north Queensland (Harding and Copley 2000).

Once formed, the density of wood fibres cannot change. However, the process of tylosis which occurs during the transformation of sapwood into heartwood can increase wood density. Wilkes (1984) examined the basic density (oven-dried) and extractive content of fast- and slow-growing coppice regrowth of six dry sclerophyll eucalypts. He found that heartwood development increased wood density by as much as 20% (from 0.72 to 0.90 g/cm³ in *E. sideroxylon*) and that faster-grown stems had a higher extractive content than slower-growing stems.

Juvenile wood (crown wood)

In *Pinus radiata* the density of the timber laid down by the cambium during the first 10 years of growth (the central 10 growth rings in a log) may be as much as 40% lower in wood density than the wood in growth rings laid down after, say, 30 years (Lavery 1986). Because of this many pine sawmillers specify that they prefer logs from forests over 25 years old, due to concerns about the strength of young timber. The industry refers to this inferior timber as 'juvenile wood'.

The average density of the eucalypt timber in successive growth rings also increases with tree age (Downes *et al.* 1997). However, the fact that the timber of many mature eucalypts is much heavier than most internationally recognised cabinet species, such as Australian blackwood and English oak, suggests that a reduction in wood density could actually be an advantage for some applications. Nonetheless, the high proportion of juvenile wood in a young tree may affect its value where density is important, such as for firewood, durable posts or structural beams. Across a range of species, juvenile wood tends to shrink more due to the greater angle of the microfibrils that make up the cell walls of each wood cell and is softer due to the lower proportion of latewood (Dean and Baldwin 1996).

The reason why the density of newly formed wood in the trunk of a young tree is lower than that produced in later years is not directly related to age

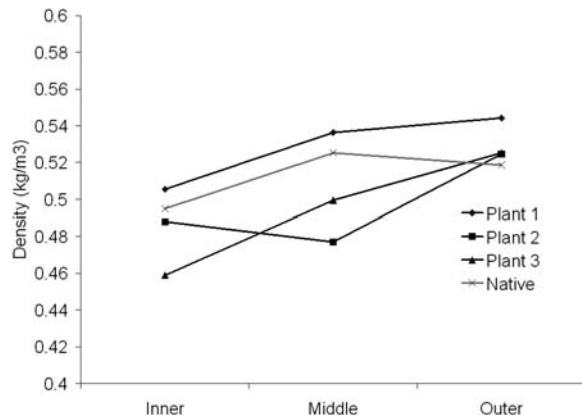


Figure 9.3: Wood density (oven dry weight/air dry volume) across the width of three 135 mm quartersawn boards sawn from 16-year-old *Eucalyptus nitens* and a similar board cut from a 65-year-old native forest *E. nitens* log of similar size. The results show the expected trend of increasing wood density with greater distance from the centre of the log and no clear effect of growth rate or age.

at all. The difference is the relative distance of the newly formed wood cells from the active canopy. In a short tree the lower stem is closer to the photosynthetically active leaves so the concentration of hormones (auxins) and sugars in the phloem will be higher than at the same height in a tall tree (Dean and Baldwin 1996; Jagels 2006). In a timber-producing forest the distance between the lower stem and the active canopy increases over time as tree height, branch length and height to the green canopy increases. This explains the trend of increasing wood density across wide quartersawn boards (Figure 9.3). 'Crown wood' is a more accurate term than 'juvenile wood', because it develops in areas close to the crown where these concentrations are greater.

Natural durability and colour

Many timbers are valued for their natural resistance to decay or insect attack. The sapwood of almost all species is not durable because the cells are open to moisture and contain life-supporting sugars and starches (Bootle 1983). Natural durability and resistance to insect attack of the heartwood of many species result from extractives that fill the cells and impregnate the cell walls during heartwood formation. The tree's ability to access or produce the chemicals and minerals that provide

resistance to decay or insect attack varies with site conditions and growth rates. Jagels (2006) suggests that soil pH and cation exchange capacity are important in that they may influence the availability of important chemicals. He cautions that high site quality, fertilisation, irrigation or the promotion of rapid growth by thinning may result in a dilution effect which could lead to formation of heartwood with lower natural durability.

Wood colour may be correlated with natural durability but is also important in its own right. The colour of freshly sawn wood and how it responds over time varies within a species and may be affected by site quality, growth rate and silvicultural management, but the relationships are poorly understood or inconsistent. Colour variation in Australian blackwood has been studied in Tasmania, New Zealand and South Africa and the findings provide some insight into the complexity of colour variation in timber. Bradbury (2006) found that although darkness was correlated with wood density in a Tasmanian trial, increasing growth rate was not shown to influence either. In New Zealand, Nicholas *et al.* (2006) found that colour varied enormously across seedlots and sites but was not influenced by stocking rate. However, their results did not support earlier South African research that had suggested blackwood colour was darker in trees growing on well-watered sites with deep organic soils (Harrison 1975).

Reaction wood and growth stresses

Compression and tension wood (collectively known as reaction wood) are abnormal wood cells that occur in softwoods and hardwoods respectively. The presence of reaction wood can have a dramatic effect on milling and drying behaviour and wood properties. In eucalypts, tension wood is more prone to collapse during drying and tends not to recover when reconditioned (Washusen *et al.* 2002). The excessive shrinkage common in tension wood can lead to extraordinary twisting and warping during drying (Washusen *et al.* 2000).

Both tension wood and compression wood can form in response to the tree leaning over or simply flexing in the wind (Washusen 2002). A leaning softwood will form compression wood on the underside of the stem whereas tension wood forms on the upper side of a leaning hardwood (Jagels

2006). Branches naturally have lots of reaction wood to hold them in position, which is why they are rarely used for solid timber.

Many people working with eucalypts have experienced end splitting in recently harvested logs or witnessed the bending of freshly sawn timber as it is milled. This is caused by a difference in tension between the outer growth rings and the log core. The development of growth stresses is natural and easily understood if we think of the standing tree trunk as a flexible, rather than a ridged, pole. As new growth rings are laid down around the standing tree, a longitudinal (up the tree) tensile stress is imposed as the cells mature. The result is that the trunk's outer surface is in tension (like an elastic band) and balanced by compression stresses (like a compressed spring) in the central core. Unlike a ridged pole, the tension near the surface allows the tree to absorb wind stress without breaking. In effect, it is similar to a concrete pole with steel reinforcing rods embedded around the perimeter.

The tension is induced during wood cell maturation. Secondary wall thickening of newly formed wood cells causes the layer of wood cells to contract. Imagine a cardboard box wrapped in shrinkwrap plastic. The plastic is first loosely wrapped around the carton and is neither in tension or compression. When treated, the plastic shrinks tight around the box, imposing an equal and opposite compression stress on the box. If the box is repeatedly wrapped and the same degree of tension applied to each layer of plastic, the box may eventually crumble. This can also occur in trees, and is seen as 'brittle heart' in the centre of the log.

If a log with severe natural growth stresses is sawn down the centre each half immediately bows out as the tension wood is able to relax. This creates problems during milling and may require special equipment or sawing patterns (Washusen *et al.* 2000). Back-sawn boards (Figure 9.4) will bow as a result of longitudinal stresses; quarter-sawn boards will spring. Bow is of less concern as the boards can be easily straightened, so mills may prefer to back-saw highly reactive logs. Spring is difficult to correct without large reductions in recovery.

Research supports the observation that growth stresses are less severe in larger diameter logs from short straight trees (Yang and Waugh 2001). There are two reasons suggested for this. First, although

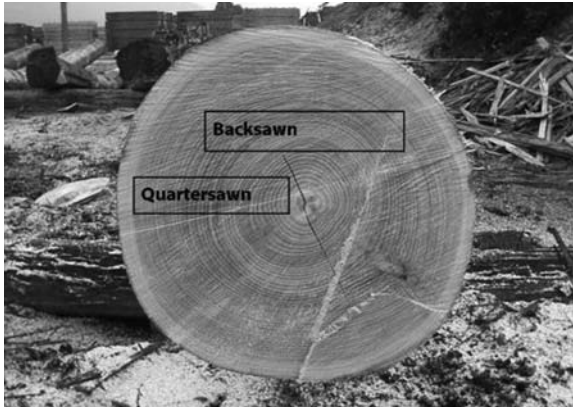


Figure 9.4: The terms quarter-sawn and back-sawn refer to the alignment of growth rings in the sawn board.

the difference between the tension in the outside of the debarked log and the pith compression in a large-diameter log may be similar, the gradient of change is greater in a small log, causing it to bend more (Figure 9.5) (Yang and Waugh 2001). Second, in tall skinny plantation trees, growth stresses are thought to be a result of bending stresses induced by or in response to wind (Washusen 2002). In one study of straight plantation-grown *E. globulus*, tension wood was most pronounced at the base of the tree on the side facing the prevailing winds and extended further up the stem in tall slender trees (Washusen 2002). Sturdy, short fat trees are less prone to wind-induced growth stresses. Leaning eucalypt trees can have both growth stresses and bands of tension wood, making them difficult to mill and diabolical to dry.



Figure 9.5: Radial splitting in this small-diameter eucalypt log illustrates the difficulty of sawing quarter-sawn boards from small-diameter logs.

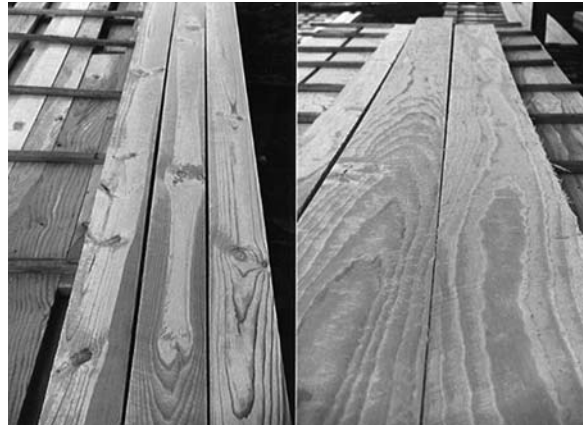


Figure 9.6: Knotty (left) and clearwood pine sawn from pruned plantations in Tasmania.

Knots or branch stubs

Knots or branch stubs can be a major defect in sawn timber (Figure 9.6). Large, loose or dead knots can greatly reduce the strength of sawn timber and can be unsightly in appearance-grade products. In this respect it is important to distinguish between structural and appearance grades. Structural timbers are graded on the basis of their suitability to carry loads. For a given species, visual grading rules specify the size, location, number and type of knots permissible for each structural grade. Increasingly, mills are using mechanical stress-grading machines to test the bending strength of each piece and grade them accordingly. It is possible that other factors, such as wood density and grain orientation, may compensate for large or numerous knots. However, knots of any size can affect wood values in appearance applications. 'Clearwood', timber that is clear of knots or other defects, is usually considered the highest-quality and valuable timber grade for use in furniture, flooring, lining boards, joinery or other applications.

There are a number of strategies growers can use to control the type, size and location of knots in the log, including stem-pruning and managing competition in the stand. These are discussed in detail in Chapter 10.

Tree form and log shape

For sawn timber production, it is often critical that the logs come from straight upright trees. In addition to forming reaction wood and growth stresses,

leaning trees also tend to develop a sweep that makes it difficult to mill long straight lengths. Sharp bends and kinks are also a problem. Although small bends in young trees may grow out over time, the wandering pith that results will lower recovery of the better-sawn timber grades. The core of the log is commonly boxed-out and discarded because of problems of drying boards containing pith.

Multi-stems and large forked trees have little or no value for sawlogs. They may be undesirable even in pulpwood and firewood plantations. A tree with two stems does not necessarily have a greater volume than if it had a single stem, since in both cases the effective canopy area is the same. The smaller diameter of the multi-stems increases harvesting costs and the area of bark that has to be removed, and may be more difficult to mechanically harvest.

The degree of taper can be critical (Figure 9.7). Where the diameter decreases rapidly up the stem the recovery of sawn timber will be greatly reduced. Logs that are near-perfect cylinders are clearly preferable for most applications. If the taper is excessive, sawmills may try to purchase logs on the basis of the volume calculated using the small-end diameter rather than the mid-point or average diameter. Taper can be influenced by silvicultural management, as discussed in later chapters.

Log length

Depending on the sawing equipment and product options, a sawmill operator should be able to specify a minimum and maximum log length. The tendency is to prefer longer logs as these will incur lower fixed costs in the harvesting, transporting, milling and drying. However, few modern sawmills can cater for logs greater than 6.5 m. In some cases sawmillers may cut longer logs in two if there is concern about severe growth stresses or taper.

Log diameter

Whatever the product, harvesting, debarking and loading costs per cubic metre of wood increase with decreasing log diameter, especially if the trees are manually felled. Once cut into lengths, it is the diameter of the log, not the height of the tree, which will be most important to the miller. Generally, the larger the log diameter the greater the sawn timber

recovery, the lower the fixed costs of milling and the greater the proportion of higher-value grades.

Larger logs can be more easily quarter-sawn, may be less prone to problems due to growth stresses and will generally have a lower proportion of juvenile wood. For products in which the sapwood is undesirable, such as species with durable or attractive heartwood, large-diameter logs are essential. Naturally, larger-dimension boards can only be cut from large-diameter logs. For veneers, the larger the diameter the higher the value.

Logs of 50–70 cm in diameter (underbark) are often preferred in mills that saw large-section appearance-grade timber. Some of the high-production softwood mills focused on producing structure pine are geared for rapid throughput and may not be able to handle logs over about 55 cm in



Figure 9.7: This pruned spotted gum (*Corymbia maculata*) has a reasonable diameter but a degree of taper. If left to grow for a few more years, the taper will become less pronounced.



Figure 9.8: Fiddleback blackwood (*Acacia melanoxylon*) is prized for guitar backs and other high-value end uses.

diameter. Post and pole markets have strict diameter length and taper requirements. For vineyard posts, the price per cubic metre for small-diameter posts of high strength can be higher than for large-diameter posts. For electricity or building poles, an even diameter along a long log length is required.

Other defects and effects

Other factors that may affect log quality are rot, insect tunnels, unusual grain patterns, fungal infection, kino veins, resin pockets and fire scars. Although some may enhance the appearance of the timber for use in crafts or designer furniture, defects rarely enhance log value. Where it is possible to see that a particular log has an interesting grain pattern, such as fiddleback or birdseye, it may be worth separating it for sale to a wood worker who can take advantage of its unique qualities.

Any foreign material imbedded in the tree, such as fencing wire, electrical insulators, horseshoes or nails, present a great risk to safety and milling equipment. If there is any risk of metal or other solid material in a log a miller will be very reluctant to purchase or saw the timber. In some cases metal detectors are used to scan the log before milling.

Log value and prices

Logs are sold in various ways. If the buyer purchases the standing trees they are said to pay a

stumpage price. This is usually an agreed price per cubic metre for different log grades. For example, a farmer might be paid \$50/m³ of sawlog and \$10/green tonne for the rest of the tree, which might be used for firewood. The volumes might be assessed on the basis of truck weighing-station measurements. When purchasing standing timber, the buyer covers the costs of harvesting and transport.

If the forest owner fells the trees and delivers them to the mill, or employs a contractor to do so, the point of sale is at the mill rather than at the stump. Sawlogs might be delivered to one buyer and pulpwood to another. The price received for each product is called the mill door price. Other ways to sell timber include selling the land and timber as a package, selling the harvesting rights as a lump sum, sorting the logs into grades and selling at the farm gate, and value-adding by processing and/or drying then selling sawn timber, firewood, posts or other products directly to wholesalers and users.

Irrespective of marketing method, the value of a grower's logs will reflect the availability of processing facilities, competition in the market, demand for the final product, the volume available for sale, ease of access and many other factors. Small growers commonly find they have insufficient volume or market leverage to negotiate a satisfactory price, especially when there are large producers in the same area providing a very similar product to a small number of buyers. It is therefore important that small growers explore ways of improving their product quality, targeting specialist markets or value-adding.

Figure 9.9 shows the price-quality curves for a range of log types sold by the Victorian government in 1995. In Australia, exotic plantation softwood logs of similar wood characteristics have traditionally been sold on the basis of diameter, with the larger logs receiving higher prices per cubic metre. As the hardwood timber industry becomes more sophisticated and the quality of logs from native forests declines, the price differential between high- and low-value eucalypt logs appears to be increasing. In some cases there are minimum specifications that, if not met, mean the logs have no value. For example, small-diameter cabinet timbers such as Australian blackwood are often not worth milling and have no woodchip market due to their colour.

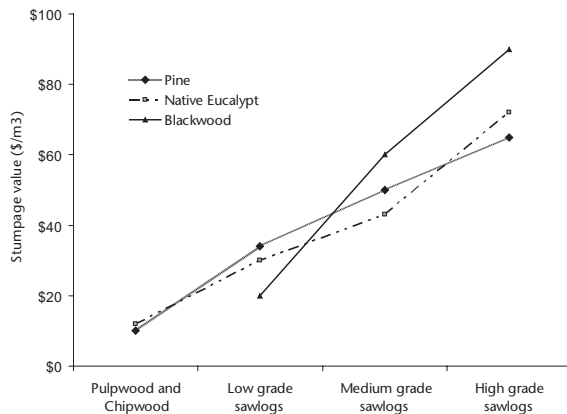


Figure 9.9: The price-quality curve for different logs based on Victorian government stumpages in 1995.

It is important that growers appreciate that many factors can influence quality. With increasing world demand for plantation-grown eucalypt pulpwood and improved technology for milling small-diameter logs, value may relate more to the economies of scale than to log dimensions. Whatever the determining factors, the steeper the gradient of the price-quality curve the greater the reward for growers who can produce higher quality. The greater demand for high-quality logs makes it easier to attract buyer interest in small lots and reduces the impact of transport distance on stumpage prices.

All too often, forest owners discover that their timber plantations or native forests are unviable to harvest due to the low value of the trees and the high costs of access, harvesting, loading and transport. The economics of harvesting dictate that where the logs are low in value, the operation must be highly mechanised to be viable. The equipment required for mechanised logging is very expensive and the contractors involved commonly prefer large forest areas with relatively easy access (Figure 9.10).

Manual falling with chainsaws and extracting logs with tractors is usually only viable when log value is high (Figure 9.11). Research in Australian pine plantations suggests this system is only competitive in well-spaced pruned stands of large-diameter sawlogs (>40 cm) (Reed 2001). One advantage of pruning is that it greatly reduces the labour required to delimb. Wider tree spacing at harvest also makes falling and access easier.

Transport costs can be as high as 10c/km/t, thereby reducing the payment to the grower by

more than \$10/m³ for logs that need to be hauled over 100 km. Growers located a long way from potential markets should consider high-value logs and partial value-adding. Value-adding may also increase the number of potential buyers and ultimately the equivalent stumpage price, particularly in areas where there are very few local processors and therefore limited competition.

The choice of site, tree species, silviculture and even harvesting method should be based on a defined product preference. It is important that these also reflect the growers' interest in non-timber values such as shelter for stock, biodiversity, aesthetics or land degradation control and their attitude to the inherent risks associated with any forestry investment.

Target tree specifications may include the species, tree and log dimensions such as diameter, length or form, branching habit and preferable harvest age. At the forest level there may be specifications related to the minimum harvest volume, preferred site attributes and access. For example, for pulpwood production a minimum harvest volume may be 1000 t. If a grower produces less it may not be possible to attract a harvesting contractor, irrespective of tree quality. Small growers, or those who do not intend to clearfell large areas, generally need to focus on producing trees of high value in order to overcome the higher management and marketing costs. Pruning, for example, is more commonly adopted by small growers because it adds value to the forest, reduces harvesting costs and may overcome the need to find markets for low-quality or small-diameter logs.



Figure 9.10: Mechanical harvesting is efficient and safe but contractors usually require large volumes and good access.



Figure 9.11: Manual falling can be efficient in mature widely spaced and pruned plantations, but requires special skills.

Product specifications are likely to vary over time so it is worth considering alternative market opportunities. The common recommendation is to aim for a high-quality forest that meets the criteria of a number of possible markets. A perfect hardwood sawlog can always be used for firewood, but a perfect firewood plantation is unlikely to produce high-value furniture timber.

Principles of silviculture

Trees and forests are, by their very nature, dynamic – they grow and decay. It is not always possible to hasten or slow growth, but it is possible to set and steer it in different directions. The term ‘silviculture’ (from the Latin ‘silva’, meaning wood) refers to the practice of purposefully manipulating forest composition and growth. Although past emphasis was on wood production, the term is now used widely to refer to managing forests to enhance their value for biodiversity, water production or any other purpose.

The ability to direct tree growth is based on an understanding of how trees grow, how their growth responds to particular environmental conditions, and the potential to intervene by pruning, thinning or other management options.

Tree growth

Tree shape, height growth, diameter increment, branch development and ultimately wood quality are defined by a combination of the apical meristem growth, which occurs at the tip of the leading stem and all the branches, and the cambial growth, which leads to trunk and branch thickening. Although both growth types may occur simultaneously on the same tree, what initiates each growth type, their pattern of development and how they respond to various growing environments are very different. Of interest to forest growers is the influence of apical meristem growth on tree height and form and the influence of cambial growth on stem and branch diameter.

Apical growth: tree height and stem form

The rate and extent of height growth in most tree species grown in Australia is governed by environmental factors such as soil structure, water availability, fertility, temperature and humidity. Height growth begins rapidly at the start of the growing season and continues until water availability or humidity decline. This growth pattern is different from some northern hemisphere temperate hardwoods species, which have a pattern of rapid early height growth at the start of the season which suddenly stops after a period determined by conditions in the previous growing season when the buds were formed (Shepherd 1986). When grown in Australia, these predeterminant growth species tend to show slower overall height growth because they can be retarded by late-season droughts and are less able to take full advantage of good growing conditions.

Exposure to damaging or drying winds or excessive solar radiation can stunt height growth. Figure 9.12 shows the average height growth of young flooded gum (*Eucalyptus grandis*) growing on a flat exposed irrigation farm in northern Victoria. The plantation was established as a variable spacing trial covering a range of stocking rates from <100 stems/ha up to more than 1000 stems/ha. The data show the value of the mutual shelter provided by the higher stockings. At three years there was little difference in average height across the range of tree stockings. However, the trees established at the higher stocking rates soon began

to shelter each other. Once sheltered, the leading shoots could achieve the maximum possible height growth for the species on that site given the prevailing soil and climatic conditions. By eight years the average height of the trees established at very low stockings (<400 stems/ha) was as much as 30% less than that of the well-sheltered trees. The mutual sheltering effect is clearly evident for stocking rates of >400 stems/ha.

Increasing the initial stocking from 400 to >1000 stems/ha had no further impact on average height growth. It is demonstrated across a wide range of species and sites that crowding does not force trees to grow taller. Crowding does, however, reduce canopy size, suggesting that height growth is driven by the photosynthetic activity occurring within or very close to the leading shoot and not by the amount or the vigour of the lower canopy. If an individual tree is unable to keep up with its neighbours the leading shoot will be shaded, stalling height growth. Overtopped trees quickly become suppressed and, depending on their shade tolerance, may succumb. Self-thinning is common in the sun-loving eucalypts whereas many rainforest species can persist below the main canopy, awaiting an opportunity should a gap be created above them.

For timber production, straight single-stemmed trees are preferred. If growing on a stable soil in a well-sheltered location, forest trees tend to grow straight unless the light distribution is uneven and the species has a tendency to bend towards the light (phototropism). When growing

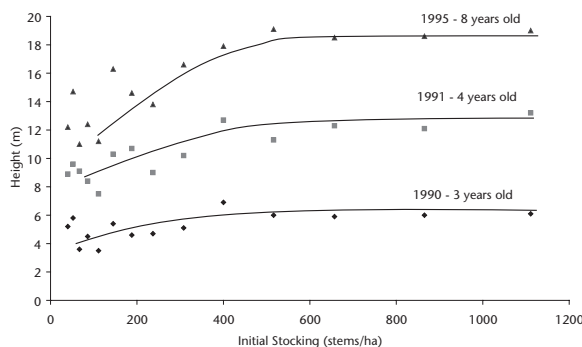


Figure 9.12: Height growth of *E. grandis* in a spacing trial at Kyabram (Vic.) over a five-year period, showing how exposure at lower stocking rates retards height growth (data provided by John Kellas).

phototropic species (*Eucalyptus*, *Acacia*, *Pinus* etc.), it is important to avoid sites with heavy shading on one side as this will cause the trees to bend. In these situations it is better to grow geotropic species, like the Australian southern silky oak (*Grevillia robusta*) and many introduced species from higher latitudes such as English oak (*Quercus robur*) that tend towards vertical growth irrespective of the light distribution.

The ultimate height which a tree will reach on a particular site is largely predetermined by the soil and climatic environment in which it is growing and the potential of that species to lift water from the soil to the uppermost leaves. The tallest trees in the world are the mountain ash (*Eucalyptus regnans*) of south-east Australia and the coast redwood (*Sequoia sempervirens*) of the coastal forests of North America. Both species can attain heights of over 100 m when grown on deep, moist soils in well-sheltered high-rainfall areas. However, if soil moisture is limited during the growing season or the leading shoots are repeatedly exposed to low-humidity air, the trees' ability to sustain water supply to the leading shoots is compromised and height growth is retarded (Salisbury and Ross 1992).

The difficulty in maintaining a continuous water supply to the leading shoots explains why tree height growth slows early on very harsh sites. Figure 9.13 shows modelled height growth curves for *Eucalyptus globulus* growing on a range of sites. Over time the plantations approach a maximum height for that species which reflects the productivity of the site. If there are no serious nutrient deficiencies, then soil depth, texture and water-holding capacity, along with rainfall, temperature and humidity, seem to be the most important factors governing site productivity. Because height growth is largely independent of stocking rate and difficult to change, the height of a plantation of a particular species at age 10 or 20 is commonly used as index of inherent site quality.

On marginal sites, where the top height is reached at an early age, it is common to find an even-aged plantation or regrowth forest of drought-tolerant eucalypts that has become 'locked up'. Height, diameter and therefore volume growth appear to have stopped. Unless the dominant trees can grow tall enough to shade their neighbours there will not be the self-thinning of suppressed

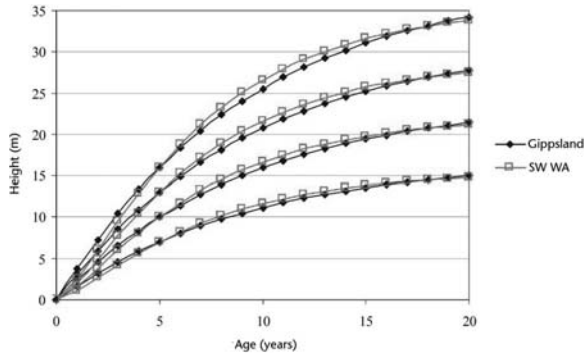


Figure 9.13: Modelled height growth of *E. globulus* in Gippsland and south-west Western Australia (reprinted from Wong *et al.* 2000). Each pair of lines represents a different site-quality class.

trees that is required to release more growing space. Growth of the dominant trees can only resume if gaps are created in the canopy by storms, fire, disease or artificial thinning.

This introduces another important relationship between height growth and tree form. If a young tree is putting on rapid height growth the lower branches, even in open-grown trees, tend to be smaller, resulting in a more conical form. When height growth slows, due to exposure or site limitations, the canopy tends to round out and the lower branches become larger. Once established, height growth can be maximised by ensuring the leading shoot is sheltered from dry or damaging winds. Increasing the stocking rate above that required to provide mutual shelter will not encourage the dominant trees to grow any taller. Increasing competition will, however, affect branch development and diameter growth which occurs at the cambium.

Cambial growth: tree diameter and branch size

The cambium is a thin layer of dividing cells located just under the bark, that produces new wood cells on the inside and bark cells on the outside. Initially the bark cells act as the phloem transporting sugars and hormones down the stem from the leaves before dying and providing protection for the cambium. The new wood cells become active sapwood, transporting water and nutrients up the stem. Both the wood and bark growth contribute to increased stem diameter,

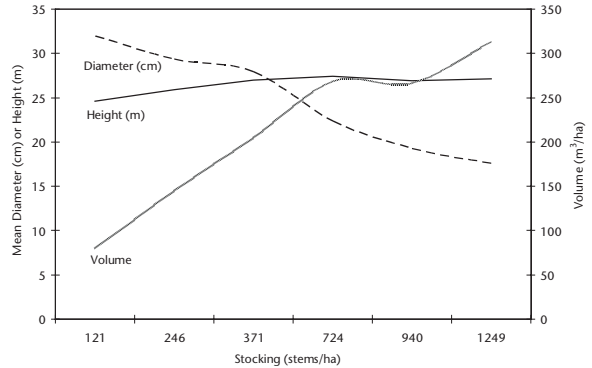


Figure 9.14: Results of a tree spacing experiment involving *E. pilularis* measured at 11 years of age (data from Borough *et al.* 1984).

although shedding of the outer bark means the increase in bark thickness is less significant.

Unlike height, tree diameters do not approach a maximum for the site. Theoretically, trees can continue to put on diameter indefinitely although they will eventually succumb to disease, drought or old age. However, the amount of wood produced by the cambium is much more sensitive to competition than is height growth (Kozłowski *et al.* 1991) because it is driven by total leaf area and vigour above that point on the stem or branch. The rate of diameter growth at any point simply reflects the concentration of carbohydrates flowing down through the inner bark.

Once site resources (particularly light and moisture) become limiting, any increase in competition will lead to a direct reduction in the size or efficiency of individual tree canopies. As a result, the amount of carbohydrates produced by the leaves and fed down the branches and trunk for cambium growth will be reduced. This results in reduced diameter growth on individual trees. The differences in diameter growth of trees of the same age growing on the same site can be startling. For example, the results of a spacing trial of *E. pilularis* (Figure 9.14) show that the widely spaced trees had a mean diameter almost twice that of trees in the dense plantation after just 10 years.

The impact of competition on diameter growth is best shown by examining the annual diameter increments (Figure 9.15). Using forest basal area as a measure of competition, it is evident that diameter growth in trees grown in open plantations can

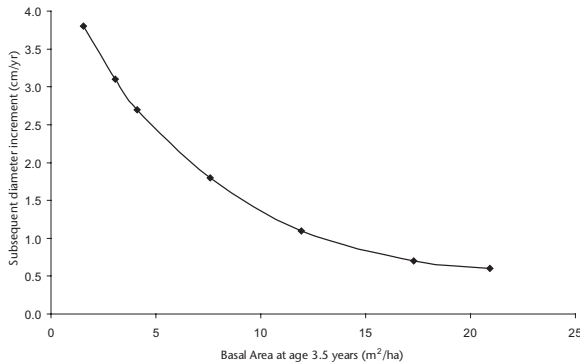


Figure 9.15: Mean diameter growth of *E. grandis* in a four-year-old spacing trial (data from Ryan 1993).

be four or five times that of the same species growing in a dense forest (Figure 9.16).

Basal area as a measure for competition

The level of competition is related to the total leaf area of the trees that make up the forest canopy. Unfortunately, it is difficult to measure total leaf area. We do know that the area of sapwood in a tree is directly related to the volume and health of its canopy (Langstrom and Hellqvist 1991). This is not surprising, given that one of sapwood's roles is to transport water to the canopy. The more canopy, the greater the area of sapwood required. Everything else being equal, if there are two trees of the same diameter the one with the more active canopy will have a wider sapwood band (Figure 9.17).



Figure 9.16: Diameter growth is driven by the leaf area, so wider spacing promotes faster diameter growth. This Sydney blue gum (*E. saligna*) is less than 20 years old (photo provided by D. Jenkins).



Figure 9.17: The width of the sapwood band reflects the vigour of the tree canopy. The teak tree (*Tectona grandis*) on the left was from a 63-year-old high-stocked plantation in northern Thailand, and the other was from a widely spaced 25-year-old plantation in the same area.

Basal area is a measure of the total cross-sectional area of the tree and includes both heartwood and sapwood. It is therefore incorrect to assume that a total basal area of 10 m²/ha implies the same level of competition in a plantation of small trees as in a plantation of larger trees. In order to maximise diameter growth in a eucalypt plantation, the first thinning may reduce basal area to less than 5 m²/ha, the second thinning to 10 m²/ha and the third to 15 m²/ha. The difference is the result of the increasing area of heartwood in the trees as they grow.

Competition and volume production

The total volume of timber in an even-aged plantation is directly proportional to the forest basal area and tree height. If, for example, all the trees in a forest were the same height and had perfectly conical form, the total volume of tree stem per hectare can be easily calculated:

$$\text{Volume (m}^3\text{/ha)} = \text{basal area (m}^2\text{/ha)} \\ \times \text{height (m)} \div 3$$

Once mutual shelter has been achieved, little can be done to enhance height growth. Basal area, on the other hand, increases with increasing tree stocking and average tree diameter. If the object is to maximise the volume of timber, it is desirable to maintain a high stocking rate (Figure 9.14). This is why pulpwood plantations are established at >1000 stems/ha (<3 × 3 m spacing) and left unthinned until harvest. If left to grow, total

volume would increase as the trees grew taller although there is a risk that trees would begin to die due to increasing competition.

Because site quality dictates potential height, the volume production of plantations is very sensitive to site quality. Performance is measured in terms of mean annual volume increment (MAI $\text{m}^3/\text{ha}/\text{yr}$) or current annual increment (CAI $\text{m}^3/\text{ha}/\text{yr}$) (Figure 9.18). In a fully stocked young stand that is still experiencing rapid height growth, it is not uncommon for a eucalypt plantation to add more than 50 m^3/ha in any one year (CAI). However, in the life of a plantation, such high annual increments are short-lived since the increasing competition soon results in reduced diameter growth and height growth begins to slow as it approaches the maximum for that site. When total volume is averaged over the life of the plantation, this may translate to a mean annual increment of less than 30 $\text{m}^3/\text{ha}/\text{yr}$ even on very good-quality sites.

On marginal or dry sites it is possible, given time, to produce individual trees of very large diameter. However, because of the limited height and basal area development on marginal sites, it is impossible, even with very long rotations, to produce a volume yield similar to that achieved on high-quality sites. For example, eucalypt pulpwood plantations in high-rainfall areas can yield as much as 300 m^3/ha whereas on medium-rainfall sites a maximum of 150 m^3/ha is more likely. Given the same establishment costs, it is not surprising that the pulpwood industry is concentrated in high-rainfall areas. The viability of industrial harvesting equipment is closely linked to tree height and stand volume, further reducing the suitability of marginal sites for pulpwood production.

However, with appropriate species selection, trees suited to sawlog production, with a mean diameter of more than 60 cm, can be produced on almost any site, albeit fewer in number and over a longer period where productivity is low. Tree height is less critical for sawlog production, since the greatest value is concentrated in the lower stem. Another commercial timber option for farmers in dryland areas might be firewood production, since yield per hectare is less critical. The following chapters examine the production of pulpwood, firewood and sawlogs from farm plantations.

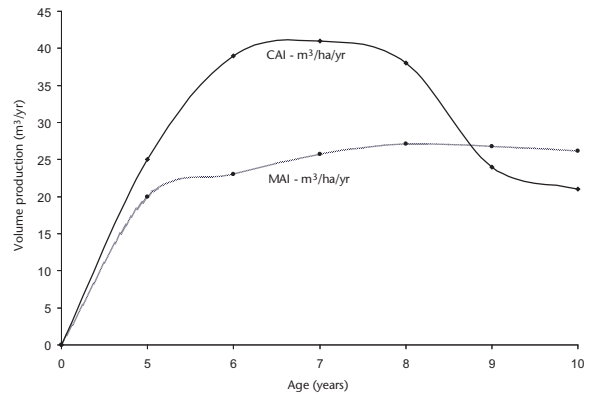


Figure 9.18: The effect of stand age on the current annual increment and mean annual increment of an *E. globulus* plantation on a very high-quality site in Western Australia (data provided by Robert Hingston).

References

- Bootle KR (1983) *Wood in Australia: Types, Properties and Uses*. McGraw-Hill, Sydney.
- Borough CJ, Incoll WD, May JR and Bird T (1984) Yield statistics. In *Eucalypts for Wood Production*. (Eds WE Hillis and AG Brown) pp. 201–225. CSIRO/Academic Press, Melbourne.
- Bradbury G (2006) How is wood quality affected by growth rate and silviculture? In *Acacia Utilization and Management: Adding Value. Australian Blackwood Industry Group: 4th Blackwood Workshop*. Rural Industries Research and Development Corporation, Victoria.
- Cown DJ, McConchie DL and Young GD (1991) Radiata pine wood properties survey. *New Zealand Forest Research Institute Bulletin* 50.
- Dean TJ and Baldwin VC (1996) Crown management and stand density. In *Growing Trees in a Greener World: Industrial Forestry in the 21st Century. 35th LSU Forestry Symposium*. Louisiana Agricultural Experiment Station, Louisiana State University Agricultural Center. (Ed. MC Carter) pp. 148–159 a–e. <<http://www.srs.fs.fed.us/pubs/viewpub.jsp?index=717>>.
- DeBell DS, Keyes CR and Gartner BL (2001) Wood density of *Eucalyptus saligna* in Hawaiian plantations: effects of silvicultural practices and relation to growth rate. *Australian Forestry* 64, 106–110.
- Downes GM, Hudson IL, Raymond CA, Dean GH, Michell AJ, Schimleck LR, Evans R and Muneri

- A (1997) *Sampling Plantation Eucalypts for Wood and Fibre Properties*. CSIRO Publishing, Melbourne.
- Harding KJ and Copley TR (2000) Wood property variation in Queensland-grown/Caribbean pine hybrids: hybrid breeding and genetics of forest trees. In *Proceedings of QFRI/CRC-SPF Symposium*. 9–14 April, Noosa, Qld. (Comp. HS Dungey, MJ Dieters and DG Nikles). Department of Primary Industries, Brisbane. <<http://www.dpi.qld.gov.au/extra/pdf/forestry/harding.pdf>>.
- Harrison CM (1975) Heartwood colour patterns in South African *Acacia melanoxylon*. *Forestry in South Africa* **17**, 49–56.
- Haygreen JG and Bowyer JL (1989) *Forest Products and Wood Science*. Iowa State University Press, Ames, Iowa.
- Jagels R (2006) Management of wood properties in planted forests: a paradigm for global forest production. FAO Forestry Department, Planted forests and trees working papers. <www.fao.org/docrep/009/j8289e/j8289E00.htm>.
- Kozlowski TT, Kramer PJ and Pallardy SG (1991) *The Physiological Ecology of Wood Plants*. Academic Press, San Diego.
- Langstrom B and Hellqvist C (1991) Effects of different pruning regimes on growth and sapwood area of Scots pine. *Forest Ecology and Management* **44**, 239–254.
- Lavery PB (1986) ‘Plantation forestry with *Pinus radiata*: review papers’. School of Forestry Review Paper no. 12. University of Canterbury Press, Christchurch.
- Nicholas I, Dungey H, Gifford H, Cox J, Hodgkiss P and Jones T (2006) Preliminary analysis of the wood properties of *Acacia melanoxylon* R. Br. Thinnings from five North Island regime trials in New Zealand. In *Acacia Utilization and Management: Adding Value. Australian Blackwood Industry Group: 4th Blackwood Workshop*. Rural Industries Research and Development Corporation, Victoria.
- Reed J (2001) Scale economics in farm forestry with special reference to timber harvesting. Master of Forest Science thesis. School of Resource Management, Dept of Forestry, University of Melbourne.
- Ryan P (1993) Hardwood plantations in Queensland? Why not! Outline of a seminar presented at Gympie, Qld, 13 August 1993. Unpublished.
- Salisbury FB and Ross CW (1992) *Plant Physiology*. 4th edn. Wadsworth Publishing, California.
- Shepherd KR (1986) *Plantation Silviculture*. Martinus Nijhoff, Netherlands.
- Teskey RO and Sheriff DW (1996) Water use by *Pinus radiata* in a plantation. *Tree Physiology* **16**, 273–279.
- Vertessy RA, Benyon RG, O’Sullivan SK and Gribben PR (1995) Relationship between stem diameter, sapwood area and transpiration in a young mountain ash forest. *Tree Physiology* **15**, 559–567.
- Washusen R (2002) Tension wood occurrence in *Eucalyptus globulus* Labill. II. The spatial distribution of tension wood and its association with stem form. *Australian Forestry* **65**(2), 127–134.
- Washusen R, Blakemore P, Northway R, Vinden P and Waugh G (2000) Recovery of dried appearance grade timber from *Eucalyptus globulus* Labill. grown in plantations in medium rainfall areas of the southern Murray-Darling Basin. *Australian Forestry* **63**, 195–201.
- Washusen R, Ades P and Vinden P (2002) Tension wood occurrence in *Eucalyptus globulus* Labill. I. The spatial distribution of tension wood in one 11-year-old tree. *Australian Forestry* **65**(2), 120–126.
- Wilkes J (1984) The influence of rate of growth on the density and heartwood extractives content of eucalypt species. *Wood Science and Technology* **18**, 113–120.
- Wong J, Baker T, Duncan M, McGuire D and Bulman P (2000) ‘Forecasting growth of key agroforestry species in south-eastern Australia’. Joint Venture Agroforestry Program, RIRDC/LWRRDC/FWPRDC. RIRDC Publication no. 00/68.
- Yang J and Waugh G (2001) Growth stress: its measurement and effects. *Australian Forestry* **64**, 127–135.

Growing high-quality sawlogs

Rowan Reid

This chapter explores tree and forest growth in greater detail, building on the outline provided in Chapter 9, and examines the application of silvicultural techniques such as pruning and thinning as tools to enhance growth rate or log quality.

Target logs for sawn timbers and veneers

At the mill the value of a particular log will reflect the volume, quality and value of the products that can be extracted by the miller. This depends not only on the characteristics of the log but also on the equipment being used, the skills of the operators, the available markets and the scarcity of alternative raw material. Generally, for logs of a suitable species and length, the larger the diameter and fewer the defects the greater the value. As well as having lower fixed production costs per cubic metre, larger-diameter logs generally yield a higher recovery of higher-grade products such as wide boards.

Recovery rate refers to the volume of marketable sawn timber that can be extracted from the round log, expressed as a percentage of total log volume. In softwoods, such as pine, recovery rates are often as high as 50–60%; for hardwoods, such as eucalypts, they are generally much lower. This reflects differences in the inherent wood characteristics, sawing patterns and market opportunities. With most sawn hardwood now going into higher-quality appearance-grade markets such as flooring and

joinery, the emphasis is more on quality and value recovery than simply on volume.

Large defect-free logs allow millers to employ selective sawing patterns to avoid defects, improve product performance and recover large-section sizes that have higher value (Figure 10.1). What constitutes a defect depends on the market. If clean, strong, consistent and attractive timber is required, the following are commonly considered defects that will downgrade the value of a piece of sawn timber or veneer:

- branch knots;
- rot or holes resulting from fungi and insect attack;
- presence of the pith;
- presence of sapwood;
- surface or internal checking;
- wane – incomplete cross-section size due to the edge of the log;
- twisting, spring, bow or cupping.

There are also factors that may increase value, such as:

- perfectly straight grain along the whole length;
- even or desired timber colour;
- attractive grain patterns such as fiddleback or birdseye;
- close or regular distribution of growth rings;
- perfectly quarter-sawn or back-sawn boards (see Figure 9.4, p. 150).

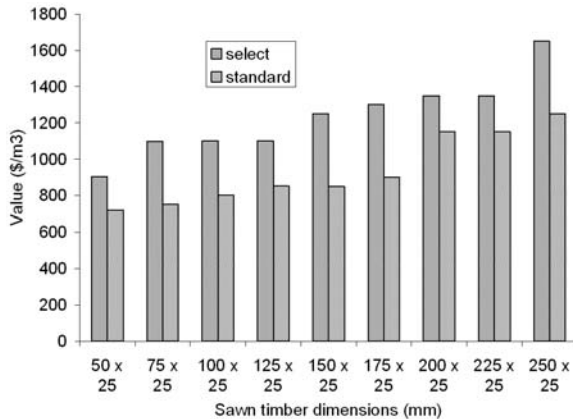


Figure 10.1: The wholesale value per cubic metre for 25 mm thick kiln-dried Victorian ash, illustrating the impact of board width and quality on value. Wide boards can only be sawn from large-diameter logs (data based on 2005 prices provided by a Victorian sawmill).

There is much the forest owner can do to enhance the value of their trees for sawlog and veneer production through silvicultural management.

What is a veneer log?

Veneers are thin sheets of solid timber that are used in the production of plywood and panels. There are two ways in which veneers are produced from a log. For plywood production, which requires large sheets of veneer, the log is peeled on a rotating lathe. A large log can produce tens of metres of continuous veneer which is then cut to size, dried and layered to form a 3, 5 or 7 ply sheet. Each layer of veneer in the plywood is aligned in the opposite direction, giving plywood its strength.



Figure 10.2: Sliced veneers of Australian blackwood (*Acacia melanoxylon*) show a range of colour and grain patterns.

Rotary-peeled veneer has the grain pattern of perfectly back-sawn timber. Clean sheets are preferred for the outer layers of the plywood sheet especially when it is to be used for panelling, doors or concrete formwork. In some cases a different species is used for the outer layer. Large-diameter logs provide the best yield, not only because of the cost of setting each log on the lathe but also because the central core is often discarded.

The alternative method of producing veneers is by slicing thin sheets off a sawn block. A 250 mm wide board is first sawn from the log in a conventional sawmill. The block is then passed through a large slicing machine which removes a thin sheet of veneer the same width as the original board. This can be dried immediately and glued onto a panel board, creating the appearance of a solid piece of timber. Sliced veneer of high-value native timbers like Australian blackwood is commonly used in commercial cabinet work. Only the most valuable or attractive timbers are sliced. The logs must be large enough for the production of wide boards suitable for slicing.

Growing clean, straight large-diameter logs

You don't need to be a sawmiller to be able to recognise a potentially perfect sawlog or veneer log tree: a tall straight bole of large diameter clear of branches, rising to a well-balanced canopy. However, you may need the eye and the ear of an experienced bushworker to be able to judge the internal qualities of a mature native tree since even the best-looking trees may carry internal rot arising from fire, disease, insect attack or wind damage.

Even in a planted forest it is difficult to know the internal qualities of the log. The outside of the tree may be clear of branches and there may be no indication of how large the tree or branches were when they were consumed by the growing stem. For this reason it is important to document the history of the forest, even to the point of taking regular photographs and measurements, to be assured of the quality of the trees. This is especially important if a premium for pruning is expected.

What distinguishes the production of sawlogs from other forms of wood production is an emphasis on diameter growth, branch development and wood quality rather than simply volume. This chapter begins by looking at what we can learn



Figure 10.3: High-quality solid timber products generally require large-diameter logs. Richard Moore stands in front of a 16-year-old *Eucalyptus globulus* with a kitchen cabinet door panel made from an earlier harvest of pruned trees from the same site.

from natural forests about how trees might grow in planted forests. The discussion is focused on eucalypts, with passing reference to other species grown for sawlogs on Australian farms. As a group, the eucalypts provide an ideal basis for discussing growing high-quality timber. Not only are eucalypt species suited to almost every farming landscape in Australia, but they also provide examples of almost every issue and challenge faced by sawlog growers.

Learning from nature: how native forests grow wood

With the vast majority of eucalypt sawlogs sourced from native forests, it is worth reviewing native eucalypt forest growth patterns and how they influence log characteristics and wood quality. Understanding how trees grow in a native forest provides some principles that growers can use to manipulate growth in their own plantations. A forest or plantation is a community of individual trees that each affect the growth and development of their neighbours. The interaction between individual trees has a direct influence on their height

growth, diameter increment, branch development, tree health and productivity.

The simplest natural forest systems in Australia are probably the even-aged single species wet sclerophyll forests of mountain ash (*E. regnans*) and alpine ash (*E. delegatensis*) in Victoria and Tasmania. These native forests behave in a similar manner to even-aged monoculture plantations, even those growing in much lower-rainfall areas. The dynamics of mixed species multi-aged forests are more complex, but the principles of forest growth in the plantations and even-aged native forests still apply.

An intense bushfire in an ash forest in southern Australia kills the mature trees, releasing their seed onto a fertile ash bed. The following spring more than a million seedlings per hectare may begin competing for the available resources. The competition results in winners and losers. The stocking drops quickly: a year later there may be 100 000 surviving seedlings per hectare and 10 years later it could drop to less than 10 000.

Figure 10.4 shows the self-thinning that occurred in a natural forest of alpine ash (*E. delegatensis*). Eucalypts are light-demanding and will succumb to competition when the canopy of neighbouring trees overtops them. From a stocking of >5000 stems/ha (an average spacing of <1.5 m) at age 10 years, the stocking drops to less than a few hundred by age 50 as the remaining trees grow larger in diameter. Diameter in a fully stocked forest tends to increase evenly over time, but this is not the case with height growth. Early height growth in a eucalypt forest is rapid but tends to slow as the trees grow taller due to the increasing energy required to lift water to the growing tips.

Because of the intense competition for light, the surviving trees in our natural forest example tend to be tall and straight with long clear boles. Shading of the lower branches eventually results in natural self-pruning, leaving small dead knots around the central core. At age 60 years the forest will be just over 40 m tall and have a stocking of around 200 stems/ha with an average tree diameter of over 50 cm at breast height (1.3 m). The forest is about at its peak for high-quality timber production. The basal area is in the order of 60 m²/ha and the total volume approaches 800 m³/ha, half of which may be suitable for sawlog.

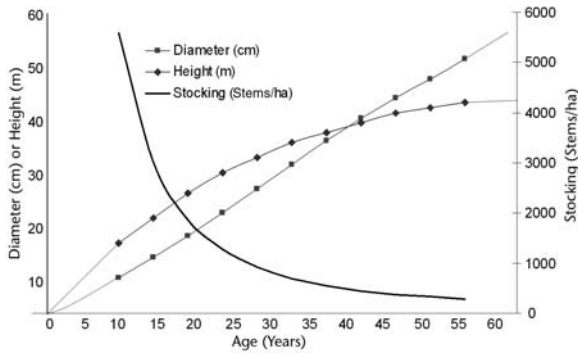


Figure 10.4: Development of a natural even-aged forest of *E. delegatensis* at Bago, NSW (Borough *et al.* 1984). Stocking curve shows a natural self-thinning line. Diameter growth increases evenly as stocking falls. Height growth decreases over time, approaching a maximum for the site.

As height growth slows further there comes a point where increasing diameter of the surviving trees is offset by the death of suppressed trees, resulting in no change in total volume. If protected from fire, the forest will eventually reach old-growth status with less than 50 large overmature eucalypts per hectare and the volume of eucalypt timber will begin to decline. Without a bushfire or logging to restart the process, the forest will slowly convert into a temperate rain-forest dominated by an emerging understorey of blackwood (*Acacia melanoxylon*) and beech (*Notofagus cunninghamii*).

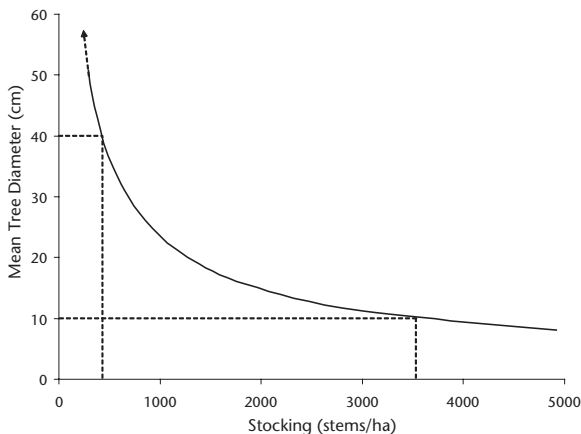


Figure 10.5: Mean diameter plotted against stocking for a fully stocked even-aged forest (*E. delegatensis* regrowth) showing how self-thinning allows the retained trees to grow larger in diameter.



Figure 10.6: Natural thinning in a wet eucalypt forest reduces the stocking rate over time, leaving very few large-diameter trees.

Self-thinning rule

Ignoring age, Figure 10.5 shows the important relationship between tree diameter and stocking rate in the same *E. delegatensis* forest. This is called the ‘self-thinning line’; it shows that as individual trees become larger they require more space (larger canopy area) and therefore the stocking rate must fall. The self-thinning line effectively shows the carrying capacity of that species on that site. For example, the site can carry about 3500 *E. delegatensis* stems per hectare when the average diameter is 10 cm but <500 when the average diameter is 40 cm.

Many scientists have studied the pattern of self-thinning in a natural forest or unthinned plantation, in response to the increasing competition. More than 70 years ago Reineke (1933) noticed that if he graphed the natural self-thinning curves of different tree species on a log-log graph comparing mean tree diameter and stocking, the self-thinning lines for different species were not only linear but had very similar gradients (close to -0.625). Extending this principle, Curtis (1982) proposed a formula for assessing the relative density (RD) of a forest and presented a self-thinning line for Douglas fir (*Pseudotsuga menziesii*) based on measured stands:

$$RD = BA \div \sqrt{D} \quad (\text{Eqn 10.1})$$

where RD is a measure of the relative density of the forest, D is the quadratic mean diameter (cm) (diameter at breast height of the tree of average basal area) and BA is the basal area of the plantation (m²/ha).

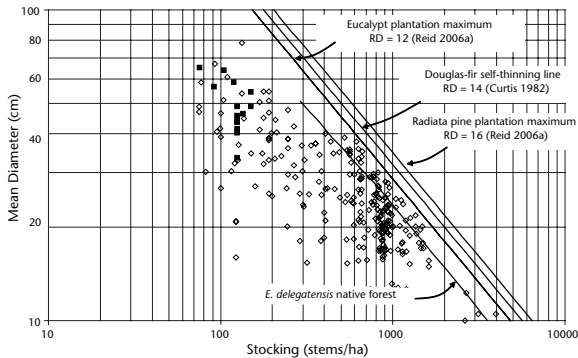


Figure 10.7: Fitted self-thinning lines for even-aged native forests of *E. delegatensis* and *E. regnans* (Borough *et al.* 1984). The gradient (-0.66) is the same as that proposed by Curtis (1982) for Douglas fir. Based on available data for unpruned (\diamond) and pruned (\blacksquare) eucalypt plantations, Reid (2006a) proposed a maximum potential line for the commonly grown eucalypts. He also proposed a maximum potential line for *Pinus radiata* plantations in Australia.

With reference to measurements of plantations grown in Australia and New Zealand, Reid (2006a) proposed that the maximum potential line for radiata pine (*Pinus radiata*) and the eucalypts commonly grown in high-rainfall areas of Australia could be represented by relative densities (RD) of 16 and 12 respectively (Figure 10.7). The difference between tree species reflects the relative difference in their tolerance of competition.

The data points in Figure 10.7 are from measurements of many different eucalypt plantations between five and 70 years of age growing on a wide variety of sites. No plantation has a relative density greater than 12. However, the data suggests that this maximum may be a little optimistic at stocking rates lower than 200 stems per hectare. This could be due to the fact that it is more difficult to fully occupy a site when there are fewer stems. To do so would require an evenly stocked stand of very large mature trees. Such forests are rare due to the pattern of thinning and the fact that commercial plantations are commonly harvested before they develop a mean diameter of >70 cm.

Eucalypt plantation stand density diagram

Knowing the maximum relative density for a species provides a basis for planning silvicultural regimes. Assuming a maximum relative density of 12 for eucalypts, it is impossible, irrespective of manage-

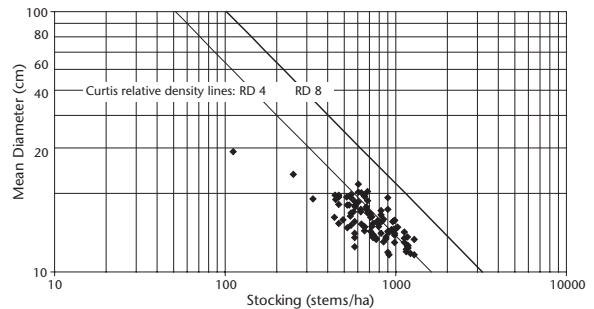


Figure 10.8: Data from measurements of *E. cladocalyx* plantations of up to 34 years old in a low-rainfall area in north-west Victoria. None achieved a relative density of 8, suggesting that the plantations become fully stocked at an RD of about 4 (data provided by Mark Stewart).

ment, site or age, to grow a eucalypt plantation with a stocking of 1000 stems/ha with a mean diameter at breast height (1.3 m) of greater than 30 cm. Growers wishing to produce eucalypt trees with a diameter of over 60 cm should assume stocking rates of under 200 stems/ha at time of harvest.

The low relative densities measured in eucalypt forests, compared to coniferous species, reflect their growth habit and physiology. Eucalypts are commonly referred to as ‘crown-shy’ because their canopies rarely interlock in the way pines or cypress crowns do (Jacobs 1955). Mature eucalypt leaves demand near full sunlight, so shaded branches will



Figure 10.9: This 50-year-old plantation of sugar gum, *E. cladocalyx*, that has become stagnant shows little evidence of self-thinning and very poor diameter growth. Thinning the poorer stems would increase the leaf area on the remaining trees and thereby increase diameter increments.

tend to die. Eucalypts also have naked leaf buds. If the tree crowns rub against each other in the wind the buds can be lost or new shoots damaged (Jacobs 1955).

The influence of site quality and climate on the maximum relative density and self-thinning in eucalypts is unclear. On high-productivity sites, rapid height growth allows the dominant trees to overtop their neighbours, leading to rapid self-thinning. As height growth slows, due to site limitations or age, it becomes more difficult for the dominant trees to overtop their neighbours. If the species is tolerant of drought the forest or plantation can become stagnant: the forest becomes locked-up with very little change in the stocking rate or mean diameter growth over many years. Thinning is required to release growing space for the better trees to develop further.

Irrespective of the maximum relative density, the impact of competition on growth will be more significant on marginal sites. Figure 10.8 shows data for *E. cladocalyx* plantations of up to 34 years growing in low- to medium-rainfall areas. None of the plantations had reached a relative density of 8, suggesting that this might represent a more practical maximum for eucalypts growing in low-rainfall areas.

Five competition zones

Reineke (1933) suggests it is possible to use the stand density diagrams to define the degree of competition in an even-aged forest using a series of lines drawn parallel to the self-thinning line. Theoretically there are five competition zones, from a zone of excessive exposure, within which tree height growth is retarded due to a lack of mutual shelter, through to a zone of imminent mortality which is presumed to be unobtainable. Within the zone of free growth, individual tree diameter increment is maximised; in the zone of full stocking, stand productivity is maximised. Once the forest passes into the fully stocked zone, the volume increment is simply distributed over a greater number of stems. Between the free growth and fully stocked zones there is presumably a zone of increasing competition, in which individual tree growth is increasingly restricted. Reid (2006a) suggests that the competition zones for commonly grown eucalypt species correspond with lines of relative densities equal to 1.5, 3, 6 and 12 (Figure 10.10).

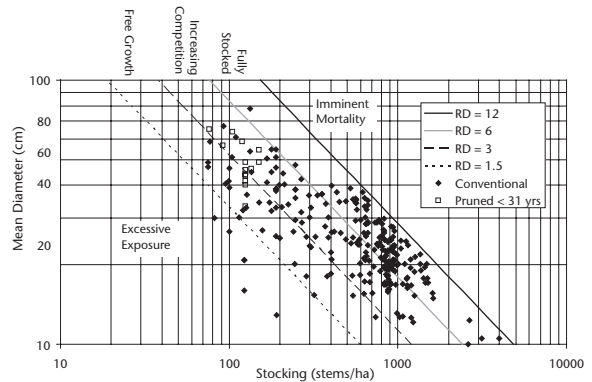


Figure 10.10: Proposed competition zones for eucalypt plantations (based on Reid 2006a). Data from a range of conventional and pruned eucalypt plantations are shown. The open squares indicate plantations which were pruned.

Target final stocking rate for sawlog plantations

A useful starting-point when designing a silvicultural plan is to identify a target mean diameter. Target diameters may be set for any product, including thinnings that may be sold along the way. The maximum theoretical stocking rate for a eucalypt plantation with an average diameter of 60 cm appears to be around 300 stems/ha (Figure 10.10). However, even if it were possible to achieve such an outcome it is unlikely that any plantation owner would expect to harvest that many trees. Not only



Figure 10.11: An unthinned 18-year-old blue gum (*E. globulus*) plantation showing evidence of poor crown development and self-thinning.

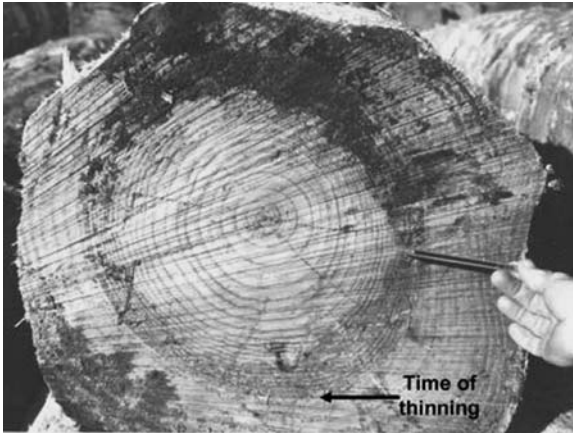


Figure 10.12: Thinning changes the competition levels in a forest. In this pine, diameter growth was reduced to less than a few millimetres per year due to increasing competition (pen point). When the plantation was thinned some years later, diameter growth rates returned to those achieved before competition became severe.

would it be difficult to achieve an even stocking of large trees across the whole site, but the plantation would have had to be fully stocked from the time that the mean diameter was about 40 cm. Diameter growth rates would have been very low for a long period and a high proportion of the trees would be extremely stressed due to the intense competition (Figure 10.11). A more practical target would be a final stocking corresponding to full stocking. If the full stocking line were represented by a relative density of 6 this would correspond to 150 healthy stems/ha when the average diameter was 60 cm.

The true position of the full stocking line for a species can be judged from measurements of a forest of that species on a similar site that is exhibiting maximum leaf area as evident from death of the lower branches. Many growers like to plan to reach full stocking at the time of harvest because it ensures a high-volume production without greatly compromising individual tree diameter growth rate. However, as the plantation approaches full stocking individual diameter increments will fall, thereby extending the time taken to reach the desired diameter.

Silvicultural regimes

Having determined the target size and stocking, the next important decision relates to the path to

be taken to achieve it. The shortest path involves avoiding excessive exposure and any competition. Because eucalypts are particularly sensitive to exposure and competition, thinning has to begin very early in plantation life to maintain free growth. Successive thinning is therefore required to hold the plantation within the free growth zone (Figure 10.12). Within this zone, pruning would be required to control branch development which would otherwise devalue log quality.

The alternative is to remove the need for pruning by growing the forest close to the full stocking line. The lower branches would die as the canopy rose, leaving small dead knots in the timber. Whether this is a realistic option depends on the market requirements and how effectively the species ejects dead branches and heals over the stubs. The trade-off is in the time it takes to grow a large-diameter log in a fully stocked forest. In practice it may take twice as long to achieve the target tree diameter in a fully stocked forest as in one managed under free growth (Reid 2006a).

To avoid excessive exposure, an initial stocking should be five, or even eight, times that expected at harvest. Overplanting provides the opportunity to select the trees of best form and vigour through a sequence of thinning operations and will ultimately ensure higher quality and productivity. As described in the previous chapter, the risk of excessive exposure will vary with the site conditions.

Table 10.1 and Figure 10.13 compare two possible silvicultural regimes for the production of eucalypt sawlogs. One involves pruning and thinning to allow the trees to be grown within the zone of free growth for much of the rotation. The alternative is the conventional approach of using several thinnings to maintain growth within the zone of competition. Figure 10.14 compares the growth of measured plantations in Australia and New Zealand that have essentially been managed in one of these ways. The six plantations that achieved an average diameter in excess of 50 cm within 40 years all had a stocking rate of less than 150 stems/ha at the time. The five that were pruned achieved that goal within 30 years.

The choice of silvicultural regime depends on a number of factors. If growers are prepared to prune, the trees can be grown in the free growth zone without concern about branch development. This will

Table 10.1: Example silvicultural regimes for eucalypt sawlogs based on the stand density diagram in Figure 10.3

1: Pruning regime free growth zone	2: Conventional regime Competition and full stocking zone
Establish 600–1000 stems/ha depending on exposure	Establish over 1100 stems/ha in order to control early branch development
1st prune 600 stems/ha (DBH 12–14 cm) Thin remaining trees Product: few options due to small diameter and low wood density.	Thin to about 600 stems/ha for firewood or posts (DBH 16–18 cm)
2nd prune 300 stems/ha (DBH 15–17 cm) Thin remaining trees. Product: Possible firewood or posts	Thin to 350–450 stems/ha (DBH 22–25 cm) for firewood, posts or pulp
3rd prune 150 stems/ha to final height (DBH 22–25 cm) Thin remaining trees Product: Possible firewood or pulp	Thin to 200–300 stems/ha (DBH 30–35 cm) for pulp or small logs
Grow to final stocking of 80–150 stems/ha Product: Pruned butt sawlogs, unpruned top logs for sawing or pulp	Grow to final stocking of 150–250 stems/ha. Product: Slow-grown butt sawlogs with large core of dead knots, knotty top logs for sawing or pulp.-
Expected rotation length: <30 years	Expected rotation length: >40 years

ensure rapid diameter growth and reduced rotation lengths. Before implementing this option growers should consider the possible impact of short rotations and rapid growth on wood quality. Density, colour, durability and stability may be different from logs of the same species grown in native forests or slow-growing plantations (see Chapter 9).

Growers who choose not to prune will need to grow their trees in the competition zone to control branch development at least until the lower

branches die. The option of thinning heavily once self-pruning has been effective up to the desired log height has been tested with mixed results. When released, severely suppressed eucalypts can respond by initiating epicormic shoots up the stem, thereby negating the value of self-pruning (Reid 2002). On good-quality sites the tall skinny trees are also at risk of wind damage if their neighbours are removed. To avoid these problems growers may need to thin the forest gradually. Chemical thinning of standing trees may reduce the shock and allow a gradual release of the retained trees, reducing these risks.

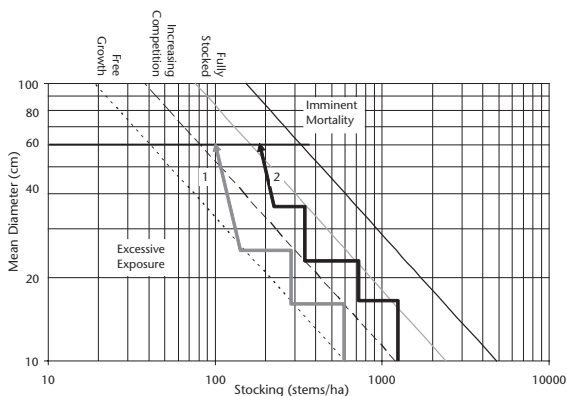


Figure 10.13: Two eucalypt sawlog regimes. 1) Thin regularly during the early years to maintain free growth. Pruning required to control branch development. 2) Adopt higher stocking rates in the early years to suppress branch growth then thin regularly when the plantation reaches full stocking.

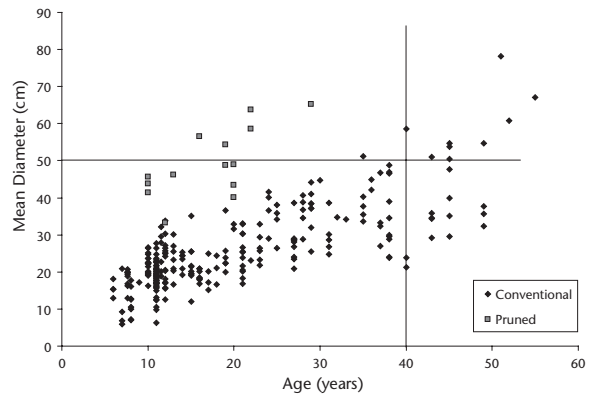


Figure 10.14: Comparison based on real data between conventional and pruning regimes for eucalypt sawlogs in Australia and New Zealand (Reid 2006a).



Figure 10.15: Widely spaced and pruned spotted gums (*Corymbia maculata*) that were spaced early to ensure that the trees are relatively free growing until they reach sawlog size.

Practical guides for managing competition

Forest growers need simple guides to help them manage competition in their forests. Basal area is one measure of competition that can be quickly assessed before and after a thinning operation.



Figure 10.16: Chemical thinning of a native regrowth eucalypt forest to stimulate diameter growth on the best stems.

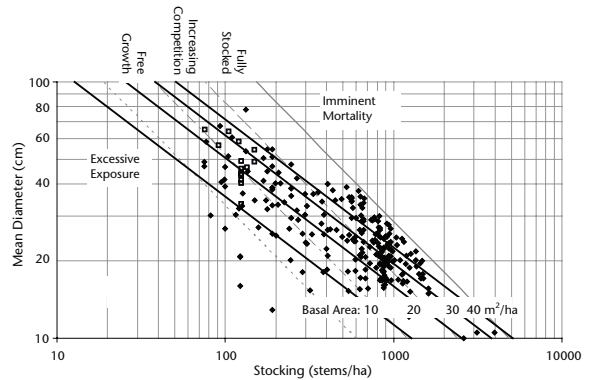


Figure 10.17: Managing a plantation along a constant basal area line will result in the forest becoming less competitive over time. Dark lines indicate constant basal areas of 10, 20, 30 and 40 m²/ha.

This section looks at how effective basal area is as a practical guide in forest management and offers an alternative method for monitoring competition that may be more practical.

Basal area

A forest maintained at a constant basal area by regular thinning tends to become less competitive over time as the trees grow (Figure 10.17). The reason lies in the fact that the measure of tree basal area includes both the sapwood and heartwood areas, whereas only the sapwood area is important in tree growth (Langstrom and Hellqvist 1991).

The sapwood basal area in a tree is directly proportional to the leaf area (Yans and Hazenberg 1991). The same is true for a forest, which suggests that once full stocking has been achieved the sapwood basal area per hectare remains relatively constant. In a forest maintained on the full stocking line, there is an increase in the total forest basal area despite no change in the sapwood basal area per hectare. The increase can be attributed to the increasing heartwood basal area. Basal area alone is therefore not a particularly useful guide for managing competition over time.

Diameter:basal area ratio

An alternative way of using basal area is illustrated in Figure 10.18. A ratio between average tree diameter and basal area is used to define a line of increasing competition as the trees grow. For example, a eucalypt plantation managed at a constant diameter

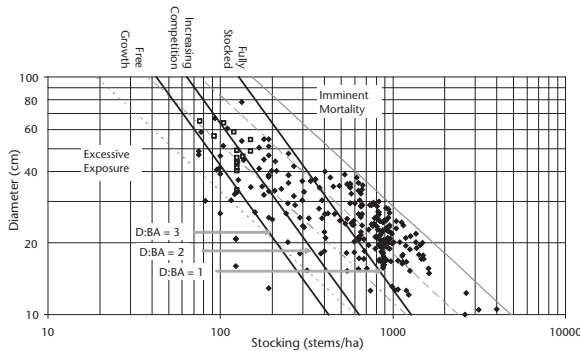


Figure 10.18: Ratio of mean diameter (DBH in cm) to stand basal area (BA in m²) as a guide to managing competition in an even-aged eucalypt plantation. Thick lines show constant D:BA ratios of 3, 2 and 1.

(cm) to basal area (m²/ha) ratio of 2 will be free growing until the trees are about 30 cm in diameter (stocking around 200 stems/ha) after which time diameter growth and branch development will be restricted by increasing competition. This may be an ideal route for growers who intend to prune since they can concentrate their pruning costs on a smaller number of free growing trees in the early years and allow increasing competition in the later years to control branch development in the canopy above the pruned height. If competition in the later years becomes a concern they may be able to commercially thin trees of around 45 cm, thereby allowing the rest to grow.

Based on measurements of mature plantations, Furrer (1977 in Borough *et al.* 1984) proposed a silvicultural regime for sawlog production from spotted gum (*Corymbia maculata*) that involves a number of thinnings to reduce the stocking rate from 1000 to 100 stems/ha. Displaying the regime on a stand density diagram (Figure 10.19) shows the practical application of relative density (RD) and the potential for using the diameter basal area ratio (D:BA) as a practical thinning guide. Furrer was not proposing that the trees be pruned and therefore suggested maintaining a level of competition sufficient to induce self-pruning (RD > 4) during the early years and repeated thinning when the competition becomes intense (RD < 6). Once self-pruning has been achieved, he suggests a heavier thinning to promote diameter increment (RD = 3) and thinning again when trees begin to compete (RD = 4). His target is a final stocking of

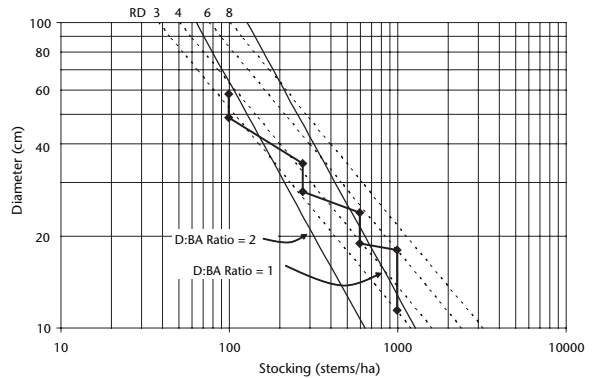


Figure 10.19: A non-pruning silvicultural regime for spotted gum (*Corymbia maculata*) sawlogs as proposed by Furrer (1971 in Borough *et al.* 1984). The regime suggests the plantation should be held at a relative density of 4–6 in the early years (D:BA ratio about 1) then 3–4 until harvesting (D:BA ratio about 2). The D:BA ratio can be used for management through the rotation.

100 stems/ha with mean diameter close to 60 cm (RD approaching 4).

Figure 10.19 includes lines of constant D:BA ratio. A practical guide for following Furrer's regimes would involve maintaining a D:BA ratio of about 1 during the early years then, after self-pruning had been effective in creating a clear bole, increasing this to a D:BA ratio of 2 during the later



Figure 10.20: This plantation of flooded gum (*E. grandis*) was commercially thinned to leave pruned trees at a D:BA ratio close to 3 to promote diameter growth.



Figure 10.21: The author measuring the basal area around a 16-year-old eucalypt growing in a mixed species plantation.

years. Furrer suggests a rotation length of 80 years. This could be significantly reduced if the grower were prepared to prune and the plantation managed at a D:BA ratio of 2 throughout the rotation. This would maintain a relative density (RD) of <3 (free growth) until the mean diameter was about 40 cm before allowing the plantation to approach full stocking late in the rotation.

Competition in forests of species other than eucalypts

Eucalypts have been used to demonstrate how tree diameter growth responds to competition and explore the tools for understanding and managing competition in a plantation. The principles are applicable for other tree species, the main differ-

ence being their relative tolerance. Using available data, it is possible to gain some appreciation for the maximum relative densities of a range of species grown for timber in Australia. In the medium- to high-rainfall areas *Pinus radiata* ($RD_{max} = 16$) tends to be more tolerant of competition than the broadleaf species such as the eucalypts ($RD_{max} = 12$) or Australian blackwood (*Acacia melanoxylon*) ($RD_{max} = 10$) (Reid 2006a, 2006b).

However, the maximum relative density is likely to be lower on less favourable growing sites. We have seen how sugar gum (*E. cladocalyx*) in medium- to low-rainfall areas may have a RD_{max} of about 8 (Figure 10.8). Based on data presented by Horn and Robinson (1987) the RD_{max} for *Callitris glaucophylla* (white cypress pine) growing in natural stands in central New South Wales may be as low as 6. Where there is little or no published data, the maximum relative density can be estimated from measurements of unthinned plantations or native regrowth stands that are clearly stagnant or are actively self-thinning. Simply determine the stocking rate and basal area, then calculate the diameter of a tree of average basal area. The relative density is derived from Equation 10.1.

Unless better information is available, it can be assumed that a plantation will be fully stocked at around half the RD_{max} and free growing when the relative density is below about a quarter of RD_{max} . If the grower is aiming for a fully stocked stand at the time of harvest it is possible to calculate the final stocking for a particular mean tree diameter (Table 10.2). For 60 cm diameter trees

Table 10.2: Stocking rate (stems/ha) required to achieve a particular relative density across a range of mean tree diameters. $RD = BA \div \sqrt{(DBH)}$ where BA is the basal area (m^2/ha) and DBH is the target mean diameter at breast height (cm).

Target relative density Fully stocked at harvest (50% of RD_{max}) Suggested species and rainfall for illustration		Target diameter (cm) (for thinning or final harvest)				
		30	40	50	60	70
RD 8	High-rainfall exotic pine (>900 mm annual rainfall)	620	403	288	219	174
RD 6	High rainfall eucalypts (>900 mm) Medium-rainfall exotic pine (>600 mm)	465	302	216	164	130
RD 5	Australian blackwood Native tropical hardwoods	387	252	180	137	109
RD 4	Medium-rainfall eucalypts (>600 mm) Exotic hardwoods (oak, black walnut)	310	201	144	110	87
RD 3	Native white cypress pine (NSW) Low-rainfall eucalypts (<500 mm)	232	151	108	82	65



Figure 10.22: (a) Radiata pine is more tolerant of competition than the eucalypts and maintains diameter growth at higher relative densities when grown on similar sites. (b) Australian white cypress pine is also tolerant of competition but when grown in very low rainfall areas can suffer from intense competition, leading to poor diameter growth and tree mortality.

this would mean a target final stocking (stems/ha) of around 220 for *Pinus radiata*, 160 for eucalypts on a good site, 140 for blackwood, 110 for sugar gum or spotted gum on a dry site and 80 for white cypress pine. Allowing the forest to approach the fully stocked state will mean that diameter increments will be quite low late in the rotation.

Pruning for clearwood sawlogs

The main purpose of pruning is to enhance timber value by increasing the proportion of clearwood. Knot-free timber commonly attracts a premium price in appearance-grade markets for pine (Cown 1992), eucalypt (Washusen 2001), teak (Centeno nd), Douglas fir (Jozsa and Middleton 1994) and many other species. Although not often specified, knot-free timber is also preferable in the structural timber market where large or loose knots can affect timber strength (Horgan 1991).

Pruning aims to confine branch-related defects to a knotty core within the log (Figure 10.23). The shape and dimensions of this core affect the recovery of clearwood in the form of sawn boards or veneer. The nature of occlusion over a pruned branch stub can lead to an extension of defects beyond the end of the branch stub. Defects include bark, resin, gum, stains or irregular grain. The diameter over occlusions (DOO) can be significantly larger than the diameter over stubs (DOS) if the pruned branches are large or if pruning cuts are

not smooth. Many years of research have suggested that in New Zealand the DOO in *Pinus radiata* will be about 3 cm larger than the DOS if pruned as recommended (Maclaren 1993).

Negatives of pruning

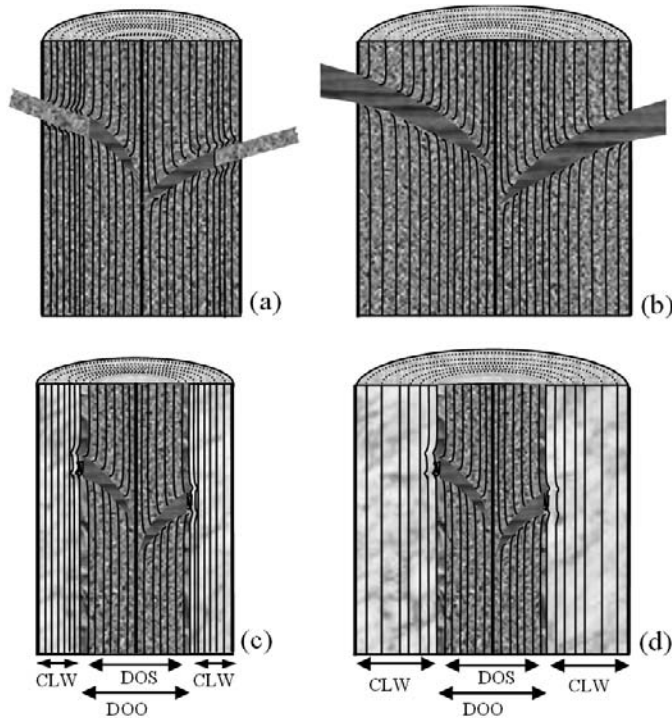
Pruning is an expensive, time-consuming and labour-demanding job that adds to the already heavy up-front costs associated with plantation forestry (Collier and Turnblom 2001). It is a job that must be done on time, to the extent that missing just one year may result in the plantation being worth less than if it had never been pruned at all. Ensuring forests are pruned on time, every time, has created real problems for industrial and small forest owners alike.

High pruning may also increase the risk of wind throw due to the increased exposure and the greater development of heartwood in the stem (see below). Increased light at ground level can exacerbate weed growth, increasing the fire hazard, encouraging noxious weeds and making plantations difficult to access. There is a risk of decay or disease resulting from pruning and uncertainty as to whether there will be a premium for pruned logs at harvest time. All this comes on top of the many environmental and market risks associated with any form of commercial tree growing.

These problems highlight the need to ensure that the silvicultural regimes adopted match the particular site, grower and market opportunities. There are no shortcuts – if growers are to maximise the benefits of pruning, they must understand how pruning affects tree growth and wood quality, be aware of the various pruning methods and strategies and be able to make well-informed decisions about when and how to prune.

Impact of pruning on growth rate and form

Where only some trees within a stand are pruned it makes sense to be concerned about the prospect of pruning setting back tree growth, even for a very short time. If pruning slows growth, the pruned trees may become suppressed by the more vigorous unpruned trees. However, where all trees are pruned, or thinning is undertaken in concert with pruning, the risk of loss of dominance is eliminated. In this case, the choice of pruning method and severity can be based on other criteria, such as



Key: DOS – Diameter over stubs, DOO – Diameter over occlusions, CLW – Clearwood

Figure 10.23: Simplistic representation of the silvicultural options facing forest owners. (a) No pruning and the use of competition to promote self-pruning. The dead branches are commonly held for many years after they die. The competition necessary to induce self-pruning also suppresses diameter growth, hence the need for a longer rotation. (b) No pruning with heavy thinning to promote diameter growth. Results in large diameter and large branches, hence low-quality timber. (c) Pruning without heavy thinning. Results in knotty core control and a high timber volume per hectare but competition suppresses diameter growth, hence the need for a longer rotation. (d) Pruning with heavy early thinning to minimise competition. Results in knotty core control and large diameter, i.e. maximum clearwood production in the shortest time but at the cost of total volume per hectare and quality of the unpruned portion of the tree (DOS = diameter over stubs, DOO = diameter over occlusions, CLW = clearwood) (Reid 2002).

wood quality, which are directly related to the reasons for pruning in the first place. If the timing and severity of pruning is based on critical target log



Figure 10.24: Pruning is labour-intensive and requires commitment over many years.

specifications it may be necessary to prune heavily even if tree growth is affected. It is no good following a pruning regime that minimises the impact on growth, if it is inadequate to control the size of the knotty core or risks encouraging decay due to large branch size.

Impact of pruning on height and diameter growth

Studies of stem-pruning for clearwood production show that pruning for clearwood production is unlikely to affect tree height (Langstrom and Helqvist 1991). The exceptions are where pruning is extended well above what would normally be required or where the trees are growing in direct competition with unpruned trees. This occurs because the carbohydrates and growth hormones



Figure 10.25: Pruning will reduce growth rates for a short time, but the aim is to produce a structure on which the tree can add high-quality mature timber in the future.

that drive height growth are produced in the upper crown (ShengZuo *et al.* 2000) independently of the lower branches. This also explains why thinning a plantation does not increase its height, despite stimulating canopy growth (Reid and Stephen 2001).

Fortunately, well-spaced trees of most species recover quickly from pruning. When part of a tree canopy is removed the photosynthetic activity of the remaining foliage increases, providing some compensation (Kozlowski and Pallardy 1997). This was confirmed in Tasmania where it was found that the photosynthetic capacity of young eucalypts increased within weeks of pruning and was sustained for almost two years (Pinkard and Beadle 2000). There was also an increase in foliage production, with larger leaves and longer retention of existing leaves on the pruned trees.

Pruning and wood quality

Because pruning influences the location and amount of canopy on the tree, it has a direct influence on growth rate and wood quality. Concerns over the development of a large juvenile wood core seem to have limited the enthusiasm of some foresters for heavy pruning and wide spacing, even though both theory and research suggest the opposite is more likely. Stem-pruning not only restricts diameter growth and hence the size of a young tree, it also reduces the concentration of carbohydrates

and auxins flowing down the trunk. Juvenile wood is produced in parts of the trunk that are close to the actively growing foliage (Cown 1992). Slowing early growth and encouraging later-age growth is a common way of improving wood quality (Cown 1992; Swanson 2001; Nicholas and Gifford 1995). Pruning and thinning may be a means of achieving this ideal.

Pruning also reduces the width of the sapwood band. The area of sapwood is related to the water demands of the canopy, so anything that reduces the size of the canopy will lead to a reduction in the area of sapwood in the trunk (Langstrom and Hellqvist 1991; Yans and Hazenberg 1991). If pruning is combined with thinning it is likely that the sapwood area will ultimately increase, as the open-grown trees develop larger canopies. The width of the sapwood band at the time of harvest will depend on the level of competition at that time. If a wide sapwood band is likely to reduce log value it may be possible to pre-determine the final stocking rate based on achieving a full stocking at the time of harvest.

Pruning and log taper

Taper refers to the rate at which the diameter decreases along the log. The ideal log is one that has no taper – a cylinder. If pruning reduces diameter growth without retarding height growth the implication is that it results in less log taper. Pruning (if combined with thinning) reduces stem taper in another way: many authors note that the largest growth rings are found near the base of the green crown, with diameter increments decreasing down the trunk (Shepherd 1986). This suggests that the concentration of auxin and carbohydrate defines the position of maximum growth in the stem. If, once pruning is complete, trees are spaced such that competition does not lead to a substantial natural rise in the green crown, it is only a matter of time until the pruned log assumes a cylindrical shape. This is unlikely to lead to the development of more juvenile wood at the upper end of the pruned log because of the length of branches in the lower canopy and the relative inefficiency of their foliage.

Epicormic shoots

If the canopy is destroyed by fire or wind (or pruned heavily), epicormic shoots may develop up the length of the trunk (Collier and Turnblom 2001).



Figure 10.26: Epicormic shoots develop in a response to a canopy area that is inadequate for the growing conditions. Heavy thinning of a forest releases growth potential but can result in excessive epicormic shoot development in trees that were previously under competition.

The shoots arise from cells in the cambium that can develop into shoots in the same way as shoots develop on cuttings. It is thought that changes in the concentrations of auxin and carbohydrates in the phloem trigger their development (Miller 1996). Rapid changes in light levels, temperature, nutrients or moisture can induce a similar response. Heavy thinning of fully stocked plantations has the same effect, suggesting that there are insufficient buds within the suppressed canopies to provide the leaf area required to match the improved conditions (Bowersox and Ward 1968). This can be seen in eucalypt plantations, and suggests that adopting a heavy stocking to suppress branches then thinning heavily to promote diameter growth may prove self-defeating (Figure 10.26).

Epicormic shoots are not true branches and do not have a knot that goes right back to the pith like a normal branch. If removed within the first season, they leave an interesting grain pattern and rarely cause any serious damage to the clearwood. If left growing, they can downgrade veneer logs to firewood. It may be possible to reduce the risk of epicormic shoots in deciduous trees by pruning when the canopy is active (ShengZuo *et al.* 2000; Jobling

1990). In very susceptible species (poplars, redwoods, cypress etc.) pruning of epicormics may be required for one or two years after the final pruned height is reached. Once the canopy develops to its full potential in well-spaced trees it can suppress the buds in the stem, and the risk of new epicormic shoots emerging declines.

Self-pruning and pruning dead branches

Self-pruning (the death of lower branches and their subsequent ejection from the stem) is common in eucalypts. Unfortunately, even in fully stocked stands, self-pruning in eucalypts is unpredictable and variable in its effectiveness and may result in a range of secondary defects (Maree and Malan 2000). When diameter increments are high, as is common in well-spaced plantations, dead branches can easily become trapped in the stem before they become brittle enough to fall.

Pruning and wood decay

Although pruning of eucalypts does increase the risk of decay-forming fungi entering the tree (Nielsen and Pinkard 1999), the decay is usually limited to the branch stub (Glass and McKenzie 1989). The incidence of decay appears to be related to the diameter of the branch, with those over 2 cm clearly at higher risk (Gerrand *et al.* 1997). Decay is more prevalent in areas of high rainfall and moist summers (Nielsen and Pinkard 1999). Once infected, the extent of decay is most advanced above and below the branch and towards the pith. No significant movement of decay outwards into the clearwood zone from a branch stub has been reported in any studies involving eucalypts (Glass and McKenzie 1989) or blackwood (Swanson 2001). The likelihood of decay arising from branches pruned in the second or subsequent pruning lifts flowing into the clearwood growing over the pruned stubs below, is still unclear (Mohammed *et al.* 2000).

New Zealand researchers, who pruned *E. nitens*, concluded that decay pockets were ‘confined, in the main, to the caroty and defective compression heart zone of the pruned logs’ (Roper and Hay 2000). The same was reported when winter-pruned *E. nitens* was milled in Victoria, despite decay in the stubs being quite common (Reid and Washusen 2001). Another New Zealand study (McKenzie *et al.* 2000), reporting on the milling of pruned

E. fastigata, stated ‘there was no internal decay associated with the pruning’. Pruning-related decay has not been raised as a concern in any Western Australian work involving a range of eucalypt species.

This pattern of decay movement in trees is explained by Shigo’s (1984) model of compartmentalisation of decay in trees (CODIT), which is well-accepted among arboriculturalists. Tasmanian research (Mohammed *et al.* 2000), testing the impact of pruning in different seasons, concluded that although the time of pruning did not have a significant effect on the presence or extent of decay, injury to the branch collar by poor pruning technique markedly increased the risk. The use of coatings, including the direct application of fungicides, has largely been discredited in the international arboriculture literature (Shigo 1984). Although the application of fungicide in one trial (Mohammed *et al.* 2000) involving eucalypts did reduce the incidence of decay (especially in spring and summer), the results were variable and the treatment expensive.

How to prune

Natural target pruning

Based on his experience and model of decay, Shigo (1984) promoted an approach called ‘natural target pruning’ (Figure 10.27). Large branches should first be cut well out from the stem to reduce their weight. If using a saw, first undercut the branch to eliminate the risk of bark stripping. Branches less than about 2.5 cm can be cut in a single action with loppers. Even slight damage to the branch collar of *E. nitens* at pruning has been shown to slow recovery and increase the possibility of decay (Gerrand *et al.* 1997). If the collar is not damaged the wound will heal quickly and evenly, with the callus forming a doughnut as it grows over the stub.

Season and frequency of pruning

The most critical factors influencing the choice of season for pruning are the risk of infection and dormancy of the cambium. In temperate areas, late winter pruning of eucalypts is generally recommended (Glass and McKenzie 1989; Reid and Stephen 2001). This reduces the risk of bark tearing or popping as the cambium is dormant, while

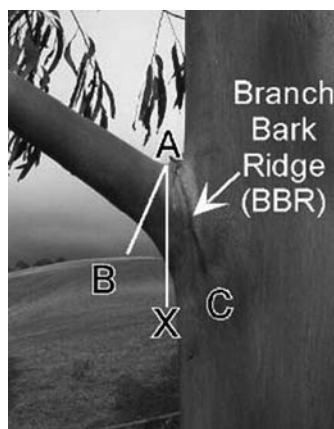


Figure 10.27: Natural target pruning involves a cut (A–B) that is the opposite of the branch–bark–ridge (A–C). In most cases this approximates a cut perpendicular to the branch, thereby minimising the surface area of the cut.

taking advantage of rapid tree growth in spring to control any decay. Dormant season pruning is also recommended for softwoods as it has been shown to result in less resin flow and hence defects developing over the branch stub (Petruncio *et al.* 1997). Although winter pruning of deciduous trees is easier due to the lack of foliage and is less likely to result in bark tearing or decay (Shigo 1984), poplars are often pruned in late summer while the foliage is still green, so as to provide useful stock fodder. This may also reduce the risk of epicormic shoots developing on the stem (ShengZuo *et al.* 2000).

Fast-growing trees need to be pruned more often to control the size of the knotty core. Because smaller branches heal faster (Petruncio *et al.* 1997) and are less likely to exhibit decay (Glass and McKenzie 1989), annual pruning is preferred where practical. Despite the greater number of visits, annual pruning may be more cost-effective because small branches are easier to prune.

Form-pruning

Early form-pruning is a means of correcting the shape of young trees to encourage them to develop a single straight stem at least as high as the expected log length. Form-pruning may not be required if there are sufficient vigorous, well-formed trees evenly spaced across the site – culling the poor trees will immediately improve the form of a plantation. However, where the selection

ratio is low, correcting tree form can enhance plantation viability.

Form-pruning may be required within the first year in systems where the planting stock produce more than one leading stem. This is the case in poplars, where a number of stems commonly arise from a planted cutting or barbatelle (rooted cutting). The best shoot is chosen no later than during the first winter, and the others removed back to the base (Pryor and Willing 1983). The same may be required where trees are grown from coppice or where young seedlings are set back by frost.

Form-pruning may also be required in later years to correct double leaders or to entice the main leader to grow straight by removing large competitive branches. True double leaders are evident from the slope of the bark ridge in the crotch between the stems. If it is vertical, one of the stems must be removed – select the straighter of the two. Form-pruning of small branches is required only if they are affecting the form of the leading stem.

Form-pruning of young deciduous trees during the dormant season can dramatically improve tree form. It has been shown, for example, that following corrective pruning of dormant black walnut (*Juglans nigra*) the retained leader, if bent, will commonly regain a vertical form (Nicholas 1986). It is also possible to physically constrain a leader into a vertical position for a period, after which it will remain straight (Beineke 1994).

A simple method of improving a very poorly formed tree that has suffered from exposure or neglect is coppicing. In species that coppice strongly, cutting them back to ground level (usually in autumn when carbohydrate reserves are at their highest) can result in a strong new shoot with much better form than the original tree.

Pre-emptive pruning

Pre-emptive pruning involves the removal of lateral branches earlier than would be the case with stem-pruning. This usually involves removing or shortening large branches that may affect the form of the main leader. Pre-emptive pruning can also reduce the costs of later stem-pruning operations and help control the size of the DOS by removing branches before they become very large. Where disease or decay is of concern, the pre-emptive



Figure 10.28: Form-pruning and pre-emptive pruning can improve tree form and reduce the time required to stem-prune in later years. Photo shows a branch >2.5 cm removed from a young Australian blackwood.

pruning of large branches may be important in reducing the risk of decay.

Annual pre-emptive pruning of *Acacia melanoxylon*, using a branch calliper of about 2.5 cm to identify any branch within the log length that should be removed, has proven an effective means of improving tree form and reducing stem-pruning costs without affecting tree growth rate (Nicholas and Gifford 1995).

Stem-pruning regimes

Stem-pruning is aimed at confining the knots and associated wood defects to a relatively uniform cylindrical core up the centre of the pruned log. Because young trees are tapered, it is usually impractical to prune to the full height in one lift, so pruning usually involves a number of lifts. Prior to the 1980s, most pruning operations were done to a fixed height, e.g. first lift to 2 m, second to 4 m and final lift to 6 m. When applied across a plantation this resulted in over-pruning of small trees and under-pruning of large ones.

For many years New Zealand researchers advocated pruning to a minimum length of green crown. For *Pinus radiata* it was felt that leaving 3–4 m of green crown would maintain growth while allowing control of the knotty core (Maclaren 1993; Maclaren and Knowles 1995). A few simple measurements made it possible to determine the diameter of the stem 3–4 m from the top. A pruning calliper corresponding to that diameter was then used to guide the pruning operation. This approach introduced the concept of variable lift



Figure 10.29: The simplest and most effective way to control the size of the knotty core and ensure all trees are pruned to the same degree is to use a calliper. All branches on the stem below the calliper are removed. The choice of calliper size depends on the species, site and management but usually ranges from 8–12 cm.

pruning, which is now recommended and should be adopted as standard practice.

More recent research (O'Hara *et al.* 1998) found that, despite variability in the length of green crown retained when using a calliper, pruning to a fixed diameter was an effective means of mimicking constant leaf area pruning (rather than constant green crown length). This allows forest growers to define their pruning regimes on the basis of size of target knotty core rather than on length of green crown retained. Pruning to a constant diameter on a regular basis is the only effective means of achieving a uniform knotty core.

How hard to prune (pruning gauge size)

The smaller the better in most cases, but there is little point in achieving a tiny knotty core if the presence of juvenile wood or other defects results in downgrading of the inner clearwood (Maree and Malan 2000). There may also be limits to how close to the core the processor is able to cut. For veneer production, the chuck diameter of the veneer cores will be critical, whereas in sawmilling it may be the size of the boxed heart.

Based on the volume of the clearwood sheath for a range of log sizes, a knotty core of less than

one-third the underbark log diameter is a useful target. This would result in about 80% of the log volume being clearwood. Achieving a DOO of no more than 20 cm the entire length of the pruned stem may require that no DOS be larger than about 17 cm. This allows for 1.5 cm all round to cover the wounds and account for sinuosity (bends) in the stem. Pre-emptive pruning of large branches (e.g. >2 cm) and annual pruning to a stem diameter of 10 cm would be sufficient in most cases to contain the DOS to less than 17 cm.

For a 60 cm log, reducing the knotty core by 3 cm to 17 cm by pruning more severely or regularly would increase the proportion of clearwood by less than 3%. However, regular pruning to a stem diameter of 8 cm rather than 10 cm may make pruning easier and cheaper due to smaller branch sizes, without significantly affecting tree height growth or time taken to reach target size. Smaller branches are also thought to be less susceptible to fungal infection.

Where the sapwood of a species is unmarketable, the diameter of the heartwood sheath, rather than underbark diameter, should be considered. This would be the case for a wide range of species including the naturally durable or coloured eucalypts like red ironbark (*E. tricarpa*) and cabinet species such as blackwood (*Acacia melanoxylon*). In such cases it may be worth pruning harder to limit the knotty core to <15 cm by using an 8 cm gauge and spacing the trees wider to encourage larger diameter growth.

Heavy pruning may increase the risk of epicormic shoot development but pruning when the canopy is active may reduce it. Unlike branches, which must be pruned carefully to reduce the risk of collar damage, epicormic shoots on hardwoods (e.g. eucalypt, poplar and oak) are easily removed from the ground using a long pole saw. Softwoods (e.g. pines and Californian redwoods) tend to produce a multitude of fine epicormic shoots up the stems that are more difficult to remove from the ground. Such trees may have to be climbed and a knife or the back of the sawblade used to scrape them off.

How high to prune

A large proportion of the market for high-quality appearance-grade timber (Horgan 1991) uses lengths of less than 1.5 m. Plywood manufacturers around the world generally use lengths shorter

than 2.5 m. Despite this, pruning to less than 3 m is unlikely to be warranted, because it would not allow the forest grower to adopt the wider spacings necessary to promote diameter growth without degrading the greater volume of unpruned timber growing above the pruned height (Maclaren 1993).

In Australia, most hardwood sawmill carriages cannot hold a log more than 6.1 m long and millers often prefer to cut logs into shorter lengths to reduce the impact of growth stresses and taper on sawn recovery. What may be more critical is the minimum length – some mills cannot restrain a log less than 3 m long on a line bar carriage. Given that harvesting and transporting costs per cubic metre are lower the longer the logs (less cross-cutting, sorting and loading), pruning to a height that allows for at least one 6.1 m pruned log seems reasonable for most markets (i.e. 6.5 m to account for the stump).

Even in a conical tree, pruning to 25% of the expected total tree height at the time of harvest still means about 60% of the tree volume is in the pruned section. As height growth slows and the pruned log section assumes a more cylindrical shape this proportion will improve even further. In 10-year-old pruned *E. nitens* nearing 23 m in height, more than 60% of the total tree volume was extracted in the 6.1 m of pruned log. About 5% of the total volume was in the 0.4 m stump, leaving about 35% of the total volume in the low-value top logs left on site (Reid and Washusen 2001).

On better-quality sites, where trees are likely to grow taller, it may be necessary to prune higher to maintain the same proportions. Fortunately, high pruning is likely to be easier on such sites, because the lower branches are less prone to growing large if height growth is vigorous. In a series of eucalypt trials in Western Australia, managers chose to prune to 9 m on the better-quality sites but only 5–6 m in the lower-rainfall areas (Moore 2000). While most managers of *P. radiata* in New Zealand aim for a final pruned height of 5.5–6.5 m, many cease before they reach that point (Maclaren and Knowles 1995).

Documented evidence

Once wood has grown over the branch stubs it is impossible to determine the size of the knotty core without cutting into the log. Log buyers may not

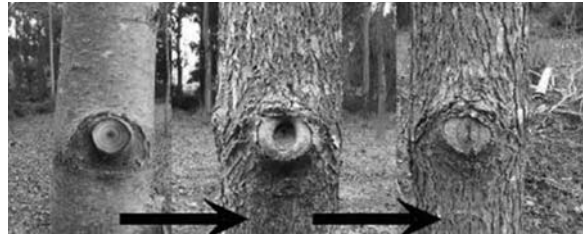


Figure 10.30: The rate of occlusion of the pruning wound depends on the growth rate. The pattern of occlusion reflects the accuracy of the pruning cut. If the collar is not damaged the callus growth forms a doughnut meeting in the middle of the wound, like this example in black walnut (*Juglans nigra*).

accept assurances that the trees were all of good form and pruned on time, every time. Australian Forest Growers provides a Pruned Stand Certification that is ideal for those with a relatively large, uniformly managed stand. Other growers should document all aspects of their management in a Tree Diary and take photographs of the stand immediately after each pruning and thinning operation as supporting evidence. Because of insect attack, the spread of decay and other factors there will always be uncertainty surrounding wood quality of standing trees. One option is to harvest a sample of trees to reassure the buyer, or growers could be paid on the basis of graded output – ‘over the saw’. This ensures neither the grower nor the processor carries the financial risk associated with uncertainty.

Silviculture for multiple values

It is possible to balance timber production with other values, such as land degradation control, agricultural production or biodiversity, especially where the emphasis is on the production on high-value pruned trees. Understorey native species can be grown between the widely spaced pruned trees, thereby improving the provision of environmental services. Farmers might choose to graze pastures between widely spaced trees or use the area for stock shade and shelter. This has the added advantage of reducing the fire hazard, and stock may benefit from access to fresh fodder from the prunings and thinnings.

The principles of pruning and thinning described in this chapter can be applied in multi-purpose

irregular-shaped forests. For example, Reid (2006a) described how to use the angle-count method of determining basal area to calculate the D:BA ratio around an individual tree. This negates the need to determine the stocking rate of irregularly spaced plantings or those where trees are growing on the edge or in a narrow belt.

Harvesting

The nature of the logs, the total volume and access to the site largely dictate the harvesting options. If timber is the only product and the aim is to maximise profit, then clearfelling large areas will reduce the costs and probably maximise the return. However, where trees also provide salinity control, wildlife shelter or other values, harvesting small volumes over a long period may be preferred. If the logs are large, pruned and well-spaced, a trained operator using a chainsaw in combination with a farm tractor, loader and log trailer can be cost-competitive against specialised mechanical log-harvesting machines. However, if the logs are small, branchy and in a dense plantation, the costs associated with the use of farm equipment can be higher than the value of the trees.

The choice of harvesting method also depends on the requirements for regeneration. Light-demanding species, such as eucalypts, generally need to be a full tree height away from mature trees if they are to grow well. This means that a gap of 30–50 m may be required. More shade-tolerant species, such as rainforest trees or softwoods, may grow well in the gap left after the harvesting of a single tree. In some cases a second generation can be grown among well-spaced older trees prior to harvest.

References

- Beineke WF (1994) Corrective pruning of black walnut for timber form. *Forestry and Natural Resources: Woodland Management*. Purdue University website <<http://www.agcom.purdue.edu/AgCom/Pubs/FNR/FNR-76.html>>.
- Borough CJ, Incoll WD, May JR and Bird T (1984) Yield statistics. In *Eucalypts for Wood Production*. (Eds WE Hillis and AG Brown) pp. 201–225. CSIRO/Academic Press.
- Bowersox TW and Ward WW (1968) Auxin inhibition of epicormic shoots in white oak. *Forest Science* **14**(2), 192–196.
- Centeno JC (nd) The management of teak plantations. *International Tropical Timber Organisation Newsletter* **7**(2). ITTO website <www.itto.or.jp/newsletter/v7n2/10management.html>.
- Collier RL and Turnblom EC (2001) Epicormic branching on pruned coastal Douglas-fir. *Western Journal of Applied Forestry* **16**(2), 80–86. Noted in *Forestry Abstracts* **62**(11), 1268.
- Cown DJ (1992) Corewood (juvenile wood) in *Pinus radiata*: should we be concerned? *New Zealand Journal of Forestry Science* **22**(1), 87–95.
- Curtis RO (1982) A simple index of stand density for Douglas-fir. *Forest Science* **28**(1), 92–94.
- Gerrand AM, Neilsen WA and Medhurst JL (1997) Thinning and pruning eucalypt plantations for sawlog production in Tasmania. *Tasforests* **9**, 15–34.
- Glass BP and McKenzie H (1989) Decay distribution in relation to pruning and growth stress in plantation-grown *Eucalyptus regnans* in New Zealand. *New Zealand Journal of Forest Science* **19**(2/3), 210–222.
- Horgan GP (1991) Market requirements for *Pinus radiata* clearwood: implications of length specifications. *New Zealand Journal of Forest Science* **21**(1), 77–95.
- Horne R and Robinson G (1987) White cypress in NSW: growth patterns and optimal thinning regimes for 60 to 80 year old stands. *Australian Forestry Journal* **50**(4), 216–223.
- Jacobs MR (1955) *Growth Habits of the Eucalypts*. Forestry and Timber Bureau, Canberra.
- Jobling J (1990) 'Poplars for wood production and amenity'. UK Forestry Commission. Bulletin 92.
- Jozsa LA and Middleton GR (1994) A discussion of wood quality attributes and their practical implications. Forintek Canada Corp. Western Laboratory Special Publication no. SP-34. Available at <http://www.lumber.com/products/pro_01130.asp>.
- Kozłowski TT and Pallardy SG (1997) *Growth Control in Woody Plants*. Academic Press, San Diego.

- Langstrom B and Hellqvist C (1991) Effects of different pruning regimes on growth and sapwood area of Scots pine. *Forest Ecology and Management* **44**, 239–254.
- Maclaren JP (1993) Radiata pine growers' manual. *FRI Bulletin* **184**. New Zealand Forest Research Institute.
- Maclaren J and Knowles P (1995) Silvicultural regimes: Radiata pine. In *Forestry Handbook (1995)*. (Ed. D Hammond) pp. 83–86. New Zealand Institute of Forestry.
- Maree B and Malan F (2000) Growing for solid hardwood products: a South African experience and perspective. In *The Future of Eucalypts for Wood Products. Proceedings of an IUFRO Conference*. 19–24 March, Launceston, Tas. pp. 319–327.
- McKenzie H, Ball R and Roper J (2000) Quality of timber sawn from pruned plantation-grown *Eucalyptus fastigata* in New Zealand. In *The Future of Eucalypts for Wood Products. Proceedings of an IUFRO Conference*. 19–24 March, Launceston, Tas. pp. 184–191.
- Miller GW (1996) Epicormic branching on central Appalachian hardwoods 10 years after deforestation cutting. USDA Forest Service. Northeastern Forest Experimental States Research Paper NE-702.
- Mohammed C, Barry K, Battaglia M, Beadle C, Eyles A, Mollon A and Pinkard E (2000) Pruning associated stem defects in plantation *E. nitens* and *E. globulus* grown for sawlog and veneer in Tasmania, Australia. In *The Future of Eucalypts for Wood Products. Proceedings of an IUFRO Conference*. 19–24 March, Launceston, Tas. pp. 357–364.
- Moore R (2000) Field day notes. Unpublished.
- Neilsen WA and Pinkard EA (1999) Developing silvicultural regimes for sawlog and veneer production from temperate eucalypt plantations in Tasmania. In *Eucalypts in Chile: Present and Future. Proceedings of 12th SILVOTECNA Conference*. Concepcion, Chile.
- Nicholas I (1986) Pruning black walnut. *What's New in Forest Research* **139**.
- Nicholas I and Gifford H (1995) Form pruning Australian blackwood (*Acacia melanoxylon*): NZ FRI experience. *What's New in Forest Research* **241**.
- O'Hara KL, Knowles RL, Dean M, West GG and McInnes I (1998) Growth efficiency of *Pinus radiata* stand elements: implications for stand growth modelling strategies. *New Zealand Journal for Science* **28**(3), 373–388.
- Petruncio M, Briggs D and Barbour RJ (1997) Predicting pruned branch stub occlusion in young coastal Douglas-fir. *Canadian Journal of Forest Research* **27**, 1074–1082.
- Pinkard L and Beadle C (2000) Factors affecting pruning responses in eucalypts plantations. In *The Future of Eucalypts for Wood Products. Proceedings of an IUFRO Conference*. 19–24 March, Launceston, Tas. pp. 328–334.
- Plumptre RA (1979) Pruning of fast growing pines for wood uniformity: can you have your cake and eat it? *Commonwealth Forestry Review* **58**(3), 181–189.
- Pryor LD and Willing RR (1983) *Growing and Breeding Poplar in Australia*. Pryor & Willing, Canberra.
- Reid R (2002) The principles and practice of pruning. *Australian Forest Grower* **25**(2), Special Liftout 60.
- Reid R (2006a) Diameter-basal area ratio as a practical stand density measure for pruned plantations. *Forest Ecology and Management* **233**, 375–382.
- Reid R (2006b) 'Silvicultural management of Australian blackwood (*Acacia melanoxylon*) in plantations and multipurpose forests. In *Acacia Utilisation and Management: Adding Value*. (Ed. A Brown). Australian Blackwood Industry Group: Fourth Blackwood Workshop. RIRDC Publication.
- Reid R and Stephen P (2001) *The Farmer's Forest: Multipurpose Forestry for Australian Farmers*. Australian Master TreeGrower Program.
- Reid R and Washusen R (2001) Sawn timber from 10 year old pruned *Eucalyptus nitens* (Deane and Maiden) grown in an agricultural riparian buffer. In *Proceedings of 3rd Australian Stream Management Conference*. 27–29 August, Brisbane, Qld. (Eds I Rutherford, F Sheldon, G Brierley and C Kenyon) vol. 2, pp. 545–550.
- Reineke LH (1933) Perfecting a stand density index for even-aged forests. *Journal of Agricultural Research* **46**(7), 627–638.

- Roper J and Hay E (2000) Sliced veneer production from pruned plantation grown eucalypts in New Zealand. In *The Future of Eucalypts for Wood Products. Proceedings of an IUFRO Conference*. 19–24 March, Launceston, Tas. pp. 106–112.
- ShengZuo F, XiZeng X, XiangJin Y and JianGuo D (2000) Effects of pruning intensity and pruning season on the growth dynamics of poplar plantations. *Forestry Abstracts* **63**(2), 143, ref. 901.
- Shepherd KR (1986) *Plantation Silviculture*. Martinus Nijhoff, Netherlands.
- Shigo A (1984) Homeowners guide for beautiful, safe, and healthy trees. NE-INF-58–84. As presented on *Guidelines for correct pruning*. <<http://www.pnwisa.org/shigo.html>>.
- Swanson S (2001) The clearwood pruning of *Acacia melanoxylon*: associated decay and discoloration. In *Silvicultural Management of Blackwood. A Blackwood Industry Group Workshop*. 30 November–December 2000, Smithton, Tas. RIRDC/LWA/FWPRDC Joint Venture Agroforestry Program. RIRDC Publication no. 01/176, pp. 40–43.
- Washusen R (2001) High-quality solid appearance products from plantation hardwoods: is quarter-sawing an option? In *Farm Forestry–Private Forestry Extension Conference*. 7–8 June, Hepburn Springs, Vic.
- Yans KC and Hazenberg G (1991) Impact of spacings on sapwood and heartwood thickness in *Picea mariana* (Mill) B.S.P. and *Picea glauca* (Moench.) Voss, *Wood and Fiber Science* **24**(3), 330–336.

Farm firewood production

Peter Bulman and Ian Nuberg

Introduction

There are two common and incorrect perceptions about firewood production on farms:

- firewood production plays second fiddle to sawlog production;
- everything that burns is firewood.

By working through these misperceptions we can learn a lot about the nature of farm firewood production and, from that, its potential role in natural resource management.

First, the iconic image of farm forestry in Australia is growing high-quality sawlogs in grazing systems. In this situation firewood production is often seen as a low-value co-product or early income as the sawlogs are growing. Firewood is often seen as the primary tree product on farms only in low-rainfall environments (<650 mm), where sawlog production cycles may be prohibitively long. However, the relative value of firewood versus sawlog production is strongly determined by the relative costs of production, changes in the value of the products and the value given to early over delayed production by applying discount rates. Depending on an array of physical and economic parameters, firewood production can sometimes compete with sawlog production even in relatively high-rainfall situations.

To support this assertion, the first part of this chapter will outline the favourable environmental conditions required for the development of a farm

firewood industry. With the shift from natural harvest to plantation systems, much interest has been generated in the silviculture of firewood, especially in reducing the costs of production by focusing on harvest and processing systems. This aspect of farm firewood production will be covered in detail.

The second misperception, that ‘if it burns it’s firewood’, is forgivable given that firewood has traditionally been harvested from natural stands. The favoured species for any regional firewood market are strongly influenced by what grows naturally within a reasonable transportation distance. However, when growing firewood in plantations, wood density and speed of growth are two important factors affecting the financial feasibility of the enterprise. This chapter will present a list of key firewood species and an explanation of market specifications for firewood. It will conclude discussing the role of firewood production systems in natural resource management.

Favourable environment for a firewood industry

There are many forces determining the future for a farm-based firewood industry; some are negative, but more are positive. Many consumers are attracted to wood energy but there is also a significant environmental reaction against the firewood industry. Strangely, some of the environmental problems also provide momentum to the movement toward plantations.

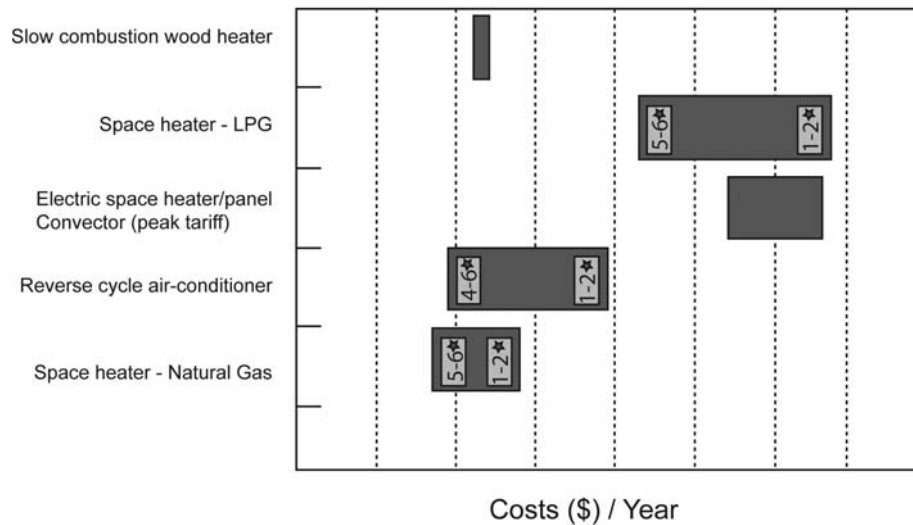
Space Heating to 60m²

Figure 11.1: Comparative annual running costs for space heaters (adapted from SEA 2002) Estimates for 8 hours heating to 21°C for a typical new home with R2.5 ceiling insulation and R1.0 wall insulation in Melbourne. Star ratings (☆) indicate efficiency of some heaters.

Until the 1950s, most houses in Australia were heated with firewood. After that time, oil, gas and electricity became convenient alternative domestic energy sources. However, the oil crisis in 1978 and an interest in natural living led to a resurgence of interest in wood heating that has not abated. By the early 1990s, 25% of all Australian households used firewood as the primary or supplementary source of heating. There is little doubt that the ambience of slow combustion wood heaters influences home heating decisions. However, slow combustion wood heaters also have real cost advantages compared with other forms of space heating (Figure 11.1). The deregulation and privatisation of the electricity market ensures that the relative competitiveness of wood energy versus electricity will remain for some time. On top of financial advantages, home owners can get an inner glow from knowing that plantation-grown firewood is a form of renewable energy that is carbon-neutral – carbon dioxide emitted during burning is sequestered by the next tree crop.

However, wood energy is not entirely without external costs. Collecting firewood from remnant native vegetation has considerable environmental impact, and wood smoke has a significant health impact. Recognition of these problems inspired a series of four Firewood Conferences across south-eastern Australia between 2000 and 2002 (Miller

2002). These conferences were heralded as ‘a turning-point in the wood-supply/wood-smoke debate where complaints and concerns have been replaced by consensus and plans for action’. The conferences produced much information about the firewood industry, that will help the development of a farm-based firewood industry.

The continuous removal of firewood from remnant native vegetation has similar effects on forest biodiversity as clear-felling does (Traill 2001). It involves the loss of:

- habitat for insects and other invertebrates, reptiles and ground-feeding mammals and birds, through removal of fallen timber;
- nesting hollows for possums, parrots, bats and other wildlife and loss of shelter or food for particular insects and insect-eating marsupials, from removal of standing dead timber;
- the number of large mature trees with abundant nectar and hollows, due to removal of large trees and the overcutting of smaller trees, preventing replacement.

In Victorian red gum woodlands, only 15% of pre-European levels of fallen timber remains on the forest floor. It seems clear that ‘tidying up’ the farm by removing unsightly fallen wood, removing dead standing trees and stand improvement activi-

ties such as removing older deformed trees to favour the younger, better-formed more vigorous trees, are all ecologically detrimental. There is good reason for more regulation of native harvest and even stronger reason to increase the supplies of firewood from plantations.

The benefits of such reforestation can also contribute to regional environmental and natural resources management goals, including:

- linking fragmented remnant native vegetation, that would not occur without a commercial return;
- reducing groundwater recharge and waterlogging and improving water quality in terms of salinity, turbidity and eutrophication;
- maintaining primary production in peri-urban areas on small-scale holdings;
- being carbon-neutral and energy-efficient, unlike fossil fuels that increase greenhouse gases and emit greater volumes of greenhouse gases per unit energy for home heating.

How significant are the air quality issues, and are these reason enough to limit or prohibit the urban burning of firewood? Regional centres such as Armidale and Launceston experience periodic severe particulate pollution, largely due to domestic wood heating. A study at Armidale (Khan *et al.*) showed, not surprisingly, that there are significant associations between particulate air pollution and respiratory symptoms that require medical attention. The Australian Lung Foundation states that for every 10 mcgm/m³ increase in particulates less than 10 microns in diameter there is a 3% increase in deaths from asthma and bronchitis (Frith 2002).

Such concerns have stimulated the design and sale of wood heaters that comply with Australian Standards to dramatically reduce emission of particulates, carbon monoxide and volatile organic compounds (Boyle 2000). This may satisfy authorities in most areas, but in areas that are subject to very unfavourable atmospheric conditions or where the density of heaters is enough to cause problems there is good reason to ban wood heaters. In such cases, for example in Launceston, a heater replacement program provides incentives for changes to cleaner forms of heating (Bagchi 2002).

State policies are taking a fairly consistent approach towards a sustainable firewood industry by regulating firewood merchants, the proficient

operation of compliant heaters and promoting plantations (ANZECC 2000).

Industry transition from native vegetation to plantations

The firewood industry is surprisingly big, with domestic firewood use estimated to be 4.5–5.5 million t/pa in 2000. It is also notably dispersed and disorganised. About half of firewood users buy their wood; of this, about 60% comes from suppliers without commercial premises. As little as 20% of firewood is purchased from commercial woodyards. The other half of firewood users collect their own firewood almost exclusively from fallen wood and some standing dead trees (Driscoll 2001).

Firewood collection generates about \$100 million pa of rural wages in largely part-time work for wood cutters. Unregulated small-scale wood cutters supply 70% of purchased firewood, estimated to be worth about \$260 million pa in 2001.

Traditionally this wood has been almost exclusively sourced from native vegetation. Over 80% is sourced from private land, with small proportions from state forests, roadsides and other public land. The best firewood comes from slow-growing dense species with greater heating value, the most popular being river red gum (1.1 million t), jarrah (0.61 million t), red and yellow box (0.54 million t) and ironbark (0.47 million t).

The environmental imperative for a transition to plantation-grown firewood seems to have provided the political environment needed to head towards greater industry responsibility. Replacing firewood sourced from native vegetation with plantation-grown wood cannot happen overnight. However, there are moves to increase accountability of wood collection and encourage plantation-grown wood, by requiring the species, source of wood and moisture content to be revealed. South Australia requires that wood be sold only by weight, thus placing pressure on suppliers without premises and/or access to a weighbridge to scale up or exit the industry. In other states there is more flexibility in how wood is sold.

Sugar gum plantations established in the early 20th century in the western district of Victoria have found a ready market locally and in Melbourne for approximately 20000 t/pa. There are other examples of utilising younger plantations for firewood, but as they are minor we will discuss

here the extent of plantations needed to replace, say, 50% of current production.

To sustainably supply 2.5 million t per year would require 250 000 ha of plantations, assuming a mean annual increment (growth rate) of 10 t/ha/yr. The total area of Australia's hardwood plantations in 2004 was just over 700 000 ha, of which just less than 50 000 ha were planted in 2004 (BRS 2005). Such a rate of plantation establishment provides an interesting perspective on the achievability of a 250 000 ha target, but it must be appreciated that this planting was strongly prospectus-driven as a part of managed investment schemes and largely for woodchip production, not firewood.

A successful transition to a plantation-grown firewood industry would logically depend not only on having the resources, but also on the development of a competitive contractor base that amalgamates the skills of traditional wood cutters with efficient small-scale harvesting and processing systems and, where appropriate, industrial-scale systems.

Plantation firewood species

Not all wood that burns well is suitable for plantation firewood. The species must be clean and hot-burning, but the optimal returns from a woodlot involves a trade-off between the mass and volume of the wood to maximise the air-dried tonnes per hectare and minimise the cubic metres of wood volume. It is not enough to select species with high wood density. For example, sheoaks (*Casuarina* and *Allocasuarina* sp.) have excellent burning qualities because of their wood density but have very slow growth rates. Their potential as a woodlot species is low because the number of air-dried tonnes per hectare will inevitably be far less than other species might produce. It is not as simple, however, as choosing the fastest-growing species regardless of wood density.

The harvesting costs of green wood are directly related to wood volume and almost unrelated to air-dried wood density. If two species produced the same air-dried weight to harvest in a given area but one species had half the air-dried density as the other (i.e. twice the volume), the harvesting costs would be close enough to double that of the dense species. The sections below on harvesting systems

and viability analysis highlight how critical this factor can be.

Which species might figure favourably in terms of growth rates and wood density? Table 11.1 presents a selection of species commonly promoted for firewood production across southern Australia. Species selected for planting need to be checked with local knowledge to ensure they can be matched to the site in terms of moisture availability (a factor of rainfall, soil depth and soil texture), fertility (able to be modified), frost incidence, salinity, exposure and drainage. The more commonly favoured species are listed closer to the top of Table 11.1.

Many other species are also well-suited for firewood production, including those grown for sawlog regimes whereby firewood is produced from the thinnings and heads of trees that are felled for sawlogs. Firewood production could provide a good product option if there were barriers to sawlog production, including suboptimal management, market fluctuations or other reasons. This does not apply to low-density, fast-growing species such as flooded gum (*Eucalyptus grandis*), which risks prejudicing the market against plantation-grown firewood.

Some revegetation experts propose the use of local native species for firewood production as a part of multi-purpose biodiversity plantings. Such species can produce good-quality firewood, but it must always be kept in mind that the yields will only be a fraction of well-selected non-local species. Most multi-purpose plantings involve some trade-off and necessarily have less of a commercial focus.

Wood density

As wood density is an important quality of firewood, farm foresters should make it their business to understand it. Wood density varies considerably between species growing as plantations on comparable sites. The density of a given species also changes with age. As trees mature, the growth rate slows and the proportion of sapwood decreases, progressively turning into heartwood, which is lignified, denser and has better burning qualities. Most of the firewood harvested from native vegetation can be expected to be $>1000 \text{ kg/m}^3$, i.e. it sinks in water. Wood from fast-grown and young plantations has a greater proportion of sapwood and is generally less dense, as illustrated in Table 11.2. The volumes refer to roundwood overbark volume; estimating air-dried yields involves multiplying

Table 11.1: Some species commonly promoted for firewood plantations

Species	Common name	Comments: growth and wood quality
<i>Eucalyptus cladocalyx</i>	Sugar gum	Impressive growth, density and wood qualities for medium-rainfall zones; marketed successfully in Victoria and South Australia
<i>Eucalyptus saligna</i>	Sydney blue gum	Favoured in Western Australia for growth rates, acceptable density and scope to be a byproduct from sawlog production
<i>Acacia mearnsii</i>	Black wattle	Burns very hot and can grow fast, but poor stem form and branching can hamper harvesting
<i>Eucalyptus globulus</i>	Tassie blue gum	Very fast growth rates offset by lower wood density, but marketed successfully in South Australia
<i>Eucalyptus occidentalis</i>	Flat-topped yate	Impressive growth rates for medium-rainfall zones and dense wood with good burning qualities
<i>Eucalyptus camaldulensis</i>	Red gum	Quality of plantation-grown wood not as good as naturally grown red gum
<i>Eucalyptus viminalis</i>	Manna gum	Good growth rates and good wood density of limited samples of plantation-grown wood, but untested in the fireplace/marketplace
<i>Eucalyptus astringens</i>	Brown mallet	Moderate growth rates for medium-rainfall zones and good burning qualities
<i>Corymbia maculata</i>	Spotted gum	Very thick bark but can be a byproduct from sawlog production
<i>Acacia dealbata</i>	Silver wattle	Similar to black wattle but requires better growing conditions
<i>Eucalyptus tricarpa</i>	Red ironbark	Slow growth rates but partially offset by wood quality and being fairly drought-tolerant; closely related to <i>E. sideroxylon</i>
<i>Eucalyptus botryoides</i>	Southern mahogany	Moderate growth rates but subject to borers when stressed
<i>Eucalyptus muellerana</i>	Yellow stringybark	Could be a good byproduct from sawlog production

Source: Bird *et al.* (1994); Hamilton and Quayle (2002); Kevin (2000); Tepper (2000); C&NR (1994); B. Hingston (*pers. comm.*).

overbark volumes less logging residues times air-dried density.

It seems that the optimal time to harvest the wood is going to be a compromise between waiting long enough for wood density to increase due to an increasing proportion of heartwood, but not so long that growth rates slow down too much. It is not difficult for a farm forester to measure wood density; it can be done quite simply in the kitchen

using scales, measuring cylinder and the oven. This notion of measurement for determining optimum time of harvest is discussed further in the following section.

Firewood silviculture

Firewood is relatively quick and easy to grow. It can be done on almost any farm site with little, if any,

Table 11.2: Wood density, ages and growth rates for a small sample of eucalyptus species

Species	Age (yr)	Rainfall (mm)	MAI (m ³ /ha/yr)	Basic density (kg/m ³ at 0% MC)	Air-dried density (kg/m ³ at 15% MC)
<i>E. cladocalyx</i>	7	<500	4–7	750	863
<i>E. cladocalyx</i>	18	<500	5–9	750–925	863–1060
<i>E. cladocalyx</i>	14	~700	?	790 ^a	910
<i>E. cladocalyx</i>	36–110	~700	<8–13 ^b	763–1090 ^{a,b}	874–1254
<i>E. viminalis</i>	17	~800	~15–20	619–750	712–863
<i>E. globulus</i>	17	~800	20–24	610–675	701–776

Source: a) Borchmann (nd). b) Theobald *et al.* (nd)

Table 11.3: Suggested initial stockings, corresponding spacings, rotation lengths and MAI for firewood plantations in different rainfall zones

Annual rainfall (mm)	Spacing (m)	Initial stocking (trees/ha)	Rotation length (yr)	MAI (air-dried t/ha/yr)
300	4–7	200–600	15–25	<1–3
500	3–5	400–1100	12–20	2–8
700	2.5–3.5	800–1400	12–15	4–14
900	2.5–3	1100–1600	12–15	6–20
Irrigation or accessible non-saline watertable	2.5–2.7	1400–1600	12–15	8–25

management such as pruning. The main silvicultural considerations are the initial stocking rate, rotation length, thinning and coppicing.

Tree spacing

As already indicated, firewood can be a byproduct of a sawlog regime but, for firewood plantations destined for clearfelling, the aim is to match the initial stocking rate with the potential site productivity. More-productive sites can support more trees per hectare than less-productive sites. The aim is to give each tree enough growing space to develop into a tree worth harvesting, i.e. a merchantable or effective stem, but not so much growing space that the trees take too long to fully occupy the site. An effective stem might need to be 12–15 cm at breast height to make it worth harvesting manually, or at least 20 cm for harvesting mechanically. Table 11.3 provides a range of suggested initial stockings and corresponding spacings.

Rotation length

Table 11.3 indicates a range of suitable rotation lengths for each rainfall zone, with a corresponding broad range of mean annual increments in air-dried t/ha/yr. It is commonly believed that a rotation length of 10 years is appropriate for firewood and pulpwood crops; this may be appropriate for a pulpwood crop where a high proportion of sapwood is acceptable. However, a farm forester growing firewood may choose to delay harvest by at least two years to increase the heartwood:sapwood ratio, thus also increasing the density. The density affects the burning qualities and the harvesting

costs per air-dried tonne. Monitoring the proportion of sapwood by felling and cross-cutting sample trees will help the grower decide when to harvest for an acceptable wood density.

Wood density has to be balanced against growth rate. Figure 11.2 illustrates the peak in growth rates that typically occur at a young age for eucalypts. The time for harvest is flexible, but the harvest should not be delayed too long past the point when the current annual increment is considerably less than the mean annual increment. Monitoring the growth rate by establishing a sample plot will provide the information needed to make a confident decision about when to harvest for optimum growth. The techniques for doing this are easy to

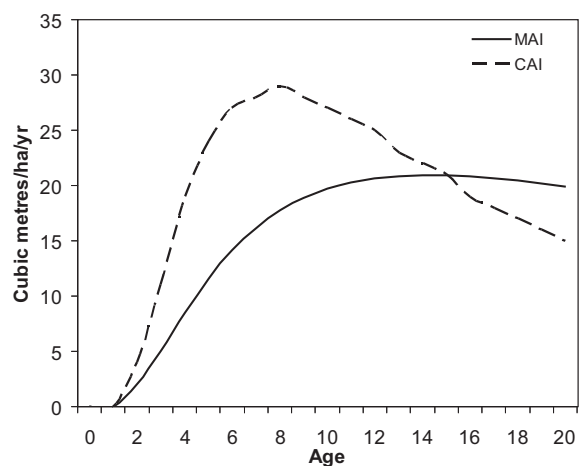


Figure 11.2: A growth curve developed for *E. globulus* (Wong *et al.* 2000) of average productivity illustrating the decline in average growth rate (mean annual increment) when the annual growth rate (current annual increment) is less than the MAI.



Figure 11.3: A firewood plantation with (a) a high proportion of ineffective stems and (b) nearby in the same plantation where many of the ineffective stems have been removed.

learn and explained in full in the *Tree Mensuration* DVD provided with this book.

Thinning

Thinning trees can cost hundreds of dollars per hectare and can be avoided if the initial stocking rate is chosen well. However, if a plantation has been planted too densely and has a significant proportion of ineffective stems, removing those stems will improve the diameter growth on the remaining trees. Figure 11.3 illustrates a young stand with many ineffective stems in the process of being removed.

Thinning small-diameter stems, whether in sawlog or firewood regimes, commonly elicits the desire to convert this waste into product, usually as firewood or as treated fence-posts. The material may be suitable for kindling or bagged wood, but

trying to produce these products, or inferior bulk wood, can be very time-consuming and not cost-effective. Usually, felling to waste is a much better idea for such small-diameter stems.

Coppice

The capacity of the eucalypt firewood species to reshoot from a cut stump (coppice) enables a second and possibly even a third crop to be harvested without replanting. A coppice crop will avoid replanting costs for the second crop, but a cost will be incurred if the number of shoots needs to be reduced. Many shoots will develop and compete for dominance, but selecting the best two or three shoots and removing the remainder with a brushcutter or small chainsaw will reduce the number of ineffective stems and the time until the next harvest. Using a brushcutter can be more productive than a chainsaw as it reduces the amount of bending and thus operator fatigue. Figure 11.4 illustrates coppice regrowth and the results of thinning.

The time of coppicing can be critical, especially with species where the young regrowth may be susceptible to frost or excessive summer heat. Autumn or spring may be better times to undertake coppicing. A useful rule of thumb is to cut stumps low



Figure 11.4: Sugar gum coppice: unthinned coppice ready for harvest (left) and one-stem-per-stump coppice following early removal of other shoots (right).

BOX 11.1

Weight–volume–density relationships

To estimate income from potential sales of recently processed firewood, it is vital to know how much air-dried wood without bark is available for sale. Even though the air-dried weight can be calculated from the underbark volume and wood density, it is likely to be more convenient to measure the loose stack volume or green weight and use a conversion factor. Measurements made during harvesting trials of 18-year-old sugar gum have been used to define the relationships between these units. They may also be helpful when considering the relationships in other species.

- Air-dried wood (no bark) densities were 863–1060 kg/m³ at 15% MC.
- Green density – 1490 kg of green wood and bark per m³ of underbark wood volume.
- Underbark roundwood volume per green tonne (including bark) – 0.67 m³/t.
- Loose stack volume per green tonne – 1.6 m³/t.
- Loose stack volume per cubic metre underbark roundwood volume – 2.47 m³/m³.
- Air-dried tonnes (at 15% MC) per green tonne: air dried weight = underbark volume (green weight × 0.67 m³/t) × average air-dried density (0.97 t/m³). Thus, air-dried weight of wood only = green weight × 0.65.
- Actual weight of air-dried wood will be greater if it includes bark.

– about half the height of the stump diameter – as this is thought to confer superior wind-firmness.

The coppicing nature of firewood plantations allows other planting configurations beyond a simple woodlot, such as a multi-row timber belt which provides shelter to adjacent grazing paddocks. In this system, single rows of the belt are harvested in sequence over a number of years. This ensures a regular supply of firewood without compromising the wind protection function of the timber belt. By the time the last row is harvested, the coppice regrowth of the first-harvested row will have reached a mature height. Another option is to leave some trees standing at harvest that will grow on to become sawlog trees amid a coppice regrowth.

Market and product specification

Farm foresters growing firewood crops need to have a good understanding of their product and its market. In most regions, it will not be enough to just grow the trees and sell them at the stump to a wood cutter. Better returns in firewood production come from being involved in as many links of the

value chain as possible. The following section discusses market preferences for wood specifications: how it is measured in terms of weight or volume, maximum moisture content, maximum dimensions, acceptable levels of bark and debris, and the marketability of plantation-grown wood.

By weight or volume?

In some states firewood is sold by weight and in others it is sold by volume, making interstate comparisons difficult. Both units have limitations. For instance, the weight for a given quantity of wood will vary according to moisture content and whether the bark is included. The volume for a given quantity of wood will vary depending on whether it is measured as underbark or overbark roundwood, or measured as a neatly or loosely stacked pile.

Box 11.1 illustrates some of the relationships between weight volume and density, knowledge of which will assist the farm forester get best value for their product. For example, where wood is sold as a neatly stacked volume, it is possible to determine

the (overbark) roundwood volume using a conversion factor of 0.825. Knowing the wood's density enables a conversion to weight.

Moisture content

In most states, the moisture content of firewood sold must be less than 20% – the lower the better in terms of heat generated for a given volume of wood. To reach an appropriate moisture content, cross-cut wood generally needs exposure to the sun in well-ventilated stacks for most of a summer and an autumn. Low-density wood generally dries more quickly than high-density wood.

Bark persisting on wood generally indicates unacceptable moisture content. The most common 'backyard' moisture test is the sound made when two pieces of wood are struck together. A nice bright sound indicates dry wood; a dull thud indicates wet wood. For more accurate measurements, wood samples can be weighed, oven-dried then reweighed to calculate the difference. A quicker and easier means of testing moisture content involves using moisture meters which measure the electrical conductivity between two pins inserted into the wood. The conductivity is directly related to the moisture content and calibrated to provide a direct reading.

Inclusion of bark and debris

Bark mixed in with dry wood creates problems for woodyards since it is not as appealing to customers as clean wood, and creates the problem of disposing of accumulated bark and debris. It is surprising how much debris, in the form of wood splinters and small chips, is generated when logs are split. As much bark and debris as possible must be left behind during loading at the plantation. Conventional front-end loader buckets pick up too much bark and soil, but a tyned or pronged 'stone bucket' that is hydraulically shaken a couple of times before loading will deliver wood with acceptably low bark levels.

Dimensions

The universally preferred length is foot wood (10–12 inches, or 25–30 cm) as it is suitable for all heating appliances. Even though most heaters take much longer pieces, potbelly heaters require the shorter wood. Some merchants also supply 18 inch wood at a slightly cheaper price. Split or unsplit,

the maximum diameter generally needs to be less than 6 inches (15 cm) for the traditional product.

Marketability of plantation wood

The attitude of woodyards varies according to the quality and quantity of wood on offer directly from growers and availability from regular suppliers. When wood is in short supply, as at the end of the season, it is a different from when there are regular supplies of a consistently high-quality product. In the latter case, the only incentives to purchase plantation-grown wood might be if the wholesale price is discounted and/or ongoing supplies are going to be needed in the future.

On a larger scale, sugar gum from extensive old plantations in the western districts of Victoria is well-accepted and sought after on the Melbourne market. There is an increasing number of smaller-scale growers successfully wholesaling bulk wood to woodyards. Retailing bulk wood and wholesaling bagged wood are alternatives to wholesaling to woodyards. However, these options may not suit the circumstances of many growers, despite the requirement in some states that wood be sold by weight.

Table 11.4 summarises prices and estimated volumes of wood consumed on a state basis at the time of writing. The price for firewood is subject to many shifting factors and these are only indicative values.

Firewood harvesting and processing systems

Firewood harvesting involves the felling of logs and extraction from the forest. Processing involves cross-cutting the logs into blocks and splitting. Harvesting and processing equipment needs to match the scale of operation and the size of logs being harvested. Industrial-scale equipment operating on large-diameter logs is cost-effective only for those larger logs. If small-diameter logs are processed using this equipment they need to be felled, extracted, cross-cut and (if needed) split many times more quickly to maintain equivalent productivity to larger logs. A 6 m log with a mid diameter of 45 cm has a volume of 0.95 m³; a log of the same length but one-third the diameter (15 cm) has a volume of only 0.11 m³, one-ninth the volume of the larger-diameter log. It is impossible to process nine little logs in the same time as one big log.

Table 11.4: Firewood prices across Australia

State	Wood consumed (M t)	Legal measurement units	Max. MC	Wholesale price	Retail price (incl. GST)
ACT	~0.1	Weight	20%	\$80–120/t	Canberra: \$140–195/t for red/yellow box; \$120/t for mixed hardwood
New South Wales	~1.4		20%		Albury–Wodonga: \$80/m ³ ex yard, \$90/m ³ delivered for red gum and box
South Australia	~0.4	Weight	20%	\$140–150/t	Adelaide: \$200–210/t
Tasmania	~0.7	Volume	na	\$55–70/cm	\$55–70/m ³ for delivered split firewood
Victoria	~1.2	Weight or volume		Up to \$160/t for red gum \$120/t offered for dry split at Lismore by Melbourne retailer Contract harvesting and processing \$60/t	Melbourne: \$220/t for 2 t delivered; \$180/t for 5+ t of sugar gum delivered Colac: \$50–85/m ³ for delivered stringybark Lismore: \$70/t for 2+ t of sugar gum Geelong: \$180/t or \$90/m ³ for red gum ex yard; \$105/m ³ cash for yellow box ex yard Shepparton: \$85/m ³ for delivered red gum Echuca: \$80/t unsplit and delivered Benalla: \$85/t red gum or box
Western Australia	~0.6	Weight or volume	15%		Perth: \$135–150/t Great Southern: \$130/t for jarrah

Source: Personal communications with L Hamilton, B Hingston, J Levison, I McArthur, L Offer, B Sonogan and G Traeger

In fact, small-diameter logs can be handled only marginally quicker than large-diameter logs. Farm foresters and the contractors that serve them need to consider the most appropriate scale of processing technology for the logs being harvested.

Less-mature plantations with relatively small-diameter trees still warrant equipment to minimise manual handling. However, farm foresters are more likely to need equipment that is cheaper to purchase and operate than conventional forestry harvesting equipment. It will be useful to examine some small-scale harvesting trials (Box 11.2) that indicate the scale of technology appropriate for farm firewood production. These show that the net returns to growers vary greatly and depend very much on the efficiency of the harvesting system and the level of involvement in marketing. The trials focused on the margins in the harvesting and production of bulk wholesale firewood. Retailing bulk and bagged wood is a further step in value-adding, and requires separate analysis.

The choice of machinery for harvesting and processing depends on the size of the trees being

harvested and the overall scale of the enterprise. Small-scale firewood cutters may make do with a chainsaw, and a trailer with or without a small tractor. It is very common to see a small sawbench, which may be cheaper to run than a chainsaw, being operated in conjunction with a hydraulic splitter. Neither involves a large capital outlay but both involve considerable manual handling. If there is no delivery system such as a log table, the logs or blocks need to be lifted each time. Industrial-scale tree felling and log-forwarding machinery can be efficiently used in firewood harvesting but only for large-diameter logs. This may limit their use in plantation firewood where trees with relatively small diameters are likely to be felled.

Viability of growing firewood

The viability of growing firewood on farms depends on the region where it is being grown, the market it is being grown for and the grower's degree of control over the process. It also depends on how firewood production compares with other land use

BOX 11.2

Small-scale harvesting trials

This brief comparison of four mechanised small-scale systems illustrates a range of technology and shows that good choice is critical in the financial feasibility of harvesting and processing firewood. The trial was undertaken in a 17-year-old sugar gum plantation near Keyneton, north of Adelaide.

The Hakki Pilki Scandinavian firewood mill is well-designed and engineered to cross-cut, split and load wood or make a pile using an elevator. The Hakki Pilki was mounted to a tractor by three-point linkage and used the tractor's power take-off. Set up with feed belt and hydraulically controlled cutting, the mill costs approximately \$15 000 (excluding the cost of the tractor and bobcat). The system relies on logs being delivered from the stump to the mill for processing.



Figure 11.5: Scandinavian firewood mill, loading log ready for cross-cutting.

The sawbench system also requires logs to be delivered from the stump to the mill for processing. The absence of a 'table' to manually or mechanically feed the wood to the sawbench meant that the billets needed to be manually handled a second time. One billet at a time is cross-cut by one operator while the other operator splits the blocks ready for loading via an elevator. Capital outlay for the system, including the stationary motor-powered sawbench for cross-cutting, splitting and loading, is approximately \$16 000.



Figure 11.6: Traditional sawbench, loading the billets onto the bobcat's forks. The pile of billets is ready for cross-cutting, splitting and loading.

The sled system involves felling, cross-cutting into 1.8 m billets, loading directly onto the sleds when green or dry (lighter and no bark), sledding to a storage area at the edge of the plantation with a tractor, cross-cutting each billet into seven 25 cm blocks using a high-capacity chainsaw with a long bar, extracting the sled from the cross-cut wood with a front-end loader, and storing or loading the wood with the front-end loader. The wood needs to be manually handled only once (onto the sleds) and the simultaneous cross-cutting of multiple logs is very rapid, but the blocks are unsplit. The outlay for the sled system is approximately \$1000 for the sleds and \$2000 for a powerful chainsaw. A tractor with front-end loader and a tiptruck or tipping trailer are also required.



Figure 11.7: Sled system: billets tied to sleds and being cross-cut by powerful chainsaws with long bars.

Using a sawbench to process (cross-cut) the wood at the stump effectively eliminates extraction costs. This 'at stump' sawbench can cross-cut multiple stems at a time and loads unsplit wood straight into the back of a tiptruck via an elevator. The prototype custom-made system was originally purchased for approximately \$6000 then extensively modified and refined following a series of field trials. The system is used in conjunction with a tiptruck.



Figure 11.8: 'At stump' system: billets being cross-cut and loaded into the tiptruck by the elevator.

Table 11.5: Forestry investment options, Mt Lofty Ranges, South Australia

	Project length (yr)	Establishment and management costs (\$/ha)	Total outlay (\$/ha)	Total returns (\$/ha)	Internal rate of return (pre-tax)
Firewood	12	3062	14 126	17 712	6.6%
Firewood	22	4403	23 669	30 996	8.1%
Wide-spaced pine	25	8313	12 633	21 500	3.4%
Wide-spaced hardwood	25	6759	13 239	11 000	-1.5%
Pine long rotation	35	5448	12 180	21 500	3.3%
Hardwood long rotation	35	5098	14 278	18 300	1.5%

Source: Bulman *et al.* (2002)

The main lesson is that the viability of firewood production is highly dependent on its physical and commercial environment, as is any farm forestry. Thus, farm foresters interested in firewood production should make detailed analyses at the levels of regional industry and individual enterprise.

Role of firewood production in natural resource management

Plantation firewood production has many beneficial impacts on our natural resources and should be seen as one of many strategies to improve biodiversity, groundwater management, soil conservation and surface water quality, and to further a carbon-neutral domestic energy economy. It provides the opportunity for a relatively low-risk, low-management enterprise diversification for farmers and other rural landholders. With efficient harvesting, processing and transport systems, growing firewood has the potential to be an attractive commercial wood production option across southern Australia, almost regardless of the rainfall.

However, there are important boundaries to this optimistic view.

The biodiversity value of firewood plantations comes largely from taking pressure off native forest stands. It may be many years before plantation firewood will completely supplant native harvest. By formalising and regulating the native harvest sector for sustainable production, the Firewood Industry Strategy will also preserve it. The biodiversity tag will probably be the strongest driver for plantation firewood. This is not to say that firewood plantations are by themselves very biodiverse. Plantations are monocultures and are unlikely to be planted with undercover species. Firewood plantations may be more likely to allow volunteer undercover species than sawlog regimes. They will have less traffic than dedicated sawlog regimes, which may be more open-spaced with grazing and subject to traffic for thinning and pruning. We do not know the specific biodiversity value of firewood plantations. However, comprehensive surveys of *E. globulus* plantations (for pulp) in south-west Western Australia reveal that they deliver a biodiversity benefit

Table 11.6: Farm forestry and agricultural enterprises, Corangamite region, Victoria

Net present value @ 6% discount rate	20 years	28 years	30 years
Sugar gum – firewood	480	–	–
Radiata pine – sawlogs	–	\$2420	–
Sugar gum – sawlogs	–	–	\$1454
Prime lamb	\$813	\$950	\$976
Merino wool	\$1262	\$1358	\$1394
Beef cattle	\$896	\$1047	\$1075

Source: URS (2003)

of 15–25% improvement over agricultural land, based on habitat complexity scores (RIRDC 2003). This is better than nothing, and may be improved through linking with native forest remnants and other strategies outlined in Chapter 6 of this book.

The impact of firewood plantations on groundwater management and salinity mitigation may be greater than it is on biodiversity, provided the plantations are located on recharge zones of local and intermediate groundwater flow systems. Firewood plantations that are managed as coppice systems can provide greater leaf area, then water use, than a sawlog regime. They also have greater potential for occupying lower-rainfall environments than sawlog systems, and it is those areas which are seeking productive perennial solutions. Some firewood species, such as *E. occidentalis*, are also suitable for slightly saline environments. However, the competition for water between crops and pastures and farm trees is more obvious in these environments than in higher-rainfall zones. For this reason, firewood crops may be best kept as woodlots than in more dispersed configurations. Firewood shelter belts may protect grain crops on light sandy soils, but on other soil types there may be no net grain crop benefit. Shelter effects on livestock may be worth the pasture lost to competition.

Tree planting of any kind has long been promoted for soil conservation and, by reducing stream sedimentation, it enhances water quality in terms of turbidity and nutrient loads. However, its effect on water quantity and stream salinity needs elaboration. It is well-known that plantations reduce the water yield of a catchment compared to under pastures (see Chapter 4). This effect is greater in higher-rainfall catchments and less marked in lower-medium to medium-rainfall zones. The influence of vegetation on stream flow decreases with distance from the stream. In larger catchments with longer hill slopes, the proportion of the catchment that effectively contributes to stream flow is smaller than in small catchments. Some of the impact of plantations on water yield can be avoided by locating them well away from streams and towards the ridges (FWPRDC 2004). The degree to which salt is exported from a catchment depends on the rainfall and how much water is intercepted by trees. While the greater water yield impacts will occur in high-rainfall catchments, the greater salt

load reductions will occur in medium- to low-rainfall zones, where streams and groundwater systems tend to have high salt concentrations.

Firewood production has many aspects that will appeal to farmers and landholders. It may be especially appealing to those on small-scale peri-urban properties where a well-designed plantation can improve the aesthetics and capital value. Firewood production is far more flexible than growing trees for sawlog or pulp. Such regimes have minimum sizes for feasibility, while firewood can be grown on any scale, from industrial-scale plantations to less than a hectare, although smaller plantings inevitably affect the economy of scale of harvesting. Firewood is relatively low maintenance compared with sawlog production and has a much shorter production cycle. It is a much easier market for a new grower to enter and the regulatory environment supports the development of firewood plantations and the marketing of firewood. In contrast, pulp production requires the grower to have a contract with a mill, and the sale of sawlogs is usually easier within a cooperative or with a consultant. Having said all this, it must be reiterated that prospective growers must undertake careful local financial assessment of this farm forestry option.

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References and further reading

ANZECC (2000) *A National Approach to Firewood Collection and Use in Australia*. Australian and New Zealand Environment and Conservation Council.

- Bagchi K (2002) Launceston wood heater replacement program: Environment Australia. In *Firewood Conference Papers. Collected Proceedings of A Burning Issue* (Bendigo 2000, Armidale 2001), *A Biodiversity, Consumer and Health Issue* (Launceston 2001) and *No Smoke without Fire* (Adelaide 2002). (Ed. J Miller). Tasmanian Conservation Trust/Natural Heritage Trust/Bushcare.
- Bird PR, Kearney GA and Jowett DW (1994) *Trees and Shrubs for South West Victoria*. Department of Agriculture, Pastoral and Veterinary Institute. Hamilton, Vic.
- Borchmann R (nd) Information sheet: sugar gum firewood. Plantation Development Services, Vic.
- Boyle R 2000 Firewood and air quality issues, EPA, Melbourne. In *Firewood Conference Papers. Collected Proceedings of A Burning Issue* (Bendigo 2000, Armidale 2001), *A Biodiversity, Consumer and Health Issue* (Launceston 2001) and *No Smoke without Fire* (Adelaide 2002). (Ed. J Miller). Tasmanian Conservation Trust/Natural Heritage Trust/Bushcare.
- BRS (2005) *National Plantation Inventory 2005 Update*. Bureau of Rural Sciences, Canberra.
- Bulman PA (1995) *Farmtree\$ for the Mt Lofty Ranges: A Regional Agroforestry Handbook*. Department of Primary Industries, Adelaide.
- Bulman PA, Geddes D, Crouch J and Stewart H (2002) 'The feasibility of attracting significant private investors (SPI) into non-prospective forestry investment'. Mt Lofty Ranges Farm Forestry Group/Farm Tree Systems.
- C & NR (1994) 'Firewood from Victoria's forests'. Department of Conservation and Natural Resources, Vic. Forests Service Bulletin no. 26.
- Driscoll DA (2001) 'Impact and use of firewood: a national perspective. In *Firewood Conference Papers. Collected Proceedings of A Burning Issue* (Bendigo 2000, Armidale 2001), *A Biodiversity, Consumer and Health Issue* (Launceston 2001) and *No Smoke without Fire* (Adelaide 2002). (Ed. J Miller). Tasmanian Conservation Trust/Natural Heritage Trust/Bushcare.
- Frith P (2002) Wood smoke harms your lungs. In *Firewood Conference Papers. Collected Proceedings of A Burning Issue* (Bendigo 2000, Armidale 2001), *A Biodiversity, Consumer and Health Issue* (Launceston 2001) and *No Smoke without Fire* (Adelaide 2002). (Ed. J Miller). Tasmanian Conservation Trust/Natural Heritage Trust/Bushcare.
- FWPRDC (2004) 'Plantations and water use: a review'. Forest and Wood Products Research and Development Corporation, Canberra. Project no. PN04.4005.
- Hamilton L and Quayle S (2002) 'Growing plantation firewood'. Publication no. AG1106 Department Primary Industries, Victoria.
- Kevin T (2000) 'Black wattle for farm forestry'. Department of Primary Industries, Vic. Publication no. AG0808.
- Khan L, Doran H, Parton K and Plummer D (2001) *Impacts of Wood Heating: Air Quality and Human Health*. University of New England/University of Sydney.
- Miller J (Ed.) (2002) *Firewood Conference Papers. Collected Proceedings of A Burning Issue* (Bendigo 2000, Armidale 2001), *A Biodiversity, Consumer and Health Issue* (Launceston 2001) and *No Smoke without Fire* (Adelaide 2002). Tasmanian Conservation Trust/Natural Heritage Trust/Bushcare.
- RIRDC (2003) 'Hardwood plantations: quantifying conservation and environmental benefits'. Rural Industries Research and Development Corporation, Canberra. Publication no. 02/083.
- SEA (2002) *Choosing a Heating System*. Sustainable Energy Authority Victoria, Melbourne.
- Tepper C 2000 'Gippsland farm forestry species'. Department of Primary Industries, Vic. Publication no. AG0784.
- Theobald RL, Hamilton L, Lang A and Grower A (nd) *Determination and Quantification of Yields and Growth for Unmanaged Sugar Gum Plantations in the Lismore (Victoria) District*. Corangamite Farm Forestry Network/University of Melbourne.
- Traill BJ (2001) Woodlands, wildlife, firewood (and lung disease): an overview of the firewood issues in Australia. In *Impacts of Wood Heating: Air Quality and Human Health*. (Eds L Khan, H Doran, K Parton and D Plummer). University of New England/University of Sydney.

URS (2003) *Agroforestry and Forestry in the Corangamite Region, Victoria*. Victorian Department of Primary Industries, Vic.

Wong J, Baker T, Duncan M, McGuire D and Bulman P (2000) 'Forecasting growth of key

agroforestry species in south-eastern Australia'. Joint Venture Agroforestry Program, Rural Industries Research and Development Corporation, Canberra. Publication no. 00/68.

Pulpwood production

Richard Harper, Keith Smettem, Rowan Reid, Andrew Callister, John McGrath and Paul Brennan

Introduction

A major change has occurred in Australia's rural landscapes since the early 1990s with the establishment of several hundred thousand hectares of short-rotation eucalypt plantations, predominantly through managed investment scheme (MIS) companies. These plantings mark a major shift away from traditional state-managed plantation forestry that was focused on lumber production from softwoods in 25–40 year rotations. The attributes that make pulpwood an attractive proposition to investors may also apply to many independent landholders.

The plantations are predominantly privately owned, established on previously cleared farmland in higher-rainfall areas (Figure 12.1) and managed in short rotations of around 10–12 years for production of pulpwood. They are limited to a few key species such as Tasmanian blue gum (*Eucalyptus globulus*), shining gum (*E. nitens*), Dunn's white gum (*E. dunnii*) and flooded gum (*E. grandis*). Of the 740 000 ha of eucalypt plantations in Australia in 2005, 61% were *E. globulus* (Parsons *et al.* 2006).

This expansion of hardwood pulpwood plantations represents a major change for the Australian forestry industry. Historically, most pulpwood was produced from the harvest of native eucalypt forests and plantation forestry with longer-rotation softwoods such as radiata pine (*Pinus radiata*), southern pines (*P. caribaea* and *P. elliottii* and their hybrids) and hoop pine (*Araucaria cunninghamii*),

grown by government enterprises. Private ownership of all plantations increased from 30% to 57% between 1990 and 2005. By 2006, approximately 390 000 ha of eucalypt plantations were in MIS woodlots, with a further 120 000 ha controlled by Australian and overseas forestry companies (Parsons *et al.* 2006). For pulpwood plantations, the overriding circumstance is thus one of corporate-owned trees planted on private land, with the existing farmers either leasing or selling land to a forestry or MIS company.

Pulpwood has been the wood product supporting the rapid expansion of industrial plantations because:

- the regional market for pulpwood is large and demand is predicted to increase, especially in China;
- pulpwood plantations have lower input costs and require fewer management interventions, and result in relatively good financial returns in a short time compared with longer-rotation timber crops.

Although the direct participation of independent private landholders in pulpwood production has been limited, with only around 7% of the eucalypt estate considered to be farm-forestry plantings (Wood *et al.* 2001), the recent expansion of industrial hardwood plantations in Australia brings the opportunity for landholders to incorporate pulpwood production into agroforestry systems that provide a wider range of benefits. Pulpwood

production has been successfully integrated into a small number of agroforestry ventures either as the exclusive wood product or as one component of multiple wood products.

The three main options for the private pulpwood grower are:

- 1 share-farming (often termed ‘joint ventures’) or rental arrangements with forestry companies or government trading enterprises, where specific areas of land are turned over to trees for an agreed period;
- 2 privately growing species suited to pulpwood production with the aim of selling all or some of the logs directly to exporters or processors;
- 3 privately growing the same species for sawlog production and selling to sawmills that can on-sell the sawmill residue as woodchips to exporters or processors.

The most common option is share farming. The attraction may be that the capital for reforestation is provided from outside the farm and there is an assured market at harvest. Similarly, much of the work is performed according to company prescriptions, often by contractors, and the landholder’s involvement can be minimal.

This chapter mainly examines the second option and describes the major aspects of producing short-rotation pulpwood crops on farmland, from the perspective of the independent private grower who finances the trees, undertakes or supervises all the work and sells the pulpwood on harvest. The information is general in nature as many management practices are tailored to suit particular growers, sites and market situations. Establishing a commercial plantation is a significant investment and it is recommended that landholders seek specific additional advice before proceeding.

Evolution of the industry

The replanting of cleared farmland with short-rotation eucalypt plantations grown specifically for pulpwood production is a relatively recent development in Australia. The industry essentially emerged in the mid to late 1980s due to the combination of a suite of environmental initiatives focused on the rehabilitation of farmland and mine sites in south-west Western Australia, and



Figure 12.1: Distribution of hardwood plantations in Australia (Parsons *et al.* 2006).

growth in international wood markets for hardwood fibre.

Salinity is a major problem in south-west Western Australia, caused by the hydrological imbalance resulting from extensive land clearing for agriculture (Wood 1924; Peck and Hatton 2002). Salinity impacts on water resources have been major and consequently a large-scale reforestation project was undertaken in the Collie River catchment (Mauger *et al.* 2001) to improve water quality (Peck and Williamson 1987). From this and associated work it was clear that the scale of reforestation required to tackle catchment salinity was much larger than initially thought, and possibly greater than landholders or the government could afford unless the trees themselves provided a direct economic return (Shea and Bartle 1988). The success of this approach has been demonstrated – the trend of increasing salinisation in the Denmark River, on the south coast of Western Australia, is being reversed following extensive establishment of *E. globulus* in its catchment (Bari *et al.* 2004).

At the same time a range of tree species were being evaluated for the rehabilitation of land following bauxite mining in the Darling Scarp of Western Australia. Together, these projects demonstrated that Tasmanian blue gum could achieve rapid early growth, particularly where planted on farmland. As in other states, research was proceed-

Table 12.1: Major pulpwood plantation areas and species in Australia in 2006

Region	Pulpwood species	Area of pulpwood species (ha)	Total area of plantations (ha)
Western Australia	<i>E. globulus</i>	257 993	377 598
Mt Lofty and Kangaroo Island	<i>E. globulus</i>	7983	28 825
Green Triangle	<i>E. globulus</i>	129 399	298 835
North Queensland	<i>C. maculata</i>	5720	29 288
South-east Queensland	<i>E. dunnii</i> <i>C. maculata</i> <i>E. grandis</i>	31 675	193 834
North coast New South Wales	<i>E. dunnii</i> <i>C. maculata</i> <i>E. grandis</i>	50 512	66 636
Murray Valley	<i>E. globulus</i> <i>E. nitens</i>	6380	184 602
Central Victoria	<i>E. globulus</i> <i>E. nitens</i>	26 300	57 185
Central and East Gippsland	<i>E. globulus</i> <i>E. nitens</i>	17 870*	92 925
Tasmania	<i>E. globulus</i> <i>E. nitens</i>	155 500	277 200

* *E. globulus* and *E. nitens* only.
Source: Parsons *et al.* (2006)

ing on various aspects of growing trees on farmland, including the development of agroforestry systems which sought to achieve multiple benefits including land degradation control and income from the sale of tree products (e.g. Prinsley 1991).

From the early 1980s trial plantings of Tasmanian blue gums were made by the (then) WA Chip and Pulp Company, and widespread plantings of blue gums were proposed in the Albany region (Shea and Hewett 1997). In the mid 1980s the Western Australian government reserved large areas of native forest as national parks and, as a consequence, investigated the use of agroforestry on farmland to provide an alternative source of logs (Malajczuk *et al.* 1984).

The concept that private investment in forestry could provide a mechanism for the rehabilitation of water catchments was proposed in the late 1980s (Shea and Bartle 1988; Bartle and Shea 1989). Initially the plan was for the establishment of belts of trees integrated with farming, with what was then seen as an ambitious target of 100 000 ha. A regional study of growth rates in relation to soils and climate (Inions 1991, 1992) indicated that relatively

high yields were achievable and 7000 ha of demonstration plantings were established, some with National Afforestation Program funding. Commitments to invest in 80 000 ha of blue gum plantations were made by various overseas corporations, backed by State Agreement Acts.

This investment was followed by the establishment of several forestry and MIS companies, who obtained finance from investors seeking portfolio diversification and tax advantages. Since these early developments, both forestry and MIS companies have expanded into other regions of Australia (Figure 12.1). Initial projects involved tree plantings integrated into farming operations, but the majority of the hardwood plantations estate exists as broad-scale fence-line to fence-line plantings. Pulpwood is being exported from facilities associated with several of the main production areas (see Table 12.1).

Contractual arrangements

The potential for landholders to enter into some form of share farming or rental arrangement with a

forestry or MIS company will depend on the interests and policies of the companies operating in that area. These agreements range from leasing arrangements over a specified period to share farming or joint venture arrangements where the landholder is allocated a proportion of the harvested crop in return for use of the land. Leasing and share farming arrangements often specify details of the period of the agreement, condition of the land on return to the landholder (e.g. removal of stumps, fertilisation), ownership of the coppiced trees and ownership of any carbon credits. In some states it is possible to register a legal title over the trees and another over the carbon contained in them, separate from the land title.

Leasing parts of a farm to a pulpwood company can provide substantial benefits to the farm owner even if they have no equity in the pulpwood crop. Parts of the farm can be selected to integrate the pulpwood production with farming requirements, for example, to provide stock and crop shelter, salinity and soil and biodiversity protection benefits. As well as shelter and other benefits, a lease arrangement provides secure, longer-term income diversification.

While some pulpwood companies may insist on large contiguous blocks, others have been prepared to establish the trees in wide shelter belts and woodlots that complement farming operations. Land for pulpwood production is increasingly difficult and expensive to obtain, so pulpwood companies may become increasingly flexible in the way they are prepared to do business.

Agroforestry using pulpwood species

Compared with longer-rotation plantations managed for sawlogs, pulpwood stands, once established, are relatively fast-growing and require only small inputs of labour. They are ideally suited to parts of an agroforestry venture designed for:

- rapid uptake of soil water or groundwater;
- rapid site occupancy to combat weed infestation;
- diversification of farm income.

They are less useful for integrated grazing systems as pasture growth beneath closely spaced trees generally ceases within three years of planting, although there are some exceptions such as with

E. camaldulensis × *grandis* plantations in the subtropics which allow more light penetration. Wide spacing of trees to enable grazing could result in loss of wood production through heavy branching, but profits from the integrated business might be better than from pulpwood alone.

Species and products

The range of species that can be used for pulpwood production is constrained by the familiarity of major pulpwood producers, and currently comprises *E. globulus*, *E. nitens*, *E. dunnii* and *E. grandis* and hybrids. Each is preferred in different geographic regions (Table 12.2). Although other species such as *Corymbia maculata* (spotted gum), *E. occidentalis* (swamp yate) and *E. smithii* (gully gum) may have potential as pulpwood species, in terms of wood basic density, kraft pulping and paper-making qualities (Hicks and Clark 2001) these are not currently used at any scale. Other species such as *E. pilularis* (NSW blackbutt) may also be suitable for pulpwood, but are not used to any extent.

Although the major product from pulpwood plantations is woodchips for export, a number of other products may develop. These include:

- sawlogs;
- manufactured wood products;
- bioenergy;
- carbon sequestration;
- other environmental services such as the protection of catchment water quality.

In most cases these will depend on local circumstances, such as a major investment in a processing plant, or the enactment of specific legislation, for example the development of emissions trading legislation. Not all these product options may be available in all regions.

Sawlogs

Although eucalypt plantations grown for pulpwood are rarely thinned and pruned, there may be some prospect of recovering a proportion of lower grade sawlog material at the time of harvest. Improved milling techniques involving the simultaneous removal of boards from each side of a log are being used to manage the growth stresses in small-diameter eucalypt logs. This process is being used to mill

Table 12.2: Broad climatic requirements for the main pulpwood plantation species, except *E. dunnii*

Species	Mean annual rainfall (mm)	Rainfall regime	Dry season (months)	Mean max. temperature hottest month (°C)	Mean min. temperature coldest month (°C)	Mean annual temperature (°C)	Absolute min. temperature (°C)
<i>C. maculata</i>	620–2000	u, s	0–5	24–32	0–13	12–23	>–8
<i>E. globulus</i>	550–1500	w, u, s	0–7	19–30	2–12	9–18	>–8
<i>E. grandis</i>	700–2500	s, u	0–7	25–34	3–16	14–25	>–8
<i>E. nitens</i>	750–1500	w, u, s	0–6	20–28	–1–7	9–18	>–12

The absolute minimum temperature provides an indication of frost risk.

Rainfall regime: u = uniform; s = summer; w = winter.

Source: Adapted from Booth and Pryor (1991).

eucalypt logs as small as 27 cm in diameter for flooring and structural timber (Cannon *et al.* 2006).

Because the logs are of small diameter and unpruned, the timber produced is almost all small-dimension, back-sawn and knotty. Depending on market opportunities, the recovery of marketable timber is likely to be lower than for large-diameter pruned logs. Because of these factors the stumpage prices paid for sawlogs extracted during a conventional pulpwood plantation harvest are likely to be only marginally higher than the pulpwood price. However, the prospect of producing sawlog material may justify extending the rotation length or thinning to promote diameter growth, with the thinnings being sold for pulpwood.

Manufactured woods

Several products can be produced from logs, with these involving the reconstitution and bonding of wood flakes or fibres under heat and pressure. Examples include engineered and oriented strand lumber (ESL, OSL), laminated veneer lumber (LVL), medium-density fibreboard (MDF) and particleboard. To date, most of these products have been based on softwood, but engineered strand lumber (ESL) plants based on *E. globulus* and other hardwoods may be constructed in the future.

ESL is made from logs with diameters larger than would typically be produced in a 10-year pulpwood production system. This must be taken into account in the silvicultural management and harvesting of the stand. ESL manufacture has a smaller input volume requirement than that required to support an export woodchip operation. Product recovery and finished product value are both relatively high, so prices for suitable logs are less constrained than for woodchip logs. These factors suggest that farm foresters will be less disadvantaged in accessing markets, against large plantation managers, than if they were competing to supply the export woodchip market.

Farm foresters may prefer to establish shelter belts and small woodlots rather than large contiguous blocks of trees. The larger proportion of edge trees will lead to a higher proportion of larger-diameter logs. The larger branches that tend to occur on edge trees are less of a problem for ESL production than they would be for sawing. Alternatively, some growers may be willing to thin a

proportion of the plantation to waste soon after canopy closure to ensure that most of the trees reach the minimum diameter for ESL.

Bioenergy

Woody plant materials have potential value as a feedstock for electricity production and for liquid fuels (Bartle 2001; Schuck 2006). Where they replace fossil fuels they represent a means of reducing net greenhouse gas emissions. Bioenergy may be a use for waste products from pulpwood production, such as bark or branches, and thus represents an additional income stream for growers. Electricity production from these materials is occurring in some parts of Australia, either as a stand-alone fuel or co-fired with coal. There have been initiatives to pelletise waste from *E. globulus* plantations and export it to other countries that have mandatory renewable energy targets.

The technology for industrial-scale production of liquid fuels from woody materials is still under development. There are two main approaches to producing biofuels from woody materials – fermentation or gasification. The latter can produce petrol substitutes such as ethanol or long-chain hydrocarbons as diesel substitutes via the Fischer Tropsch process (Sartori *et al.* 2006).

The rate of adoption of biomass as a renewable energy feedstock depends on state and national renewable energy and carbon emission policies, the cost-competitiveness of biomass compared with fossil fuels and alternative renewable energy sources, and the demand for reconstituted wood products. The Australian Government and some states have set, or are considering, renewable energy targets as part of their response to projections of future climate change.

Carbon sequestration

The Kyoto Protocol, which is part of the UN Framework Convention on Climate Change, contains a series of measures aimed at tackling climate change and specifically decreasing the concentration of carbon dioxide in the atmosphere. Article 3.3 allows the use of reforestation of farmland as a carbon sink and the trading of carbon credits. Australia ratified the Kyoto Protocol in 2007 and is designing a national emissions trading scheme to commence by 2010 at the earliest.

It is likely that the Carbon Pollution Reduction Scheme (CPRS) will use the Kyoto Protocol's rules for reforestation of farmland. The main points related to obtaining payment for the carbon contained in a pulpwood plantation under the rules of the Kyoto Protocol include the following.

- The plantation must be established on farmland that was not forested at the beginning of 1990.
- The carbon that is sold is likely to include not only that in the bole, but that in the remainder of the above-ground biomass and in the roots. The measurement units for carbon sequestration are given in CO₂ equivalents (CO₂-e), measured in t/ha.
- If the trees are harvested or destroyed and not replaced, any carbon credits will have to be refunded. Thus, if the grower wishes to return to farming after harvesting the trees, they will need to buy back (at the prevailing rate) any carbon credits they had sold. Future rules may make allowance for the carbon stored in wood products.
- For small plantings, the transaction costs associated with registering the carbon and finding a buyer may outweigh the returns. In this case, it may be preferable to join a carbon pool run by a third party. Such pools are being developed and represent a method of smoothing the emissions of carbon from harvested forestry projects.

Various studies have estimated the amounts of carbon that can be sequestered by different plantation species. It has been generally assumed that there is no change in soil carbon content following reforestation (Polglase *et al.* 2000) so the focus has been on the above- and below-ground woody component of the forest. The Australian Government produced the National Carbon Accounting Toolbox to help predict the amount of carbon sequestration in many plantation species.

An example of converting stem volume to carbon dioxide equivalent is given by Harper *et al.* (2005). The steps for *E. globulus* are given as an example.

- 1 *Conversion of stem-wood volume to stem-wood mass.* The bole volume (m³/ha) is multiplied by the wood's basic density, estimated from studies that have taken into account variations with

environmental conditions and tree age (Ilic *et al.* 2000).

- 2 *Conversion of stem-wood mass to above-ground biomass.* A review of this expansion factor (Snowdon *et al.* 2000) suggests that the ratio is 1.3–1.5 for forests of harvestable age.
- 3 *Conversion of above-ground biomass to total biomass.* To estimate the amounts of carbon in roots, use root: shoot biomass ratios of 0.20–0.25 (Snowdon *et al.* 2000).
- 4 *Total mass to carbon mass.* It is assumed that the carbon content of wood is 50% (Gifford 2000).
- 5 *Carbon to carbon dioxide.* Carbon accounting often uses carbon dioxide equivalents (CO₂-e). The conversion factor is 3.67, calculated from the molecular weights of carbon and oxygen.

Under the Kyoto Protocol's rules, carbon sequestration requires a permanent land use change from agriculture to forestry. Thus, irrespective of the long-term store of carbon in wood products, roots and debris, if a plantation is harvested and replaced by agriculture there is considered to be no net change in carbon storage. It is assumed that all carbon is emitted when a plantation is harvested, even if it is subsequently re-established. This ignores the fact that the average carbon stock over time on a site used for a succession of commercial plantations will begin at approximately half the total achieved at the end of the first rotation, and increase over time due to the increasing store of carbon in timber and paper products (where this is recognised under scheme rules). The amount of carbon stored on a particular site will increase with plantation age, thus longer rotation lengths result in greater net carbon storage (Harper *et al.* 2007).

Other environmental services and environmental payments

Plantations may provide a range of benefits to the environment, including improved water quality, erosion control and shelter. The example of reversing salinisation trends in the Denmark River catchment in Western Australia was cited earlier. The impacts of plantations on groundwater largely depend on the location and proportion of the catchment planted (Peck and Hatton 2002).

The concept of environmental services is that the environmental benefits of private plantations

will be paid for by a range of users or beneficiaries. Where these benefits occur off-site and benefit the community, it can be argued the beneficiaries should help pay for their provision. This is the concept of 'public goods'. Although there have been some transactions related to plantation establishment and improvements in water quality (e.g. Macquarie River in New South Wales), these are few. Funding for replanting with public good outcomes is sometimes available through government environmental grants programs.

Potential negative impacts of plantations

An issue that has gained increasing prominence in Australia in recent years has been the debate between water managers and plantation owners about the water use of plantations. There are clear water quality benefits associated with the reforestation of salinising catchments, but the establishment of plantations can also result in a reduction of fresh-water flows or recharge to aquifers and thus may reduce downstream or aquifer water supply. A difficulty in this debate is establishing the initial frame of reference. Most of the debate has assumed a change in the status quo – plantations are replacing cleared farmland. However, most of the farmland had replaced perennial vegetation so, in a sense, plantations are re-establishing the pre-clearing status quo.

In some regions the introduction of exotic or non-indigenous tree species may be opposed on the basis of the potential of the plantation species to become an environmental nuisance. The main risks associated with introduced species are that they may contaminate the gene pool of endemic species or invade adjacent natural ecosystems. These risks are relatively low for many plantation species, but awareness of the potential of introduced species to become environmental weeds has increased. Local forestry agencies, councils or environmental agencies may be able to provide local advice about the potential weediness of different plantation species.

Market prospects

The decision to embark on a pulpwood venture ultimately depends on analysis of likely profitabil-

ity compared to existing land use options and consideration of the non-timber benefits of plantations, such as controlling watertables or providing shelter. These points must be compared with other forms of forestry, such as growing the same or other species in longer rotations for high-quality sawlogs. Due to the nature of the pulpwood industry (a few large producers and only one or two buyers operating in a region), potential pulpwood growers must first consider the issue of market access. Other key considerations include the following.

- Is there an existing pulpwood processing facility within 100–120 km of the farm?
- Do the existing companies enter into share farming or rental arrangements with farmers?
- Do the existing forestry and MIS companies enter into supply agreements with individual producers?
- Are there additional markets for other products produced from the plantation, such as bioenergy, manufactured wood, wood pellets or carbon sequestration, or are these likely to develop in the future?
- Are there local contractors who can harvest and transport the pulp logs?
- Does the buyer require logs to be from certified stands?

As with any forestry enterprise, an assessment has to be made on the returns for pulpwood 10–12 years into the future. With several hundred thousand hectares of pulpwood plantations already established in Australia, an obvious question is whether there will be an oversupply of pulpwood and a consequent future depression of prices. Currently, 85% of Australia's pulpwood exports are to Japan, but there may be changes in regional demand from countries such as from India and China as they increase in wealth and change their demand for paper products.

To promote consumer confidence, and increasingly to ensure end-product market access, some buyers require that logs be sourced from stands certified through the Australian Forestry Standard or Forest Stewardship Council. These certification schemes have standards for plantation management and chain of custody for logs, chips and resulting products. The standards for forest management are most relevant to growers. The

standards require that growers can demonstrate and provide evidence to independent verifiers that they have complied with relevant legislation, codes of practice and other scheme-specific criteria relating to sustainability.

Legislation and codes of practice vary across jurisdictions and obtaining certification can be costly. To date, few private growers have obtained certification for their stands. Growers interested in certification can seek advice from experienced forestry consultants. Relevant codes of practice can be obtained through forestry agencies in each state.

Profitability

The overall profitability of a pulpwood plantation will depend on the wood yield and the likely price. Factors affecting profitability include:

- the rate of growth and actual pulp yields;
- contractor costs for planting, harvesting and transporting the pulp logs to a mill. The harvest and transport of logs from the farm to the mill is a major cost in any forestry operation. The types of costs for a typical pulpwood plantation are summarised in Table 12.3;
- prevailing interest rates.

One of the most critical factors in determining the profitability of a pulpwood stand is the haulage distance to port or pulp mill. It is most likely that smallholdings of standing pulpwood will be harvested by contractors who predominantly work for a large grower who has export woodchip supply agreements in place. Such companies will inspect stands of third-party pulpwood and offer the landholder a stumpage rate, currently \$25–40 per green metric ton (GMT) for *E. globulus*. The price is primarily determined by deducting the harvesting and haulage costs from an agreed mill-door price. Distance to the mill and volume available for harvest therefore have a direct influence on the price. As a rule, if there is sufficient volume to warrant moving the harvesting equipment to the site, the stumpage offer will decrease by around \$1/GMT for every additional 10 km of haulage. Generally, a potential pulpwood plantation site should be within 150 km of a port or mill assuming a reasonable area and growth potential, or within 200 km if the growth potential and thus log volume recovered per hectare is considered to be very high.

Table 12.3: Typical costs associated with establishing, managing and harvesting a pulpwood plantation assuming a second coppice rotation

Year	Type of cost
0	Establishment costs Soil assessment Rabbit and vermin control Fencing Ripping and mounding Herbicide and application Seedlings and planting Fertiliser and application Insecticides and application Permits and licences
1	Herbicide and application (year 1)
1–10	Nutrient analysis, fertiliser and application Insecticides and application
10	Harvesting and transport
11–13	Thin coppice Nutrient analysis, fertiliser and application
14–20	Firebreaks Insurance Professional advice

Source: Dept of Conservation and Land Management (2002)

The main determinant of pulpwood yield is wood quality. The most important wood property considerations are pulp yield, basic density and colour. Pulp yield is the proportion of raw dry matter recovered after pulping and is reported as a Kappa number, which is related to the amount of oxidising agent used in the pulping process. Pulp yields greater than 50% are usually considered acceptable, and high-yielding species such as *E. globulus* typically have pulp yields of 52–55%. Basic density is calculated as oven-dry mass divided by volume (kg/m^3) and values lower than 650 kg/m^3 are usually acceptable for pulping. This threshold is above the typical value for the typical pulpwood species used in Australia (see Table 12.1). As woodchips are traded on weight rather than volume, higher basic densities bring greater value to the grower. Wood colour is of some concern to pulp mills, as darker-coloured woods require greater bleaching. Blonde woods such as *E. globulus*

and *E. nitens* are therefore preferred over red woods such as *E. grandis*.

Site and species selection

The pulpwood industry is concentrated in several broad geographic areas (Table 12.1, Figure 12.1) and the key criterion for the participation of an individual farmer is the presence of an existing industry and buyers. Once it has been decided that there is a reasonable prospect of successful sale of pulpwood, the landholder will need to consider:

- whether the local climate is conducive to productive growth of suitable pulpwood species;
- whether pulpwood plantations have been successfully grown on soils similar to those on the farm;
- the profitability of growing the pulpwood crop in relation to other forms of farm-forestry and existing crops;
- whether there will be any benefits from integrating trees into the farm, such as land conservation or stock or crop shelter.

Climate

The site requirements and limitations discussed in this section are relatively general. Booth and Pryor (1991) provide a broad summary of the climatic requirements of the main pulpwood species (Table 12.2).

Plantation productivity is strongly affected by climatic conditions, in particular the gross water balance of a site and extremes of temperature. The overall water balance of a site can be estimated from the rainfall (supply) and the pan evaporation (demand) to provide an index of climatically available water. This is illustrated in Figure 12.2, for *E. globulus* plantations, across south-west Western Australia. Although there are clear increases in growth with increasing rainfall, productivity also decreases with increasing evaporative demand.

A key climatic feature of any area is the frequency and severity of droughts. Other important aspects of climate include the frequency of extreme temperatures, especially frosts. Some degree of frost tolerance can be obtained through species selection. For example, *E. nitens* is more

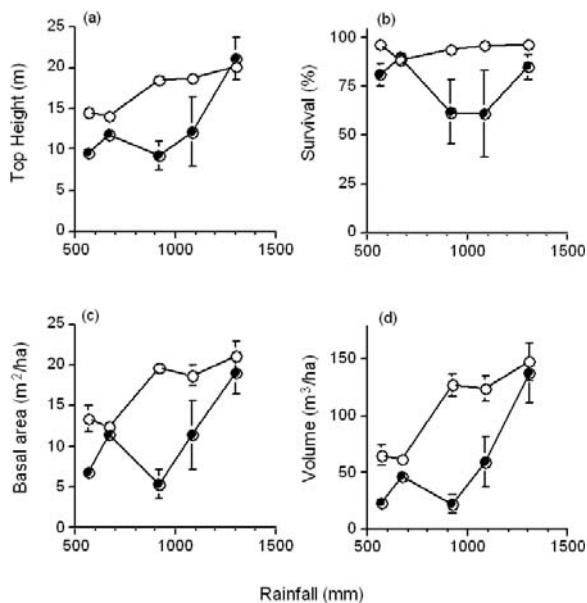


Figure 12.2: Performance of six-year-old *E. globulus* planted on farmland across south-west Australia, in relation to rainfall and pan evaporation (Harper *et al.* 1999). Although there are large increases in growth with increasing rainfall, they are affected by evaporation. ○ <math><1500</math> mm, ● >1500 mm total annual evaporation.

frost-tolerant than *E. globulus* (Table 12.2). As a starting-point, it is reasonable to assume that in areas where significant plantations have been established, climatic risk analysis has been undertaken and the region has been deemed suitable for the planted species.

The risk of serious damage to plantations from wide climatic variations such as droughts and storms should be considered. The frequency and severity of droughts is generally assessed on the basis of previous rainfall patterns, however, many studies suggest that Australia's climate will change in the future (CSIRO and Australian Bureau of Meteorology 2007). The projections of future climate change are general but it is likely that a reduction in rainfall will be among the major changes across some pulpwood regions. It is also likely that the frequency and severity of other weather events such as storms will also change. Given the influence of rainfall on yield and tree survival, it is reasonable to assume that climate change will reduce yield and increase the risk of droughts and other extreme events.

Soils and landscapes

Site selection

Broad suitability of the farm

For areas in which a farm-forestry industry already exists, a preliminary step to establishing a pulpwood plantation is to determine if the soils and landforms of the farm are broadly suitable. Many regions of Australia have soil landscape mapping at scales of 1:100 000 to 1:250 000, which will provide a basis for determining broad suitability by comparing the location of existing plantations with those of the farm. A formal approach of using soil- and landscape-level data is described by Harper *et al.* (2005).

Farm planning considerations

Once a decision has been made that a property is broadly suitable for pulpwood, there are several considerations as to where the pulpwood plantation should be placed. These include planning and design considerations.

- Land zoning – are there any local government regulations that relate to the establishment or harvesting of trees?
- Are there any easements and encumbrances on the property, such as mineral rights, road reserves or native title claims?
- Are there any licensing requirements for trees in terms of accessing water?
- Does the area contain remnant natural vegetation? In many areas, clearing of remnant native vegetation is not allowed.
- What is the location of the plantation in relation to farm infrastructure such as buildings, fence-lines and services such as powerlines, phone cables, gas and water pipes?
- What are the likely environmental benefits of the plantings? For example, protection of creek lines from water erosion and provision of wind protection for specific paddocks.
- Can tree growth be enhanced by taking advantage of the movement of fresh water through the landscape, such as in lower landscape positions above seeps or as contour plantings? Waterlogged and saline sites must be avoided.
- Are there any considerations for harvesting and management? Although some areas may pro-

duce a profitable plantation there may be issues with harvesting, such as on sites with steep slopes or where roads have to be built to extract the timber. Such areas should be identified prior to planting and future costs taken into account in estimates of likely profitability. Approvals may be required to haul timber on certain roads.

Soils

There are many examples of pulp-plantations failing or performing poorly due to unfavourable soil conditions, even in regions where a plantation industry has been established. Typical reasons for failure include subsoils that tree roots cannot readily penetrate, resulting in insufficient soil water-holding capacity to survive droughts. Other causes of failure are saline soils, saline groundwater and soils with low strength, which can lead to wind-throw problems.

Some of these soil conditions may result in poor growth or enhanced susceptibility to pests and diseases, rather than death. Poor growth may also result from nutrient deficiencies or inhospitable subsoils, particularly those that are poorly drained, acidic or sodic. While not all failed or poorly performing plantations are due to soil conditions, identifying problematic sites prior to planting is a proven way of reducing the risks of pulpwood production and allowing the targeting of species and site treatments to where they are better suited.

It is essential to examine soils at the sites broadly considered suitable for a plantation. This process has two main steps:

- soil mapping, which identifies the different soils and their distribution;
- interpreting how soil properties will affect pulpwood plantation yield and the management inputs required. Local knowledge of the likely response of the trees to soil properties can be useful at this stage.

There are three possible responses to this process:

- avoidance of particular areas, such as where the soil limitations cannot be economically modified and productivity or survival will be poor;

Table 12.4: Key soil and hydrological properties that affect tree growth

Observation	How measured	Details	Management response
Soil depth	Auger Backhoe pit	Provides an assessment of the total water-holding capacity of site. Depth of rooting can be impeded by: bedrock and stone-lines; pedogenic hardpans (e.g. silcrete, ferricrete, laterite); soil structure; waterlogged layers and chemical barriers (e.g. extremes of pH, high Al concentrations)	Avoid planting sites <2 m deep unless root limitation is caused by hardpan which can be disrupted
Soil pH		Plant performance can be affected by extremes of pH	Extremes of pH can affect root growth and nutrient availability. High pH (alkaline) soils can have Zn, Mn deficiencies. Low pH (acid) soils can have Al toxicity.
Waterlogging		Interpretation via site position (e.g. flat areas). Soil colours can provide some clues to the likelihood of waterlogging, but Australian soils are often very old and these colours may be relict from previous climatic conditions. Dark colours near soil surface generally indicate sites that are more productive. Mottling of subsoils may indicate seasonal waterlogging. Gleyed colours	Waterlogging of long duration can affect tree growth and survival.
Soil salinity	Soil sample EM38		Avoid planting the site. Salt-tolerant species may be planted, but they may not be accepted in the market
Groundwater hydrology	Piezometer and dipwells, if available. Regional groundwater reports	Key factors are the salinity, depth of groundwater and trajectory of groundwater (e.g. rising or falling)	
Nutrient deficiencies	Soil sample for macronutrients. Plant sample from pastures for micronutrients		Apply fertilisers, where required. Consider cost in terms of whole rotation budget

- rectification of soil limitations prior to planting, such as by applying fertilisers or ripping hard layers in the soil;
- planting the site anyway, recognising that yield will be lower and that the risks of failure are higher.

Soil mapping

Although a farm forester may not be able to utilise the site evaluation technologies used by large

plantation companies, a backhoe examination at representative points across a site is highly recommended. Methods of soil mapping are described in several publications, with Gunn *et al.* (1988) providing an excellent overview for Australian conditions. A chapter by Murtha (1988) provides good pointers on interpreting different soil features in terms of their likely effect on plant performance. Various soil and forestry consultants can also provide this service, but they must have a

proven understanding of soil requirements for successful plantations.

Soil surveys have been undertaken across broad areas of rural Australia but often at scales (1:100 000 to 1:250 000) that are unsuitable for farm management. At a scale of 1:100 000, for example, 1 cm² on the map represent 100 ha on the ground. Another limitation is that soil surveys are often undertaken with agricultural uses in mind and are thus confined to inspections of the surface 20–50 cm. Evaluation of a site for farm forestry needs to consider soils to depths of at least 1–3 m. It is always necessary to examine a site in detail before committing to the significant investment of a pulp plantation.

Despite their limitations, existing surveys serve a useful purpose in that they allow the broad comparison of soils across a district. For example, if a successful plantation occurs within a certain mapping unit in one area, it is likely that, given a similar rainfall and other climatic conditions, similar results will occur on the same soil unit elsewhere in the district. Such surveys are also useful in determining the broad suitability of a district for a plantation scheme (Harper *et al.* 2005).

The common method of preparing a soil map is to use a relatively large-scale (1:10 000 to 1:20 000) aerial photo as a base. The colours and tones of the photo can help interpret the ground conditions. Observations are made of the soil at different points across the proposed plantation area, aimed at identifying likely limitations to growth (Table 12.4).

Interpreting the soils

Soil observations and their interpretations are presented in Table 12.3. Soil factors affect tree growth in a number of ways, with some important at establishment and others important later in the rotation. The factors can be broadly grouped as follows:

- soil factors affecting young trees (e.g. waterlogging, nutrient supply);
- soil factors that are important during extreme events (e.g. flooding, wind-throw, drought);
- soil and site factors that become important after a plantation has been established (e.g. groundwater rise, lack of accessible soil volume, depletion of nutrients over time).

In simple terms, the aim of site assessment is to determine whether the site will provide adequate amounts of water to the trees during their

growth, in particular whether there is sufficient accessible water storage to allow tree survival during annual or periodic droughts. The site assessment should provide information on particular nutrient limitations and detail specific site hazards. For example, in some areas of southern Australia the presence of high boron levels can be problematic; in other areas, such as the subtropics, it may be limiting.

Water

The major factor controlling the growth of pulpwood plantations in Australia is the availability of water. The accessible water storage capacity of the soil is critical, particularly in regions with summer drought. For this reason, shallow soils (e.g. <2 m deep) or soils where deeper access to roots is limited are generally avoided. Soil volume is constrained by the occurrence of bedrock or hard pans within the soil. Common examples of hard pans include those that have formed from ironstone, humus or calcrete. Soil acidity can be regarded as a ‘chemical pan’ in that roots will be constrained by acidic layers.

Seasonal surface waterlogging can pose a problem for some species. This can be identified from landscape position and soil properties such as upper soil bleaching, and subsoil gleying and mottling. Waterlogging can be partially overcome on some sites by drainage and mounding. Trees can sometimes obtain water directly from groundwater, as long as it is fresh and occurs within about 6 m of the surface (Benyon *et al.* 2006).

Highly saline groundwaters can cause dryland salinity. Most pulpwood species, including Tasmanian blue gum, are quite susceptible to salinity and will suffer reduced growth rates and possibly death (Bennett and George 1995). It is relatively easy to identify salinised areas through visual observation, soil analysis or the use of an electromagnetic induction meter such as an EM38. In districts where salinity is known to be a problem, advice will be required on the likely depth and salinity of groundwater systems to determine whether this will affect the plantation’s performance.

Nutrients

Although Australian soils are naturally infertile, farming practice has overcome this through the application of fertilisers that include phosphorus

and trace elements, or through the use of leguminous pastures for nitrogen. The nutrient requirement of many plantation species is generally lower than that of agricultural crops and pastures, so pulpwood plantations established on farmland usually have sufficient residual nutrients from the previous farming enterprise. There are circumstances where nutrients are limiting, particularly on sandy or low organic matter soils. Phosphorus deficiencies can be identified through soil analysis but, unlike agricultural systems, the values may not have been well calibrated against plant response. There are no reliable soil tests for trace elements important to tree growth.

Yield prediction

Two main approaches are used to predict the yield of pulpwood plantations:

- 1 empirical models or yield tables, based on prior measurements of trees;
- 2 process-based models, such as 3PG (Landsberg and Waring 1997) and CABALA (Sands *et al.* 1999; Battaglia *et al.* 2004) that integrate climate and soil conditions.

Growth rates are clearly important, but final yields are determined by the carrying capacity of the site. As described in Chapter 9, the height potential of a forest on a particular site is governed by the soil and climate. The potential to achieve rapid early growth does not necessarily indicate a high-productivity site since many factors may become limiting in the later part of the rotation. Cleared farmland has invariably accumulated water and nutrients, which can enhance early growth and may give a false impression of the site's true productivity in the longer term.

Unfortunately for the farm forester, there are limitations with both approaches. Yield tables may not have been developed for the region, or may not be publicly available. Process-based models, on the other hand, require detailed information and expert skills. Broad estimates of a site's productivity can be gauged from existing plantations in the area and from discussions with forestry company staff and harvesting contractors.

Commercially valuable information may be more readily available to farm-foresters who are prepared to enter into marketing agreements with

forestry companies. In all regions, managed investment scheme companies produce public disclosure documents to raise funds. These often contain information on likely growth rates.

The productivity of a pulpwood plantation is commonly described by calculation of the annual wood volume increment. Mean annual increment (MAI) is the total standing volume of the plantation divided by its age ($\text{m}^3/\text{ha}/\text{yr}$). Current annual increment (CAI) is the actual increase in volume that occurs in a particular year ($\text{m}^3/\text{ha}/\text{yr}_x$).

The CAI increases rapidly as the plantation dominates the site then declines almost as quickly as height growth slows and competition between trees reduces stand basal area increment (Figure 12.3). In some cases the CAI can fall very rapidly, particularly on ex-pasture sites with restricted soil accessibility or depth. The trees initially grow rapidly, utilising stored soil moisture from below the rooting depth of pasture species. When further root expansion is restricted the plantation becomes dependent on rainfall. Such plantations are commonly said to have 'hit the wall': total plantation leaf area falls dramatically, growth rates drop accordingly, pest and disease issues become more evident and drought deaths are more common.

Because the MAI is the average of the total volume growth over the full age of the plantation, it lags behind the CAI, peaking only when the CAI falls below the MAI. The comparative site quality is commonly defined by the height of the plantation at a particular age (e.g. 10 years). On a higher-quality site the maximum MAI tends to occur at a later age. Assuming the pattern of growth is similar in subsequent rotations, harvesting when the CAI is equal to the MAI would maximise productivity from successive rotations. These concepts are illustrated with data from *E. globulus* plantations in south-east Australia (Figure 12.3).

Site and stand management

Site preparation

Cultivation

The main types of cultivation are ripping, mounding and scalping. Ripping is used to disrupt compacted layers and hardpans that may represent a barrier to root development and thus root access.

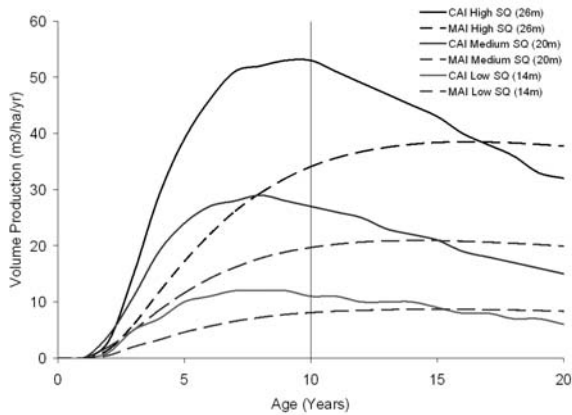


Figure 12.3: Modelled growth patterns for *E. globulus* plantations growing on a range of site qualities based on trials (all >15 years old) in South Australia. Site quality is defined by the dominant height of the plantation (m) at age 10 years. (Wong *et al.* 2000, p. 45).

Compacted layers include those developed as a result of livestock and machinery movement, whereas hardpans occur naturally in the soil. Examples include ironstone, calcrete and coffee-rock. In some cases these occur too deep within the soil profile (e.g. >60–100 cm) to be disrupted economically. Ripping can also make it easier to plant seedlings with hand tools.

Mounding is mainly used to alleviate seasonal waterlogging and as an adjunct to weed control. The mounds may be up to 50 cm high along the planting rows, which are usually about 4 m apart. Mounding may be preceded by ripping if a hardpan has been identified, although ripping and mounding are usually done in the same pass. Where possible, mounds should be established across slopes on the contour to avoid concentrating water and causing soil erosion.

Scalping is used in some circumstances, such as where herbicides cannot be used. It involves the displacement and removal of the top 15–20 cm of the soil. Seedlings are planted into the exposed subsoil. Scalping can aid the penetration of water in non-wetting soils. Because most nutrients are concentrated near the soil surface, scalping can result in early nutrient deficiencies.

Weed and pest control

A major factor in successfully establishing a plantation on farmland is weed and pest control. The farming systems in areas where most pulpwood

plantations have been established traditionally relied on annual or perennial pastures involving a range of improved species such as clovers and grasses. The pastures include a range of weed species. As plantation establishment involves small seedlings, it is imperative that these be planted into a weed-free environment. This is usually achieved through a combination of cultivation and herbicide application. Herbicides are mostly applied in the first year and occasionally again in the second year of growth, after which canopy closure usually suppresses weed growth. The rates and timing of application of specific herbicides should be consistent with permitted uses (as per the label or any off-label permit) and may vary according to the local weed population, tree species being planted (or planted), soil properties and climate. Specific advice will be required.

Continuous monitoring of tree growth and health is important in pulpwood plantations. The efficiency of mechanical harvesting operations is reduced if survival and growth is uneven and the trees are malformed or heavily branched. Pests and diseases can affect survival, uniformity of growth and tree form at almost any stage of development. In *E. globulus* plantations, beetles, magpies, rabbits, hares, stock and wallabies can destroy newly planted seedlings. Sap-sucking and leaf-eating insects can stunt growth during the juvenile leaf phase, setting back the time of canopy closure. Parrots and koalas may damage the main stems, inducing multi-leaders, and wood borers may attract cockatoos that can seriously damage mature trees (Ritson 1995). The application of specific pesticides requires specific advice. A range of tactics can be used to control grazing animals, including fencing; parrots can be scared by various devices used by orchardists. If the damage is noted early it may be possible to reduce the impact by replanting, pruning or thinning the stand.

Planting

Planting stock should be sourced from reputable nurseries and should originate from the most advanced genetic material available. Genetically improved seed from commercial seed orchards is available for *E. globulus*, *E. nitens*, *E. dunnii* and *E. grandis*.

Seedlings are planted into prepared ground in early winter in southern Australia on frost-free

sites, and in spring on frost-prone sites. In subtropical and tropical climates planting is recommended early in the wet season. Seedlings are commonly planted at around 2 m intervals within the cultivated rows, spaced at around 4 m intervals, to produce an initial planting density of 800–1250 stems/ha. Stocking is generally lower on drier sites and higher on moister sites.

The optimal stocking for a site depends on a number of factors including climate and local soil conditions. High densities are often used with the aim of quickly achieving canopy closure, making maximum use of a site's resources and controlling branch development. Higher planting rates are also used in higher-rainfall parts of the subtropics where early site capture is important for weed control. This has to be balanced against whether the early growth advantage is maintained to the end of the rotation, and the extra cost associated with harvesting extra stems. Similarly, setting up large tree canopies early in the rotation can predispose a plantation to more risk from a fluctuating climate. Farmers may find that the research required to determine the optimal rate of stocking for a particular locale has either not been done, or is not within the public domain.

Fertilisation

The major nutrients that are likely to be required by pulpwood plantations include the macronutrients, nitrogen and phosphorus, and trace elements copper and zinc. These nutrients are often applied in agricultural systems or, in the case of nitrogen, derived from the N-fixation of pasture plants. Many pulpwood plantations, established on farmland, will not require any fertilisation. There are exceptions to this rule, such as:

- where the farmland has been poorly managed and nutrient applications have been erratic;
- for soils where nutrients have been leached, converted to unavailable forms (particularly for phosphorus) or pasture plants have failed to grow and fix enough nitrogen.

Nutrient status can be monitored in the first two to three years by analysing nutrient concentrations in foliar samples (Dell *et al.* 2001). The ongoing management of nutrients through the pulpwood rotation and into subsequent rotations has been

considered in several studies (Grove *et al.* 2001). As with other aspects of pulpwood plantation management, the results are location-specific and depend on how the site is managed.

The total harvesting of biomass, as in some harvesting systems, or use of waste as a bioenergy feedstock removes considerably more nutrients than harvesting the woody stems alone. This is because the nutrient content of leaves and bark is much greater than that of wood. These removals, and their replacement, should be considered when budgeting costs for these systems.

Stand management

Pulpwood plantations typically require little work after the first two years. Ongoing monitoring to identify problems such as insect attack or nutrient deficiency, plus maintenance of firebreaks, will be required. Growth rates should be regularly measured to monitor performance, plan harvesting operations and aid in negotiations with potential buyers. Information on how to accurately determine the plantation area and total wood volume is provided elsewhere in this book.

In many cases, sheep are grazed in the plantations once the trees are well out of their reach. Grazing is a useful means of reducing fuel load, keeping the firebreaks open and controlling weeds. Grazing with cattle is less common as there is a risk they might damage the trees, even in older plantations. Even so, cattle-grazing is often used in the subtropics.

Although thinning of any form is rarely practised by industrial pulpwood growers, there may be some advantages to small growers if they cull multi-stemmed or deformed trees early in the rotation in order to concentrate growth on single-stemmed trees. Thinning may also be warranted if the stocking rate is too high to allow the trees to achieve the optimum diameter for the harvesting equipment that is likely to be used.

Harvesting

The optimal harvest age for a pulpwood plantation depends on factors other than simply the annual volume production. For example, the density of the wood produced by the tree at any point on the stem tends to increase as the tree matures. Older plantations therefore have a higher average wood density

and higher value per cubic metre if the logs are sold on the basis of dry weight or pulp yield.

Older plantations may also be more viable to harvest given the higher total volume that is available to offset the fixed costs of preparing for harvesting – the costs of preparing harvesting plans, obtaining approvals, negotiating with contractors, roading and moving equipment onto the site. Since each tree needs to be felled and debarked, increasing tree size results in greater harvesting efficiencies.

The choice of harvest time will be a judgement that balances total volume, expected future growth rates, opportunity, interest rates, wood prices, regional demand, contractor availability and risk.

Two main approaches are used for pulpwood harvesting: harvesting and transport to a central chipping facility on log trucks, or in-field debarking and chipping then carting to a mill or export facility. Private growers may have little influence over the method or timing of the harvest, as the company buying the wood will conduct the operation. It is important for the grower to be able to negotiate a favourable time and price and reach agreement as to who is responsible for access and roading and the post-harvest condition of the site. Growers entering into a one-off sale should consider a legal contract of sale or even engage their own harvesting consultant or broker to oversee the operation.

Pulpwood sales are generally based on the weighbridge measurements of logs or chips recorded at the port or mill door. Although the weight of a cubic metre of freshly cut young plantation wood is close to 1 tonne, the dry weight of the wood may only be around 600 kg/m³. Because growers are paid on the basis of weight, the moisture content of timber affects the price. It is therefore important that the trees are transported to the mill as soon as possible after harvesting, particularly during periods of hot dry weather.

Buyers and harvesting contractors prefer to harvest larger areas to achieve efficiencies and may only be willing to move into relatively small private plantations if they are working in the local area or larger plantations are unavailable. An important consideration for independent pulpwood growers is the ease of access and the quality of the local road network. If a site is accessible during wet weather due to its location or soil type, this may be a dis-

tinct advantage as contractors may be short of work at that time.

Due to the fixed costs of planning a new harvesting operation and moving large harvesting equipment and building the necessary roads and loading areas, the viability of a pulpwood harvesting operation often hinges on the available wood volume. Growers wishing to stagger their harvest to maintain non-timber values, such as shelter or recharge control, need to carefully consider how they will ensure harvest viability for each operation. Typically, a minimum of 1000 m³/ha is required for a viable harvesting operation. There are also lower limits to the amount of wood removed per hectare for viable operations, which can vary with terrain and thus equipment types needed. Specific advice will be required from harvesting contractors.

Coppicing and removal

Following harvest, there are three possible decisions that can be made with the pulpwood plantation.

- 1 Replant the site. This may be preferred where plantations have performed poorly due to poor initial stocking or poor genetic material, and better material is available.
- 2 Coppicing. Following harvest, several stems can resprout from the stump and some of these can form the next rotation. Coppicing may be a viable option for good-quality sites, and may be cheaper than replanting in terms of avoiding costs of cultivation, herbicides and seedlings. There is, however, labour cost associated with reducing the numbers of stems on each stump.
- 3 Revert to farmland. This may be preferred on sites which have yielded poorly, or if the profitability of the farming system is likely to be greater than another rotation of pulp logs and the other benefits from trees are no longer considered important.

Replanting involves killing the stumps and removing or burying them, followed by replanting with new seedlings.

If coppicing is the chosen option, the harvesting operation has to protect the stool (stump) from excessive damage, particularly stripping of bark (Archibald *et al.* 2002). Other issues include the harvesting season, stool height and trash management. Generally one to three stems per stool are

retained. Some studies suggest there is poorer overall growth with more stems and harvesting costs are higher due to the need to handle more stems, each generally of smaller size. The optimum regime for a particular species and area will depend on local research results.

The reversion of pulpwood plantations to farmland has occurred on some small areas (Archibald and Watt 2002) which produced poor first-rotation yields. The costs of removing live stumps can be high; an alternative approach is to kill the stumps to prevent coppicing and leave for several seasons while the stumps and root systems decay. Grazing can occur during this time but the stumps may make pasture renovation difficult. The stumps can be left to decay or removed later when partly decayed.

Conclusion

This chapter has described the growth and management of pulpwood crops on farms. The major issues that landowners need to consider before investing in pulpwood crops are whether there is an accessible market or one likely to develop during a rotation. The ultimate success of the pulpwood planting depends on adequate evaluation of site (soil and climate) conditions and correct matching of species to site.

As a large hardwood plantation resource has developed in Australia, a number of processing options and markets are emerging. For example, efforts to mitigate climate change may result in the emergence of markets for carbon credits and bioenergy, while the collateral environmental benefits of the pulpwood planting may attract environmental service payments for water or biodiversity protection.

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References

Archibald R and Watt P (2002) 'Resuming agriculture after a bluegum plantation'. Western Aus-

tralian Department of Agriculture. Farm Note no. 62/2002.

- Archibald R, Little K and Harper RJ (2002) 'Managing bluegum (*Eucalyptus globulus*) coppice'. Western Australian Department of Agriculture. Tree Note no. 35.
- Bari MA, Mauger GW, Dixon RNM, Boniecka LH, Ward B, Sparks T and Waterhouse AM (2004) 'Salinity situation statement: Denmark River'. Department of Environment, WA. Water Resource Technical Report no. WRT 30.
- Bartle JR (2001) New perennial crops: Mallee eucalypts – a model, large scale perennial crop for the wheatbelt. In *Managing Agricultural Resources. Proceedings of Outlook Conference 2001*. Canberra, ACT. pp. 117–128. ABARE, Canberra.
- Bartle JR and Shea S (1989) Development of a pulpwood cropping industry in Western Australia. *Land and Water Research News* 1, 5–9.
- Battaglia M, Sands P, White D and Mummery D (2004) CABALA: a linked carbon, water and nitrogen model of forest growth for silvicultural decision support. *Forest Ecology and Management* 193, 251–282.
- Bennett DL and George RJ (1995) Using the EM38 to measure the effect of soil salinity on *Eucalyptus globulus* in south-western Australia. *Agricultural Water Management* 27, 69–86.
- Benyon RG, Theiveyanathan S and Doody TM (2006) Impacts of tree plantations on groundwater in south-eastern Australia. *Australian Journal of Botany* 54, 181–192.
- Booth TH and Pryor LD (1991) Climatic requirements of some commercially important eucalypt species. *Forest Ecology and Management* 43, 47–60.
- Cannon T, Pask G and Jessup D (2006) The EcoAsh™ marketing journey. In *Proceedings of Australian Forest Growers Conference*. 22–25 October, Launceston, Tas.
- CSIRO and BOM (2007) 'Climate change in Australia'.CSIRO and Bureau of Meteorology, Canberra. Technical Report 2007.
- Dell B, Malajczuk N, Xu D and Grove TS (2001) 'Nutrient disorders in plantation eucalypts'. ACIAR Monograph no. MN74.
- Department of Conservation and Land Management (2002) 'Growing Tasmanian blue gum for pulpwood: the profit potential in the greater

- than 600 mm rainfall zone'. Western Australian Department of Agriculture, Tree Note no. 28.
- Gifford RM (2000) 'Carbon contents of above-ground tissues of forest and woodland trees'. Australian Greenhouse Office, Canberra. National Carbon Accounting System Technical Report no. 22.
- Grove TS, O'Connell AM, Mendham D, Barrow NJ and Rance SJ (2001) 'Sustaining the productivity of tree crops on agricultural land in south-western Australia'. Rural Industries Research and Development Corporation, Canberra. Publication no. 01/09.
- Gunn RH, Beattie JA, Reid RE and van de Graaff RHM (1988) *Australian Soil and Land Survey Handbook: Guidelines for Conducting Surveys*. Inkata Press, Melbourne.
- Harper RJ, Edwards JG, McGrath JF, Reilly TJ and Ward SL (1999) Performance of *Eucalyptus globulus* plantations in south-western Australia in relation to soils and climate. In *Balancing Productivity and Drought Risk in Blue Gum Plantations*. 9–10 November, Karri Valley Resort, Pemberton, WA. (Ed. DA White). CSIRO Australia.
- Harper RJ, Smettem KRJ and Tomlinson RJ (2005) Using soil and climatic data to estimate the performance of trees, carbon sequestration and recharge potential at the catchment scale. *Australian Journal of Experimental Agriculture* **45**, 1389–1401.
- Harper RJ, Beck AC, Ritson P, Hill MJ, Mitchell CD, Barrett DJ, Smettem KRJ and Mann SS (2007) The potential of greenhouse sinks to underwrite improved land management. *Ecological Engineering* **29**, 329–341.
- Hicks CC and Clark NB (2001) 'Pulpwood quality of 13 eucalypt species with potential for farm forestry'. Rural Industries Research and Development Corporation, Canberra. Report no. AFT 01–164.
- Ilic J, Boland D, McDonald M, Downes G and Blakemore P (2000) 'Woody density phase 1: state of knowledge'. Australian Greenhouse Office, Canberra. National Carbon Accounting System Technical Report no. 18.
- Inions G (1991) Relationships between environmental attributes and the productivity of *Eucalyptus globulus* in south-west Western Australia. In *Productivity in Perspective. Proceedings of 3rd Australian Forest Soils and Nutrition Conference*. Melbourne, Vic. (Ed. PJ Ryan) pp. 116–132. Forestry Commission of NSW, Sydney.
- Inions GB (1992) Studies on the growth and yield of plantation *Eucalyptus globulus* in south west Western Australia. PhD thesis. University of Western Australia.
- Landsberg JJ and Waring RH (1997) A generalized model of forest productivity using simplified concepts of radiation-use efficiency, carbon balance and partitioning. *Forest Ecology and Management* **95**, 209–229.
- Malajczuk G, Morrison D, Havel J, Anderson G and Moore R (1984) 'An economic study of agroforestry in the Manjimup region, Western Australia'. Forests Department of Western Australia, Perth. Technical Paper no. 10.
- Mauger GW, Bari M, Boniecka L, Dixon RNM, Dogramaci SS and Platt J (2001) 'Salinity situation statement: Collie River'. Water Resources Commission. Water Resource Technical Report no. WRT 29.
- Murtha GG (1988) Soil properties and soil performance. In *Australian Soil and Land Survey Handbook: Guidelines for Conducting Surveys*. (Eds RH Gunn, JA Beattie, RE Reid and RHM van de Graaff) pp. 241–257. Inkata Press, Melbourne.
- Parsons M, Gavran M and Davidson J (2006) *Australia's Plantations 2006*. Bureau of Rural Sciences, Department of Agriculture, Fisheries and Forestry, Canberra.
- Peck AJ and Hatton TJ (2002) Salinity and the discharge of salts from catchments in Australia. *Journal of Hydrology* **272**, 191–202.
- Peck AJ and Williamson DR (Eds) (1987) *Hydrology and Salinity in the Collie River Basin, Western Australia*. Elsevier: Amsterdam.
- Polglase PJ, Paul KI, Khanna PK, Nyakuengama JG, O'Connell AM, Grove TS and Battaglia M (2000) 'Change in soil carbon following afforestation or reforestation'. Australian Greenhouse Office, Canberra. National Carbon Accounting System Technical Report no. 20.
- Prinsley R (Ed.) (1991) *The Role of Trees in Sustainable Agriculture*. Albury, NSW. Bureau of Rural Resources, Department of Primary Industries and Energy.

- Ritson P (1995) 'Parrot damage to bluegum tree crops. A review of the problem and possible solutions'. Western Australian Department of Agriculture, Perth. Resource Management Technical Report no. 150.
- Sands PJ, Rawlins W and Battaglia M (1999) Use of a simple plantation productivity model to study the profitability of irrigated *Eucalyptus globulus*. *Ecological Modelling* **117**, 125–141.
- Sartori F, Lal R, Ebinger MH and Parrish D (2006) Potential soil carbon sequestration and CO₂ offset by dedicated energy crops in the USA. *Critical Reviews in Plant Sciences* **25**, 441–472.
- Schuck S (2006) Biomass as an energy source. *International Journal of Environmental Studies* **63**, 823–835.
- Shea SR and Bartle JR (1988) Restoring nature's balance: the potential for major reforestation of south western Australia. *Landscape* **3**, 3–14.
- Shea SR and Hewett PJ (1997) The development and future potential of tree crop industries on farmlands in Western Australia. In *New Zealand Forest Research Institute, 50th Jubilee Forestry Celebration Day*. Rotorua, New Zealand.
- Snowdon P, Eamus D, Gibbons P, Khanna P, Keith H, Raison J and Kirschbaum M (2000) 'Synthesis of allometrics, review of root biomass and design of future woody biomass sampling strategies'. Australian Greenhouse Office, Canberra. National Carbon Accounting System Technical Report no. 17.
- Wong J, Baker T, Duncan M, McGuire D and Bulman P (2000) 'Forecasting growth of key agroforestry species in south-eastern Australia'. Rural Industries Research and Development Corporation, Canberra. Publication no. 00/68.
- Wood WE (1924) Increase of salt in soil and streams following destruction of the native vegetation. *Journal of the Royal Society of Western Australia* **10**, 35–47.
- Wood M, Stephens N, Allison B and Howell C (2001) *Plantations of Australia: A Report from the National Plantation Inventory and the National Farm Forest Inventory of Australia*. National Forest Inventory, Bureau of Rural Sciences, Canberra.

Trees in grazing systems

Rowan Reid

Introduction

There are more than 400 million ha of agricultural grazing land in Australia, spread from the wet tropic plains to the temperate alpine grasslands. The vast majority is managed as rangeland running low-intensity grazing operations based on native grasses, trees and shrubs. Trees and shrubs have always played an important role in supporting rangeland farming systems by providing emergency drought fodder, critical shelter for stock, replenishing soil organic matter and fertility, and protecting soils from wind and water erosion.

Although there are many native pasture species that are well-adapted to Australia's unique climate and soils, few have proved suitable as a basis for the development of intensive grazing systems in the more productive regions. The introduction of phosphate fertilisers, new plant varieties and intensive management options has seen native pastures replaced by exotic pasture species on about 40 million ha of farmland in the medium to high rainfall areas. After the Second World War, grazing systems research and development focused on forage conservation, supplementary feeding, nitrogen-fixing pasture species, irrigation and improved grazing management. In this new grazing landscape, trees were largely regarded as an impediment rather than an asset.

This changed in the 1980s. Rather than focusing on pasture productivity at the paddock scale, scientists and farmers lifted their gaze to consider

the whole farm and even looked over the boundary fences to consider catchment-scale issues such as salinity and biodiversity. This was reflected in the rise of whole farm planning, Landcare groups and the recognition of the impact of exposure on animal production and welfare. There was also an imperative to look further into the future and question the sustainability of agricultural production and the environmental assets that underpin farming and the communities that depend on it.

In 1991, the Bureau of Resources sponsored a national conference at Albury, titled 'The role of trees in sustainable agriculture' (Anon 1991). Drawing together farmers, scientists, extension agents and policy-makers from across Australia, this important gathering explored the role of trees in controlling land degradation, sheltering crops and stock, providing supplementary fodder and diversifying farm production. The conference recognised that there was a need for trees on farms and a potential for trees and shrubs to enhance production and sustainability of farming systems. There was also a need for more research, more practice and more thought as to how farmers might integrate trees into their farming systems for both conservation and profit.

After the Albury conference, research on trees and shrubs in agricultural landscapes increased dramatically. Rather than demonstrating that all trees on farms were good, the results underlined the importance of careful design and strategic management of revegetation in order to balance

the positive and negative impacts of trees on farm productivity and environmental integrity. The application and innovation by farmers was to become as important as the research effort in developing and extending practical tree-growing techniques and designs for grazing systems.

This chapter reviews our understanding of the impact of trees on pasture and animal production, then explores the integration of multi-purpose tree growing into a farming landscape.

Pasture production near trees

Trees compete with pasture for light, moisture and maybe even nutrients. Any increase in the number (or size) of trees growing across a pastured paddock tends to result in a reduction in the pasture yield. Kingma (1974), for example, developed joint production functions for native white cypress pine (*Callitris glaucophylla*) and pasture production systems in central New South Wales (Figure 13.1) which clearly demonstrated that increasing timber production came at a cost to agricultural production. There was no obvious gain in animal production at any level of tree cover. Kingma showed that increasing inputs, such as fertilisation, increases both agricultural production and tree growth but did not change the inherently competitive relationship.

A long history of research trials and field observation involving the combined production of pruned *Pinus radiata* and pasture in New Zealand has allowed researchers to develop a robust under-

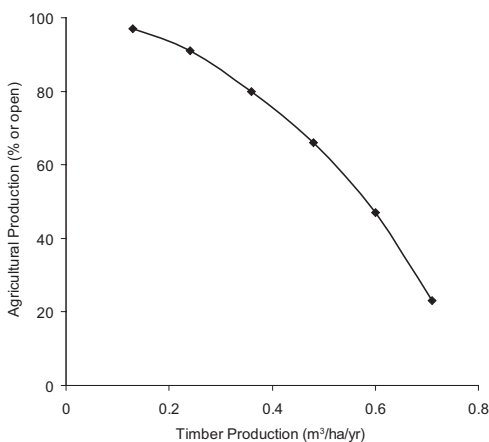


Figure 13.1: A joint production function for cypress pine and agricultural production from pasture (Kingma 1974).

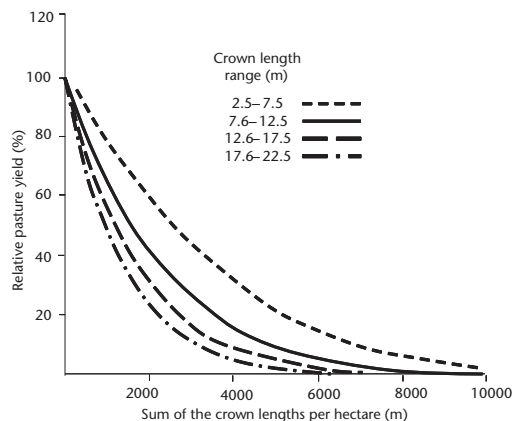


Figure 13.2: A joint production function for pruned *Pinus radiata* and pasture in New Zealand (Percival and Knowles 1986).

standing of the interactions between the two. Percival and Knowles (1986) presented their joint production function as a relationship between the crown characteristics of the trees and pasture production as a percentage of that achieved in an open paddock (Figure 13.2). Again, the relationship suggests direct competition between the trees and pasture across the range of possible options.

Australian research with *Pinus radiata* has shown similar relationships with increasing tree stocking and age. Early trials in Western Australia (Anderson and Batini 1983) involved thinning and pruning a 13-year-old plantation and undersowing new pasture. By age 15 years, when the remaining trees had begun to take advantage of the available growing space, pasture yields under stocking rates of 143 and 261 stems/ha were 84% and 68% of open pasture respectively.

Where *Pinus radiata* has been planted directly into pastures and managed for clearwood timber, the pruning and thinning debris become a major factor affecting pasture production (Anderson and Moore 1987). At the large Tikitere agroforestry trial in New Zealand, researchers did not remove the debris resulting from silvicultural treatments that culled 75% of the initial stocking and involved pruning the retained trees up to 6 m. Annual pasture production measurements showed fluctuations in pasture production during this silvicultural phase (Knowles *et al.* 1993). Pasture production fell immediately after each thinning and pruning operation, recovering slowly as the debris decomposed (Figure 13.3).

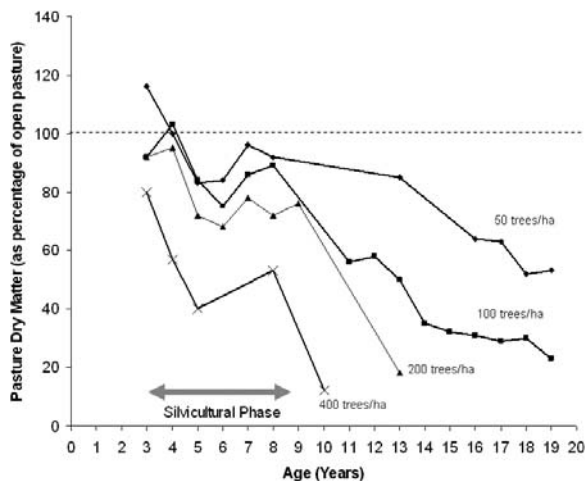


Figure 13.3: Pasture dry matter production under widely spaced and pruned *Pinus radiata* at the Tikitere agroforestry trial near Rotorua in New Zealand (Knowles *et al.* 1993).

If the debris can be removed from the site, pasture production can be maintained at a higher level for much longer into the rotation. Alternatively, higher pasture production levels could be sustained through this period by adopting lower initial stocking rates, thinning earlier when the trees are smaller, or performing the pruning and thinning on a regular basis so that stock can consume a greater proportion of the fresh foliage. Anderson (1985) tested the feed value of fresh pine foliage in pen feeding trials and reported that, although the needles had a low *in vivo* digestibility (36%) and high lignin content (15%), free access to pine needles reduced the amount of supplementary feed required to maintain sheep live weight.

Cameron *et al.* (1989) established a variable spacing trial of *Eucalyptus grandis* across pasture in south-east Queensland with tree stocking rates of 42–3580 stems/ha, and monitored the growth of trees and pastures for almost five years. Pasture production began declining within six months and was dramatically reduced at tree stockings of over 1000 stems/ha within 18 months. By age four years pasture production was significantly reduced at stockings of only 305 stems/ha. Soil moisture competition from trees was thought to be a major constraint affecting pasture yields, with the trees at higher stocking drying out the soil to a depth of more than 4 m (Cameron *et al.* 1989).

In New Zealand, Power *et al.* (1999) found that surface soil moisture contents were unaffected by an increasing cover of *E. nitens* or *Acacia melanoxylon*. Under eucalypts, 50% shading reduced pasture yields by a similar amount. The drop in production was less under *A. melanoxylon*, suggesting that some Australian native timber species may be more compatible with pasture than are eucalypts and pine. Bird *et al.* (1994) reported on measurements of pasture production under variable spacing trials (35–225 stems/ha) of a range of tree species established in western Victoria in 1984. While the growth of perennial pasture was substantially affected by increasing tree cover under *Pinus radiata* and all six eucalypt species tested, the response under *Casuarina cunninghamiana* (river sheoak) was quite different (Figure 13.4). Pasture production actually increased with tree stocking of river sheoak up to 175 stems/ha and was still greater at 225 stems/ha than at the lowest stocking rate. The trees were <6 m tall at the time; pasture production presumably would, at some point, begin to decline due to increased shading.

Casuarina cunninghamiana was one of five tree species in a similar experiment involving replicated variable stocking plots near Gympie in south-east Queensland (Taylor *et al.* 1996). At age seven years, when the river sheoak was about 10 m tall, pasture production (dominated by kikuyu) did increase with increasing tree stocking up to a point (about 200 stems/ha) then began to decline, eventually dropping below that of the open pasture at about 300 stems/ha. Pasture production under *Grevillea robusta* (southern silky oak, then around 8 m tall) and *Araucaria cunninghamianii* (hoop pine, then about 6 m tall) showed a similar trend. Interestingly, pasture yields under *E. camaldulensis* (river red gum), which was the least competitive eucalypt species in the Victorian trial (Figure 13.4), were maintained at close to open pasture levels at stocking rates of up to about 600 stems/ha despite the trees being of similar height and diameter to the *Grevillea robusta*. The researchers attributed this to the lower leaf area index of the river red gum.

Marginal gains

The quality and productivity of pasture growing under trees will reflect the availability of light, moisture, nutrient and soil space and the impact of competition for these resources on the growth,

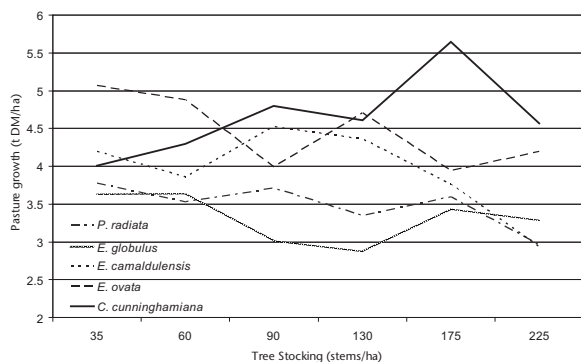


Figure 13.4: Effect of tree spacing on pasture growth (t DM/ha) from mid-June to mid-December under seven-year-old variable spacing trials at Hamilton, western Victoria (Bird *et al.* 1994).

persistence, reproduction, competitiveness and feed value of a species. Like many of the tropical grasses, kikuyu uses a C4 photosynthesis pathway. C4 plants commonly show no photosynthetic rate saturation up to and beyond full sunlight levels (Salisbury and Ross 1992). This implies that, where light is the limiting factor, any increase in shading will result in a significant reduction in yield. The temperate grasses and crops tend to have a C3 photosynthesis pathway and often reach light saturation at levels well below that of full sunlight.

In western Victoria, pasture production predominantly occurs during spring as temperatures increase and continues until moisture becomes limiting in summer. Shading may reduce pasture vigour during early spring, but it is likely to be the reduction in soil moisture due to competition from trees that ultimately affects total pasture yields. Bird *et al.* (1994) attributed the increase in pasture production under lower stockings of *C. cunninghamiana* to a better balance of shading (reduced evaporation) and lower moisture competition compared to the eucalypts. Although they entertained the possibility that leaf litter and fine root turnover by this nitrogen-fixing tree species may contribute to enhanced soil fertility, it was not measured.

Bino (1994) examined soils under a young plantation of *C. cunninghamiana* in northern Victoria but found no evidence of enhanced soil nitrogen. In New Zealand, measurements of pasture production under another Australian native nitrogen-fixing timber species (*Acacia melanoxylon*) found that at low shade levels (<20%) total pasture production

and pasture legume yield were often higher than in open pasture, whereas they were always much lower under the equivalent amount of *E. nitens* shade (Power 2002). Pot trials confirmed that nitrogen uptake by ryegrass was higher in soils collected from under blackwood.

Cameron *et al.* (1989) suggested that pasture growth under the *E. grandis* spacing trial was slightly enhanced at lower stocking rates. This was most apparent during the winter months, when the pasture in the open was regularly frosted. They provided some evidence that pasture quality (predominantly *Setaria*, a C4 grass) was also improved by shading – a higher proportion of the yield was allocated to green leaf with a higher nitrogen content than the more exposed pasture, suggesting that nutrient cycling may have had an influence.

Australian research in the natural eucalypt woodlands of northern Australia generally supports the view, strongly held by local farmers, that reducing tree cover increases pasture yields. However, in some cases pasture quality (in terms of N% and digestibility) may be higher under trees (Jackson and Ash 1998), although this is largely attributed to a nitrogen dilution effect that occurs with increasing production rather than any positive impact of the tree cover on nitrogen availability.

Further south, Williams *et al.* (1999) reported on native pasture production from native woodlands and clearings in the Southern Tablelands of New South Wales. In three of the five seasons of measurement, pasture productivity (quality and quantity) was significantly higher under reasonably dense mature native eucalypt cover. The response was most significant during the winter months and continued into spring in non-drought years. The authors attributed the results to an improved microclimate (higher winter temperatures and lower evaporation) and the higher soil organic matter content under the trees.

Trees can enhance soil fertility but it may take many years and is easily masked by the addition of fertilisers or redistribution of fertility by stock (Prinsley and Swift 1986). Trees can also improve soil structure and water-holding capacity, but this is easily overshadowed by the increased competition in Australia's water-limited farming systems. However, there are clear opportunities for achieving marginal gains in pasture production and quality

by selecting less-competitive tree species, targeting sites where environmental extremes are affecting pasture production (waterlogging, frosts, hot dry winds, excessive sunlight, shifting sands, salt-laden winds etc.) and carefully managing the extent of tree cover over time (thinning and pruning).

Natural pest control

In theory, increasing the diversity within an otherwise homogeneous farming landscape increases the number and effectiveness of natural predators of agricultural pests, thereby providing a direct economic benefit. Horticulturalists have long known the value of ladybirds, hover flies and lacewings for controlling aphids (Chapman *et al.* 1986). Some farmers are purposely planting nectar-bearing trees and shrubs to feed parasitic wasps which are known to lay their eggs in the larvae of many agricultural pests, including pasture grubs (Goodyer 2007). Native birds may also play a role: 100 straw-necked ibis are said to consume up to 25 000 insects (notably locusts and grasshoppers) per day (Davidson and Davidson 1992).

Unfortunately, the difficulty associated with field experimentation and the many confounding influences on pest and predator relations means there is little empirical evidence of productivity gains from enhanced natural pest control through revegetation. Tsitsilas *et al.* (2006) report on a replicated field trial examining the role of shelter belts as a refuge for predators of three important winter pasture pests of southern Australian grazing areas: the blue oat mite, the red-legged earth mite and the lucerne flea. The research showed that shelter belts can act as a refuge for predatory mites and spiders but that their influence on pest populations may extend less than 20 m into the adjacent pasture areas. Grazed and ungrazed shelter belts were included in the study, leading the authors to suggest that long grass in the ungrazed shelter belts was probably the most important factor since it was likely to provide a better environment for these predators than either grazed grass or bare ground (Tsitsilas *et al.* 2006).

Unfortunately, the wildlife that ‘compete with agriculturalists are much more apparent than those that assist’ (Breckwolfdt 1983, p. 5). There is clear evidence that forest areas can provide a refuge for

agricultural pests. A study on a Tasmanian farm showed that native wallabies, kangaroos and deer sheltering in native forests and plantations were responsible for over half the pasture grazed (Dunbabin 2007). Foxes, rabbits, hares and other introduced pests not only seek refuge in forests and plantations, but can be more difficult to control there than in open farmland.

Grazing near trees

Irrespective of the impact of trees on pasture production and quality, utilisation of the pasture requires direct grazing or mechanical harvesting. The presence of trees and their associated root systems, leaf litter and woody debris can make effective grazing or harvesting impractical or even impossible. Reid and Wilson (1985) and Haines (1997) reported on a range of formal trials and anecdotal experience involving grazing sheep and cows in recently established plantations. The results are mixed: young stock are preferred; grazing when the pasture is lush may increase browsing and ring-barking behaviour; short mob stocking is better than set stocking; some tree species may not be susceptible to browsing at all. However, they also provided examples that appeared to contradict almost all these suggestions.

Haines (1997) tested the effect of simulated browsing on the survival and growth of 18 eucalypt and acacia species. Generally, a single browsing event that removed the side branches and resulted in some damage to the apical tip in the spring following winter planting had no effect on survival and growth. However, if the damage was repeated in the following autumn there was significant loss of growth. Once the foliage is out of stock reach, the only risk is from rubbing or chewing on the bark. As the bark thickens, it is safe to begin unprotected grazing under most tree species. Some species, such as the stringybark eucalypts, are particularly susceptible to ringbarking, with many examples of large mature trees being killed by cattle and horses. There have also been many cases where cows have torn the bark of *Pinus radiata* during spring, particularly where the sap is exuding from recently pruned branch stubs.

For many years researchers in Australia and New Zealand have explored the use of repellents to

deter browsing by farm stock, wallabies, deer and rabbits. More-effective mixtures include eggs, fish, dog urine, animal fats, iron filings, kerosene, paints and other ingredients (Reid and Wilson 1985; Haines 1997). Some are used commercially but their potential is limited due to the need to regularly reapply the mixture to protect new growth.

The ability to cut pasture from between trees for hay or silage, while trees are small, may overcome the need to graze the site at all. To be effective the trees must be planted in rows spaced appropriately for the machinery, with adequate room for manoeuvring at the ends of the rows. Alternatively, depending on growth rates, the period before the trees can withstand direct grazing pressure could be used for alternative crops or as an opportunity to sow new pastures, establish and strip graze fodder crops or entirely spell the site from grazing.

For most landholders, grazing stock among newly established trees requires some sort of barrier such as individual tree guards or group fencing. In strictly economic terms, if the costs associated with protecting the trees are greater than the benefits derived from grazing or cropping the area, it may be better to exclude agricultural production until the trees are large enough to withstand grazing. If, as is the case for some species, the trees remain vulnerable even when they are well-established (because of their small size, susceptibility to ringbarking or shallow root systems) it may be necessary to exclude grazing from the site. The choice depends on management objectives, equipment and management resources, stock type, management intensity and risk scenarios. In some cases, leaving an area ungrazed for even a short time may put undue pressure on other areas of the farm, increase the risk of fire or lead to weed development and reduced pasture quality.

Individual tree guards can be cost-effective and practical if tree stocking rates are low and the benefits of continued grazing are high. If the trees need to be individually guarded from pests such as kangaroos, wallabies or deer, there may be no additional cost associated with guarding them from sheep. The author has trialled a number of individual and small group guarding options to allow sheep grazing, including solid wire mesh, electrified rings and tall plastic sleeves.

Unless stocking rates are very low or it is feasible to continue thinning to control the amount of tree cover, almost every tree–pasture combination eventually leads to a decline in pasture production and quality as the trees mature. In temperate areas competition will be most intense in summer, and can result in total loss of improved perennial pasture species and legumes. Depending on the proportion of their grazing enterprise under trees, this changing productivity may present management problems for farmers intent on maintaining stock numbers or agricultural productivity. On the other hand, if the trees are developing into a commercial crop or providing alternative income, this may represent a welcome transition away from dependence on grazing.

The practical option for most farmers is to adopt a planting pattern that allows trees to be fenced as a group, whether in a belt or a block, and managed separately from the pastures. Rather than being concerned about the agricultural productivity of the area under the trees, the more important consideration is the interaction across the boundary between the trees and pasture. A number of different edge-effect scenarios are theoretically possible (Figure 13.5), but the most common in Australian agricultural systems is where pasture or crop production is significantly reduced along the edge of the trees (Abel *et al.* 1997). In Australia,

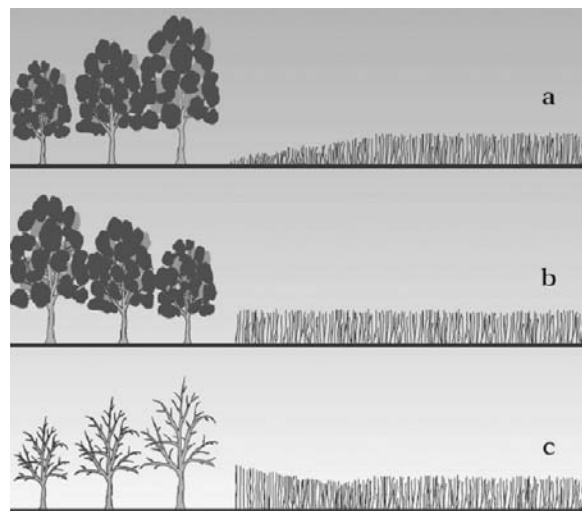


Figure 13.5: Three scenarios showing the productivity of trees and crops along a tree/crop interface (Abel *et al.* 1997).

this competition zone is typically within one tree height of the belt but may extend to three times the height of mature trees growing on shallow soils (Cleugh 2003).

Albertsen *et al.* (2000) studied the effects of plantation belts of *E. globulus*, grown for pulpwood, on adjacent pasture production in Western Australia. They found that tree belt orientation and tree age were the most significant variables determining the extent of pasture production loss along the edge of the belts. Pasture loss was greater on the north side of the belt and lowest on the western edge. Accounting for both sides of the belt, the east–west oriented belts resulted in approximately 20% greater pasture loss on the edge than the north–south belts. Tree height was not a significant variable, suggesting that the extent of the no-yield zone beside the eucalypt belt was almost entirely related to root development and competition for moisture. Root-pruning along the edge of tree belts has proven effective in increasing crop yield on shallow soils in Western Australia, however, the impact may be short-lived on deeper soils as roots rise from below the depth of the ripping to reoccupy the surface soils (Stirzaker *et al.* 2002; Cleugh 2003).

Significant increases in pasture production over and above that of open areas have been measured in Australia and New Zealand well out from the competition zone, at two and 10 tree heights away from the tree belt (Bird 1998). The degree to which an increase in pasture production in this sheltered zone can compensate for the loss of land to the trees and the competition along the edge of a belt is uncertain. Bird (1998, p. 49) concluded that ‘despite a century or more of spasmodic research ... we are not yet in a position to provide unequivocal advice to farmers on windbreak outcomes for pasture production in particular circumstances or regions’.

Stock shade and shelter

In addition to influencing pasture production or quality, Bird *et al.* (1992) suggested that tree cover can improve animal production directly by:

- reducing losses of newborn stock or recently shorn sheep during periods of wet, windy and cold weather;

- reducing livestock maintenance requirements caused by excessive heat or cold;
- reducing the impact of heat stress on animal fertility;
- providing foliage or fruit available to stock by direct grazing, leaf or fruit fall or management intervention (cut and carry).

Animal stress induced by wind, sun, rain or dust can also influence stock behaviour, resulting in uneven grazing patterns, areas of excessive concentration resulting in nutrient loading and soil erosion, or making stock mustering very difficult. In hot weather, without adequate shade, cows and sheep may concentrate around watering points, fouling dams and waterways.

Thermoneutral zone

Animal physiologists use the notion of upper and lower critical temperatures to describe the effect of environmental conditions on animal production (Ames 1980). Below the lower critical temperature stock endeavour to maintain their core body temperature by increasing feed intake, increasing their metabolic rate (shivering) and seeking shelter. Above the upper critical temperature animals will increase evaporative heat loss (by panting, sweating etc.), reduce feed intake, increase water consumption and seek shade or windy areas. Between the upper and lower critical temperature is the thermoneutral zone, within which animal production and behaviour is not affected by temperature (Figure 13.6). The actual upper and lower critical temperatures, and the width of the thermoneutral zone, depend on each animal’s body condition, breeding, age, health, previous exposure (acclimatisation), reproductive status and other factors (Donnelley *et al.* 1974; McCrabb *et al.* 1993).

Bianca (1976) presents indicative effective temperatures for the thermoneutral zones of four species of farm animals, which clearly illustrate the risk to young stock and the susceptibility of mature cows to heat stress under Australian conditions (Figure 13.7). Not surprisingly, newborn chicks and piglets are commonly held indoors under controlled conditions to maximise productivity. However, as sheep and cows are usually left outside to give birth, sometimes in the coolest months, it is almost certain that calves and (particularly) lambs

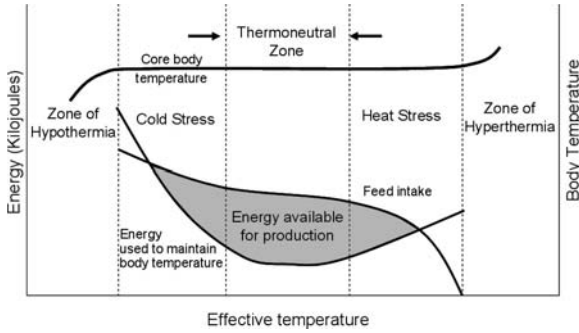


Figure 13.6: Effect of temperature on animal production (adapted from Ames 1980).

will suffer cold stress in their first few weeks. Sheep, in full wool, have the widest temperature range within which production is unaffected (Bianca 1976). Ames (1980) provides estimates that suggest a lower critical temperature for recently shorn sheep of around 28°C which drops to 25°C, 22°C, 9°C and finally -3°C as the fleece grows to 5, 10, 50 and 100 mm respectively.

Other environmental factors also influence animal response; these include wind, humidity and rain (Howden and Turnpenny 1998; Ames 1980). Increasing wind speed dramatically reduces the effective temperature. There are a number of wind-chill indices. Some, such as the Steadmen index adopted by the Australian Bureau of Meteorology (BOM 2006), are for humans and assume that people will be wearing appropriate clothing for the conditions (Figure 13.8). The effective temperature experienced by a ‘bare’ animal in an unprotected paddock would be lower again. If a human’s clothing or animal’s coat were to get wet,

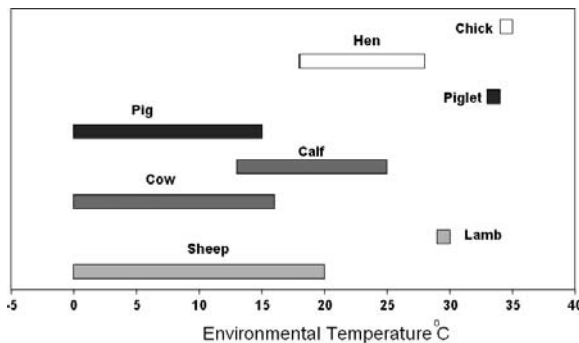


Figure 13.7: Typical thermoneutral zones for different types of livestock (adapted from Bianca 1976).

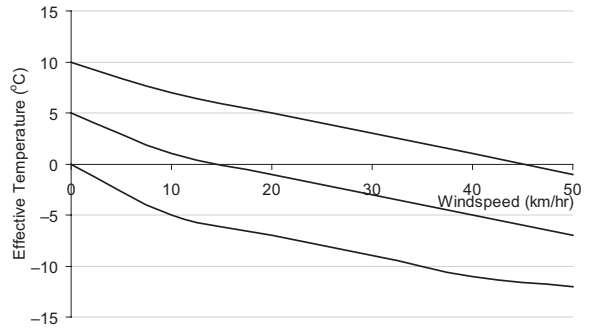


Figure 13.8: The wind-chill index adopted by the Australian Bureau of Meteorology is for humans and assumes that they will be wearing clothes appropriate to the conditions (data available from BOM 2006). For newborn lambs or freshly shorn sheep, the wind-chill effect is likely to be greater.

the cooling effect would be greater than that predicted by this model and the chance of hypothermia would be greater.

Heat stress

The impact of heat stress on animal production is most notable within the dairy industry. Milk yields, as well as the protein and fat concentration in the milk, have been shown to fall dramatically during hot humid weather in Queensland dairy herds (Davison *et al.* 1996). Armstrong (1994) identifies four environmental factors which influence the effective temperature experienced by cattle: air temperature, relative humidity, air movement and solar radiation. Temperatures as low as 27°C, even on days of low humidity, are above the comfort zone for high-producing dairy cows. Dairy cows respond to heat stress by reducing their feed intake, increasing water intake and increasing evaporative losses by sweating and panting (Armstrong 1994). If they cannot control heat gain their body temperature increases, risking their health.

Dairy researchers in North America developed a temperature-humidity index (THI) table, which is a useful measure of the impact on heat stress on dairy cows (Armstrong 1994; Howden and Turnpenny 1998) (Figure 13.9). Research in Australia and North America suggests that a THI of over 80 is likely to significantly affect production. Deaths among adult cattle due to heat stress are rare but they do occur during extended periods of hot weather, particularly if the night-time tempera-

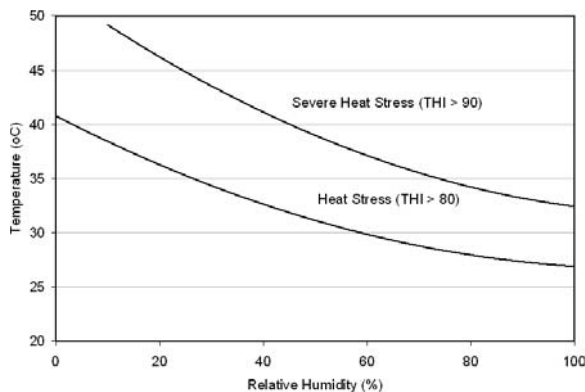


Figure 13.9: Influence of relative humidity on heat stress in dairy cows (based on Armstrong 1994).

tures do not fall below 20°C (Daly 1984). Calves born in the morning of a hot day, a long distance from shade and water, are at great risk.

Fertility rates may fall in cattle and sheep affected by heat stress. Heat-stressed rams are likely to have lower sperm counts and heat stress among ewes can reduce the probability of conception (McCrabb *et al.* 1993; Roberts 1984). This is clearly a risk in the sheep areas of southern Australia, where most stock are joined in late summer and early autumn. Once pregnant, ewes subjected to heat stress are likely to have lambs of lower birth weights, which are more susceptible to cold stress (Roberts 1984).

Cold stress

It is estimated that 20% of pregnant ewes in Australia may fail to rear lambs to marking and that exposure to cold stress may account for at least half this lost potential (Donnelly 1984; Pollard 1999). Lambs are particularly susceptible to exposure in the period immediately after birth and until they begin suckling, but remain seriously at risk for another 48 hours (Gregory 1995). This suggests that if all the sheep in a flock become pregnant within one oestrous cycle, an average of 6% of the ewes would be expected to lamb on any one day and about 12% would be vulnerable at any one time. Based on field trials, Donnelly (1984) predicted that in the Southern Tablelands of New South Wales the risk of death due to exposure was as much as 50% greater for merinos born as twins compared to their single birth cousins. Lamb bodyweight and breed were clear determi-

nants, with larger crossbred lambs at little risk of dying.

Wet windy weather can result in large losses of recently shorn adult sheep, particularly if they are in poor physical condition. Sheep are particularly susceptible for the first 24 hours after shearing as their waterproofing cover of lanolin replenishes, but remain susceptible for seven days or more (Bird *et al.* 1992). A farmer might only have 12% of lambs at risk during a single extreme weather event, but it is possible that almost all recently shorn sheep will be vulnerable at the same time. Individual farms can suffer very high stock losses. This was demonstrated on 2 December 1987 when an estimated 100 000+ newly shorn sheep were lost in south-west Victoria alone.

Trees for shelter

The most common motivation for planting trees is agricultural shade and shelter (Wilson *et al.* 1995). Trees rarely have a direct impact on the ambient temperature, but can significantly improve the effective or environmental temperature experienced by animals and thereby enhance productivity and improve animal behaviour and well-being. Trees do this by shading stock from direct solar radiation, reducing wind speed and therefore the wind-chill factor, sheltering animals from rainfall, frost and dew, and possibly reducing local temperatures through increased evaporative cooling.

Shade trees

Davison *et al.* (1996) reported a study which examined the value of various cooling options for reducing heat stress in dairy cows. The most effective treatment involved solid corrugated iron shading and sprinklers to water the animals. Shade cloth, which might simulate the shade produced by trees, was less effective but still significantly improved milk production during hot weather.

Armstrong (1994), in a review of shade management options for dairy cows in North America, concluded that 'trees are the most effective shade producers: they combine protection from the sun with the radiation sink effect created by cool leaves evaporating moisture'. Studying the cooling effect of urban parks in Israel, Shashua and Hoffman (2000) found that the ambient temperature on days

of over 32°C was reduced by as much as 4°C. This was associated with an increase in the relative humidity by as much as 10%, suggesting some evaporative cooling effect. Interestingly, they also noted that the cooling effect of urban parks has been shown to extend 200 m or more in the direction of the wind.

Shade is particularly important around stock yards, laneways, holding paddocks and other areas where stock may be concentrated for long periods. The fact that stock use shade in open paddocks suggests that it may be important in improving animal welfare and long-term productivity. Shade can be a useful management tool in guiding animal behaviour and grazing patterns. If there is insufficient shade, stock tend to concentrate their grazing around watering points, often fouling dams and baring the soil (Daly 1984).

Because wind flow is important in reducing heat stress it may be beneficial to locate shade trees away from dense vegetation or shelter belts and to prune the lower branches. This will help in maintaining a pasture sward under the trees, thereby reducing the likelihood of soil erosion around the root system and excessive weed growth due to manure loading. The concentration of stock over the root system of trees can be avoided by having tall trees with clear boles that will cast shade well away from their roots during the heat of the afternoon. It is preferable to select tree species which allow greater grass growth under the canopy and have a tight bark that is resistant to browsing.

Shade trees can be established individually, using tree guards, or in small fenced clumps. Once established, the fences can be removed or set back under the trees to allow stock to seek shade below the canopy. The author has used this method effectively along a wide riparian creek planting with the fence protecting understorey trees and the creek banks set well inside the edge trees.

Wind shelter

The wind-chill model presented in Figure 13.8 shows how reducing the wind speed from 40 km/h to 20 km/h can increase the effective temperature experienced by an animal by as much as 5°C. This shows the value of trees for protecting lambs and off-shears sheep from death during extreme events and for generally improving the productivity of

farm stock. Strategic placement of perennial vegetation, in association with appropriate paddock design and stock management, can reduce the exposure of susceptible stock to the high wind speeds that can cause severe cold stress.

Bird (1998), Bird *et al.* (1992) and Bird *et al.* (2007) present field-based research that demonstrates that tree belts can reduce wind speeds by as much as 60% at a point three to six tree heights away on the leeward side. Wind speeds begin to fall before the wind reaches the belt, suggesting the belt acts as a physical barrier to the movement of air and forcing it to go over, through or around in a manner similar to water flowing over a barrier in a river. The greatest reduction in wind speed is not immediately behind the barrier but further out on the leeward side. The wind speed gradually returns to open field strength at a point as far as 30 tree heights away from the belt.

Based on wind tunnel research, the extent of wind speed reduction at any point behind a shelter belt is known to be a function of shelter belt height, distance from the belt, height above the soil surface, roughness of the land surface on both sides of the belt, belt porosity and atmospheric stability (McNaughton 1988). The influence of some of these variables is shown in Figure 13.10. For example, if the shelter belt shown was 20 m tall rather than 10 m, the greatest reduction in wind speed would have still occurred at around six tree heights but this would have been at a point 120 m from the belt rather than 60 m. Because of this relationship, height is used as a standard basis for describing the wind profile behind shelter belts.

Shelter belt porosity refers to the proportion of the air flow that travels through the belt rather than over or around it (Reid and Bird 1990). Shelter belts with a lower porosity result in a greater reduction in wind speed behind the belt, but do not change the distance at which the winds return to open wind speeds. The exception is a solid barrier which, due to the lack of air flow through the belt, creates a very sheltered area immediately behind the structure. The air pressure vacuum this induces on the leeward side leads to a rapid rise in wind speed within the zone usually associated with the greatest shelter. Open areas under the canopy of a shelter belt can lead to increased wind speeds as the

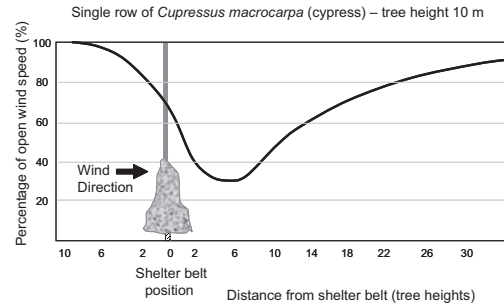


Figure 13.10: Wind profile behind a shelter belt of Monterey cypress in western Victoria (Bird *et al.* 2007).

air tunnels through the gaps (Figure 13.11). This is a common problem in unfenced shelter belts or those dominated by species, such as eucalypts, that tend to self-prune.

Aerodynamic porosity is often estimated from the proportion of direct light that can be seen through the belt (optical porosity). This may be appropriate for two-dimensional and textured barriers, such as shade cloth, but may be unreliable in irregular or wider tree belts (Bird *et al.* 2007). Despite being unfenced and having little foliage close to ground level, a 20 m wide belt of direct-seeded sugar gum resulted in a wind speed profile that suggested there was no wind tunnelling under the canopy (Figure 13.12).

The longer the shelter belt, the less impact wind flow around the end of the belt has on the sheltered area. However, with any end there is a risk of increased wind speed. It is best to create a network of vegetation across the landscape which links shelter belts to remnant forest areas, riparian plan-

tations and woodlots. Although orientation is important when examining the effectiveness of a single shelter belt, it is less important if there is a network of belts. The risk of wind tunnelling through gateways can be avoided by locating them in naturally sheltered areas such as beside a perpendicular shelter belt or a forested area. Even if the wind is running parallel to a shelter belt or forest block, the roughness of the edge still provides good shelter for one or two tree heights (Burke 1998). Alternatively, gateways can be protected by establishing overlapping running angled laneways through wider belts or forest blocks (Abel *et al.* 1997).

Based on wind tunnel research, Nageli (1964) showed that when wind flows across a series of parallel shelter belts each belt becomes less effective in reducing wind speed (Figure 13.13). The belts are inducing greater turbulence in the approaching wind, thereby reducing the percentage of wind speed reduction and the distance at which the wind

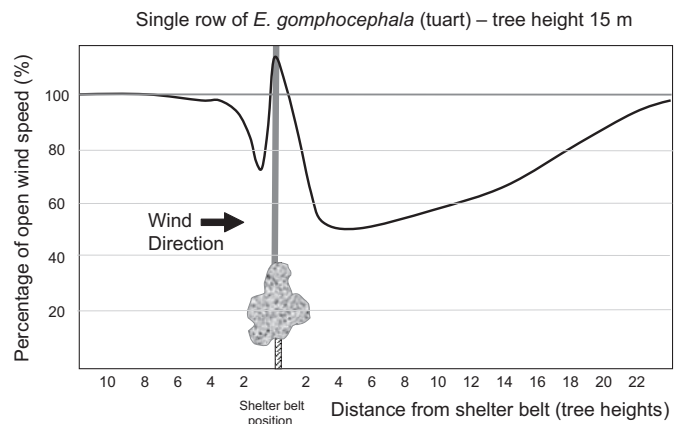


Figure 13.11: Effect of a single row of tuart trees (15 m tall) on wind speed (Bird *et al.* 2007).

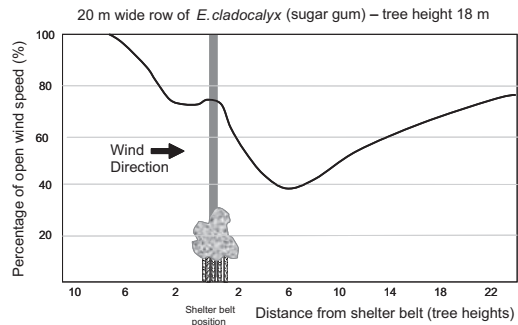


Figure 13.12: Wind speed profile through a 20 m wide shelter belt of direct-seeded sugar gum (Bird *et al.* 2007).

returns to open wind speed. As the belts become closer they begin to mimic what occurs in an open woodland or widely spaced plantation. Hawke and Wedderburn (1994) measured wind speeds under a range of pruned *Pinus radiata* tree stockings at the Tikitere Agroforestry Research site in New Zealand and showed wind-run reductions of around 50% by age 10 at only 100 stems/ha. Increasing the stocking to 200 stems/ha had no additional effect, suggesting that the roughness caused by the trees was encouraging the bulk of the wind to flow over

the tree tops. Bird measured wind speeds in a paddock of widely spaced mature red gums (only 17 trees/ha) and found a relatively even wind speed reduction across the paddock of around 40%.

An even wind speed reduction across a paddock may be more appropriate than the variable pattern of wind speed reduction behind a shelter belt for providing lambing shelter, as it ensures lambs are born within the sheltered area irrespective of the ewes' shelter-seeking behaviour. For off-shears sheep, which do not require the same quality of pasture, a dense plantation may be even better. Hawke and Wedderburn (1994) found that wind flow in a high stocking (400 stems/ha) of 10-year old pruned pines, under which there would be very little quality pasture, was less than 20% of that in the open areas at a similar age. Dense foliage cover can intercept a high proportion of the rainfall and thereby help keep stock dry, further increasing their chances of survival (Gregory 1995).

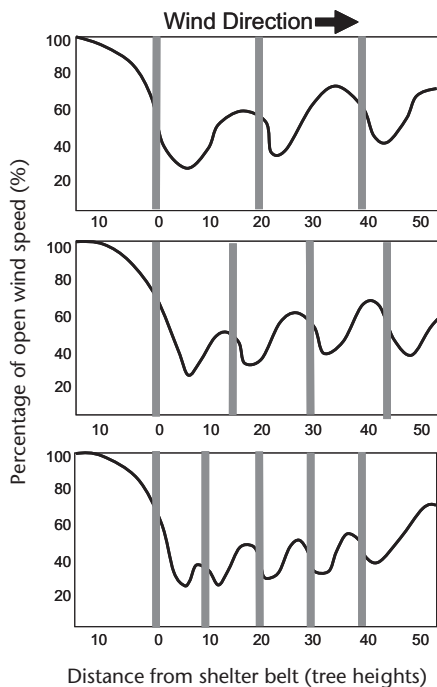


Figure 13.13: A series of parallel windbreaks shows a reducing shelter influence as a result of increased air turbulence (Nageli 1964).

Integrating trees and grazing at the farm level

Using the concept of a joint production function at the farm level, rather than the paddock level, Figure 13.14 illustrates a number of possible relationships between percentage of tree cover and agricultural productivity. Trees have been shown to be very competitive at the paddock scale but it can be argued that this may not be the case at the farm scale. Across most of the range any increase in the area of tree cover will result in a proportional drop in agricultural returns, but there are likely to be greater opportunities for enhanced agricultural productivity at low levels of tree cover.

Most properties have areas of relatively low agricultural productivity or sites in need of revegetation that can be fenced out and excluded from grazing without reducing agricultural productivity, irrespective of the shelter benefits for stock. Where farmers have an interest in off-site water quality, soil conservation control, biodiversity enhancement and landscape values, they may be very willing to incur the costs involved in the establishment and management of trees on these sites. Most Australian farms have less than 1–2% tree cover, so it seems appropriate to look at how farmers might identify low-risk opportunities to increase tree cover on the property, rather than seek to identify the most economic joint production functions at the paddock scale.

Most of the benefits associated with growing trees accrue in the medium to long term, so farmers starting from a low tree cover base might be biased towards maintaining or enhancing agricultural yield and profitability; that is, they will only be prepared to commit land to trees to the extent that they believe the forests complement their current farming systems. If they are less dependent on agricultural income, have a personal interest in particular tree products or services or can adopt a long-term view, they may be willing to increase farm tree cover to the point where it significantly compromises agricultural yields in the short term. For most Australian farmers, this situation is some way off.

Based on the shelter benefits to livestock, Bird *et al.* (1992) suggested that the systematic planting of 5–10% of the non-arid grazing areas of Australia in a network of tree belts and cluster plantings would substantially improve livestock and pasture production in the short and long-term. In a review of the role of shelter belts on grazing properties in New Zealand, Gregory (1995, p. 444) suggested that ‘on flat or gently undulating ground, approximately 3% of the land area would need to be planted with shelter belts to provide adequate livestock shelter, whereas in the hills as much as 20% may be needed’.

While being motivated to plant trees by a perceived need for shelter, in practice a shelter belt may not be the best place for a farmer to start. Trees planted for soil conservation, aesthetics and biodiversity can play an important role as part of a shelter belt network on the farm. Where a farmer is

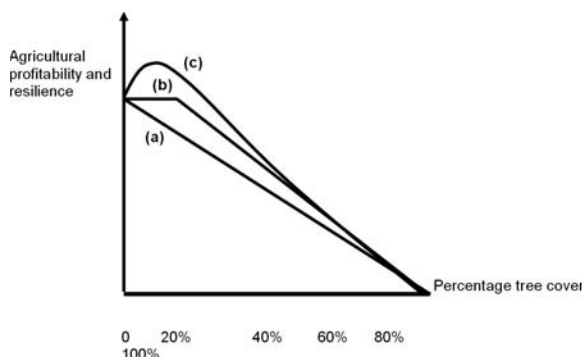


Figure 13.14: Possible impacts of increasing farm tree cover on agricultural productivity. (a) Competitive – any increase in tree cover reduces agricultural production. (b) Initially supplementary – increasing tree cover does not affect agricultural production until a threshold is achieved. (c) Initially complementary – agricultural profitability increases with increasing tree cover before becoming competitive.

willing to fence their watercourses from stock, this is a logical starting-point.

Riparian forests

Unprotected watercourses on grazing properties are at high risk of soil and water degradation and can make stock mustering difficult. Landcare groups, water authorities and catchment groups tend to focus on waterway management and revegetation because of the downstream impacts of stock fouling waterways or degrading stream banks, and are often willing to provide support and assistance to farmers who are prepared to fence their creeks (Stanton and O’Sullivan 2006). Other than the need to provide off-stream watering points and manage flood damage, fencing and revegetating waterways may be the most cost-effective and least intrusive place to start planting trees for shelter, timber production and other productive values.

The drainage density in farming areas varies with climate, topography and soil structure but is commonly between 1 km of watercourse per square kilometre on the plains to almost 5 km/km² in deeply dissected hill country (Pitt 1981; Gordon *et al.* 2004). The most appropriate width of a buffer strip for soil conservation and water quality will vary from a minimum required for bank stability, to much wider belts where soils are unstable or overland flow rates are high. Research (Hairsine 1997; Prosser *et al.* 1999) focusing on the potential

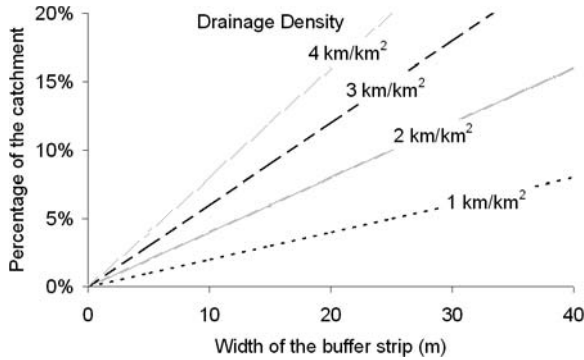


Figure 13.15: The percentage of a catchment that would be incorporated into a riparian buffer strip of different widths. Note that a 10 m wide buffer would represent a 20 m riparian corridor if both sides of the stream were planted to trees.

of buffer strips to trap sediments, commonly involves grass or forested strips of around 10 m. This would represent less than 5% of most agricultural landscapes (Figure 13.15).

The biodiversity value of vegetation cover along waterways is more complex. Tree cover has a moderating effect on water temperatures; forested waterways tend to retain more water in deeper pools during the dry months and contain more woody debris than open waterways. Wide strips are preferable, but even a narrow buffer of 5 m on each bank is likely to improve the aquatic habitat and act as a corridor for small animals (Lynch and Catterall 1999). In practice, the greatest initial environmental gain comes from the exclusion of stock grazing from the channel itself and from the shading of the waterway by the trees. There are only marginal or species-specific benefits derived from increasing the width of the belt above that required for soil conservation or trapping sediments (Hairsine 1997).

Shelter belts

Based on the anticipated pasture response curves in adjacent paddocks (Figure 13.16), it is possible to estimate the impact on pasture production of increasing the percentage of flat farmland incorporated into shelter belts of varying widths (Figure 13.17). Narrow shelter belts occupy little land and, if planted across less than 1% of the farm, may actually increase pasture production. However, increasing the area of farm dedicated to narrow

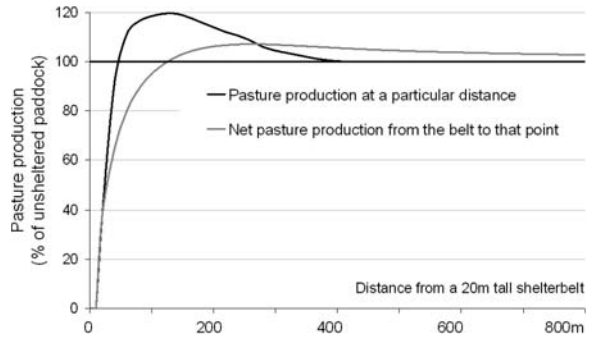


Figure 13.16: Relative pasture yield behind a 20 m tall shelter belt in western Victoria (Bird 1998).

belts can dramatically reduce agricultural yields. By contrast, shelter belts that are as wide as the trees are tall can be planted over as much as 5% of the farm before agricultural production is reduced. Wide belts are likely to be more useful for stock shelter, wildlife habitat and timber production and less susceptible to problems such as wind tunneling through gaps or below the canopy.

Multi-purpose trees in the agricultural landscape

Corridors of riparian vegetation along waterways, linking with strategically placed shelter belts to form a network of vegetation for shelter and land protection, may constitute as much as 5% of the agricultural landscape. Well-integrated tree cover across 5% of the farming landscape can provide short-term benefits and presents no risk to agricultural productivity. It is likely that the medium- to

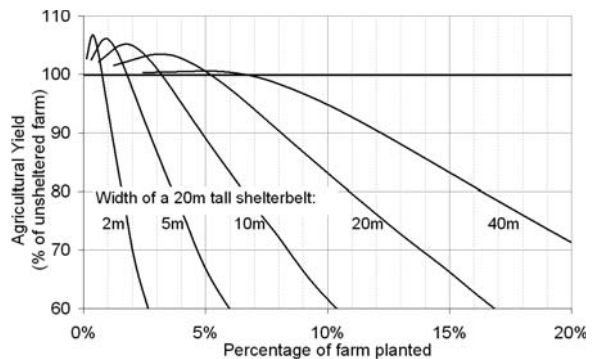


Figure 13.17: Anticipated percentage tree cover and pasture production impacts of 20 m tall shelter belts of varying widths across a flat open farm in western Victoria (based on Figure 13.16).

BOX 13.1

Fitting multi-purpose trees into a grazing system

Today, in 2009, our 230 ha farm looks completely different from what it was like 17 years ago, in 1992. The property has been transformed from 3.5% tree cover (plantations and remnant vegetation) in 1992 to 15% by 2005. More than 34 000 trees and shrubs have been established. The farm is not only a much more aesthetic and pleasant environment to work in, but also more productive due to changes in stock and pasture management and protection of land and livestock with revegetation. Strong prime lamb prices over the last couple of years have enabled more investment into natural resource management.

My children are the fifth generation of Stewarts at Yan Yan Gurt West. By 1990 our farm, like so many, was essentially cleared of native trees and shrubs with just a few patches of remnant vegetation and the occasional narrow shelter belt. As a family we recognised that if we were to remain viable we had to diversify our income and better manage our natural resource base. A number of management problems were identified, including salinity, gully erosion, stream bank erosion, waterlogging, lack of shade and shelter and lack of ecological balance on the property. There was also a lack of land class subdivision, with paddocks being too big for effective grazing management.

Farm forestry has been a catalyst for a wide range of landcare, water quality, landscape, habitat and animal productivity outcomes on Yan Yan Gurt West. In 2003, we produced 1600 prime lambs and joined 82 heifers and had 3.5 ha of remnant vegetation and 30 ha of planted trees and shrubs, 16 ha of which was being managed for commercial timber production. These plantings are growing into a source of farm income while providing other benefits to the property and the sheep and cattle enterprises. The farm forestry developments have allowed us to generate some income by running tours for school groups, university excursions and international study groups.

Whole-farm plan

A whole-farm plan was developed which incorporated objectives of the local landcare group's management plan for the Yan Yan Gurt creek catchment. It included the development of riparian buffer strips, shelter belts and wildlife corridors for erosion control, shelter, land protection and enhanced aesthetics. We have added another dimension by moving the fences out wider than conventional landcare plantings and high-pruning wide-spaced trees for sawlog production.

The whole-farm plan includes land class fencing with the integration of commercial and non-commercial trees and shrubs along drainage lines and land class boundaries. Stream sides were revegetated with a range of species arranged to provide environmental benefits as well as the prospect of commercial timber production. The long-term view involved improved and sustainable agricultural production and development of income security, with commercial trees playing an integral role as superannuation. It was considered that strategic revegetation would also halt the spread of dryland salinity in the lower parts of the landscape.

The result is a diverse range of planting patterns, species and management that have evolved out of a farm-planning process. Each provides a number of benefits and neatly fits into the commercial agricultural landscape:

- fenced wetlands for wildlife, aesthetics and stock protection;
- blue gum (*E. globulus*) plantings along land class boundaries for woodchip production (joint venture with a timber company);
- native species for pruned sawlogs, shining gum (*E. nitens*), blue gum, spotted gum (*Corymbia maculata*) and blackwood (*Acacia melanoxylon*), with understorey along riparian zones to protect creek banks and provide other farm production and environmental services;
- pruned radiata pine (*Pinus radiata*) for Christmas trees and sawlog production adjacent to gully erosion areas;
- pruned radiata pine and native species in belts along the break of slopes to provide shelter as well as address salinity and waterlogging;
- direct-seeding of 19 indigenous species among remnants of messmate (*E. obliqua*) on a recharge site for shelter and biodiversity;
- a seed orchard of spotted gum and sugar gum (*E. cladocalyx*) in a joint venture with a private seed company.

The property now has 'Land for Wildlife' status and is registered with the Surfcoast Shire's Biodiversity Incentive Program. Bi-monthly bird observations are made in eight sites throughout the property in accordance with Birds Australia methodology and 104 species have been identified. Analysis of data will help guide future plantation designs.

What we have found

While we know we are receiving many benefits from the trees, it has been difficult to measure them. With all the variables involved it has been too difficult to set experimental controls and, besides, we simply do not have the time and resources to undertake rigorous scientific studies. However, we are confident about making certain statements based on our observations and some real agricultural production measurements.

With 15 % revegetation, our stocking rates have not declined.

The plantation system has offered considerable benefit to deep-rooted, perennial herb summer fodder crops such as chicory and plantain by reducing evapotranspiration due to hot north-westerly winds. This allows us to better meet prime lamb production targets and hence improve marketing options and profitability.

104 species of birds have been recorded on the property, including magpies and large numbers of ibis, which prey on insects such as grasshoppers and cockchafer grubs.

The biodiverse plantations appear to be increasing the populations of spiders that prey on the red-legged earth mite, which can devastate legumes such as clover.

We scan ewes 90 days after joining. Twin-bearing ewes are placed in the best sheltered paddocks with the best alpacas (to reduce fox predation of newly born lambs). The twin-bearing ewes gain significant benefits from the tree shelter. The plantation system also gives us greater flexibility and confidence for choice of lambing time.

Fencing out creeks and drainage lines has made the property safer for stock and easier to muster and produced a healthier environment. The wet and boggy areas, which are more

prone to harbouring animal disease, have been eliminated from the grazing system. Fortunately, these areas are often the best places for productive trees because they are low in the landscape, thus offering seedlings some protection, and commonly have greater moisture and nutrient concentrations.

In wet years (which seem to have escaped us for the past few years) waterlogging is reduced, which makes the property more trafficable and healthy.

A badly salt-scalded area has been transformed from a scar on the landscape into a bird haven and place of beauty and is a safe haven for off-shears sheep, turning a problem into an opportunity.

There are now a number of off-shears havens scattered throughout the property ready for use when a big bad weather event comes. And one will come – it is only a matter of time.

The aesthetics of the property have improved greatly and the property is a far more enjoyable place to work, leading to better psychological health and probably physical health for everyone involved.

Strategic and biodiverse revegetation has significant increased property value, thus improving our equity percent and borrowing power.

I can remember a big wind blow that blew our topsoil out to the ocean. Now that we have 15% of the property revegetated with trees and shrubs this is far less likely to happen again.

The web of plantations throughout the property reduces spray drift.

Andrew Stewart, Yan Yan Gurt West, southern Victoria

long-term benefits of revegetation, including biodiversity enhancement, landscape improvement and commercial tree production, can be achieved at little additional cost by incorporating them into the this web of trees and by adopting multi-purpose forest management.

Accepting that trees grown for conservation and shelter can be managed for production invites farmers to move the fence back a little from the creek and widen their shelter belts in anticipation of future income for themselves or their children. The costs of establishment and much of the maintenance can be justified on the basis of the non-timber benefits rather than the sale of products. The same is true for the land costs and, to a lesser extent, the time trees take to grow. Because of this, farmers commonly talk of the timber return as a bonus. Growing species that can be used as firewood or posts or milled on-farm for fencing and building products overcomes problems of marketing.

Andrew and Jill Stewart run a sheep and beef property in southern Victoria. In the early 1990s

the property had a number of short, unlinked narrow shelter belts and a few scattered remnant trees. Adopting a whole-farm planning approach to the design and development of integrated multi-purpose tree plantations, they have increased the tree cover to more than 15%, which also increased grazing production and diversified their business. The case study in Box 13.1 illustrates that there is more to fitting trees into a grazing system than just planting shelter belts.

References

- Abel N, Baxter J, Campbell A, Cleugh H, Fargher J, Lambeck R, Prinsley R, Prosser M, Reid R, Revell G, Schmidt C, Stirzaker R and Thornburn P (1997) *Design Principles for Farm Forestry. A Guide to Assist Farmers to Decide Where to Place Trees and Farm Plantations on Farms*. Joint Venture Agroforestry Program, Rural Industries Research and Development Corporation, Canberra.

- Albertsen L, Eckersley P, Blennerhassett S, Moore R and Hingston B (2000) 'Blue gum timberbelt design for alley farming'. Joint Venture Agroforestry Program, Rural Industries Research and Development Corporation, Canberra. Publication no. 00/154.
- Ames D (1980) Thermal environment affects production efficiency of livestock. *Bioscience* **30**(7), 457–460.
- Anderson G (1985) Green *Pinus radiata* needles as a feed for sheep. *Australian Journal of Experimental Agriculture* **25**, 524–528.
- Anderson GW and Batini FE (1983) Pasture, sheep and timber production from agro-forestry systems with subterranean clover sown under 15-year-old *Pinus radiata* by a method simulating aerial seeding. *Australian Journal of Experimental Agriculture* **23**, 231–238.
- Anderson GW and Moore RN (1987) Productivity in the first seven years of a *Pinus radiata*-annual pasture agroforestry in Western Australia. *Australian Journal of Experimental Agriculture* **27**, 123–130.
- Anderson G, Hawke M and Moore R (1985) Pine needle consumption and bark stripping by sheep grazing annual pastures in young stands of widely spaced *Pinus radiata* and *P. pinaster*. *Agroforestry Systems* **3**, 37–45.
- Anon (1991) *The Role of Trees in Sustainable Agriculture. Proceedings of a National Conference*. 30 September–3 October, Albury Convention Centre, Albury, NSW.
- Armstrong DV (1994) Heat stress interaction with shade and cooling. *Journal of Dairy Science* **77**, 2044–2055.
- Bianca W (1976) The significance of meteorology in animal production. *International Journal of Biometeorology* **20**(2), 139–156.
- Bird PR (1998) Tree windbreaks and shelter benefits to pasture in temperate grazing systems. *Agroforestry Systems* **41**, 35–54.
- Bird PR, Bicknell D, Bulman PA, Burke SJA, Leys JF, Parker JN, Van der Sommen FJ and Voller P (1992) The role of shelter in Australia for protecting soils, plants and livestock. *Agroforestry Systems* **20**, 59–86.
- Bird PR, Cayley JWD, Kearney GA and Aldridge EK (1994) Pasture growth among various tree species grown at various spacings. In *Faces of Farm Forestry. Proceedings of AFG Conference*. Australian Forestry Group. pp. 297–300.
- Bird PR, Jackson TT, Kearney GA and Roache A (2007) Effects of windbreak structure on shelter characteristics. *Australian Journal of Experimental Agriculture* **47**, 727–737.
- Bino B (1994) Soil properties under *C. cunninghamiana* in N. Victoria. Master of Forest Science thesis. University of Melbourne.
- BOM (2006) About the WBGT and apparent temperature indices. <http://www.bom.gov.au/info/thermal_stress/#wc>.
- Breckwoldt R (1983) *Wildlife in the Home Paddock*. Angus & Robertson, Sydney.
- Burke S (1998) *Windbreaks*. Inkata Press, Melbourne.
- Cameron DM, Rance SJ, Jones RM, Charles-Edwards DA and Barnes A (1989) Project STAG: an experimental study in agroforestry. *Australian Journal of Agricultural Research* **40**, 699–714.
- Chapman B, Penman D and Hicks P (1986) *Natural Pest Control: An Australian Guide for Commercial Growers, Orchardists and Farmers*. Nelson, Melbourne.
- Cleugh H (2003) 'Trees for shelter: a guide to using windbreaks on Australian farms'. Joint Venture Agroforestry Program, Rural Industries Research and Development Corporation, Canberra.
- Daly JJ (1984) Cattle need shade trees. *Queensland Agricultural Journal* **110**(1), 21–24.
- Davidson R and Davidson S (1992) *Bushland on Farms: Do You Have a Choice?* AGPS, Canberra.
- Davison T, McGowan M, Mayer D, Young B, Jonsen N, Hall A, Matschoss A, Goodwin P, Goughan J and Lake M (1996) *Managing Hot Cows in Australia*. Queensland Department of Primary Industry.
- Donnelly JR (1984) The productivity of breeding ewes grazing on lucerne or grass and clover pastures on the Tablelands of Southern Australia. III. Lamb mortality and weaning percentage. *Australian Journal of Agricultural Research* **35**, 709–721.
- Donnelly JB, Lynch JJ and Webster MED (1974) Climatic adaption in recently shorn merino sheep. *International Journal of Biometeorology* **18**, 233–247.
- Dunbabin T (2007) Nature conservation on private land: not just threatened species. Paper

- presented at *Biodiversity: Balancing Conservation and Production*. 26–28 June, Launceston, Tas. Tamar NRM.
- Goodyer GJ (2007) Scarab grubs in northern tableland pastures. *Primefact 512*, NSW Department of Primary Industries.
- Gordon ND, McMahon TA, Finlayson BL, Gippel CJ and Nathan RJ (2004) *Stream hydrology. an introduction for ecologists*. John Wiley & Sons, New York.
- Gregory NG (1995) The role of shelterbelts in protecting livestock: a review. *New Zealand Journal of Agricultural Research* **38**, 423–450.
- Haines PJ (1997) 'Integrating trees with livestock grazing'. Rural Industries Research and Development Corporation, Canberra. Research Paper Series, no. 97/47.
- Hairsine P (1997) 'Controlling sediment and nutrient movement within catchments'. Cooperative Centre for Catchment Hydrology, Industry Report 97/9, October 1997.
- Hawke MF and Wedderburn ME (1994) Microclimate changes under *Pinus radiata* agroforestry regimes in New Zealand. *Agricultural and Forest Meteorology* **71**, 133–145.
- Heisler GM and Dewalle D (1988) Effects of wind-break structure on wind flow. *Agriculture Ecosystems and Environment* **22/23**, 41–69.
- Howden SM and Turnpenny J (1998) 'Modelling heat stress and water loss of beef cattle in subtropical Queensland under current climates and climate change'. CSIRO Wildlife and Ecology, Resource Futures Program. Working Document 98/03.
- Jackson J and Ash AJ (1998) Tree–grass relationships in open eucalypt woodlands of north-eastern Australia: influence of trees on pasture productivity, forage quality and species distribution. *Agroforestry Systems* **40**, 159–176.
- Kellas JD, Bird PR, Cumming KN, Kearney GA and Ashton AK (1995) Pasture production under a series of *Pinus radiata*-pasture agroforestry systems in south-west Victoria, Australia. *Australian Journal of Agricultural Research* **46**, 1285–1297.
- Kingma OT (1974) Recursive economic systems, land tenure and multiple use management. PhD thesis. University of New England, Armidale.
- Knowles RL, Hawke MF and Maclaren JP (1993) Agroforestry research at Tikitere. Unpublished report of the NZ Forest Research Institute.
- Lynch RJ and Catterall CP (1999) Riparian wildlife and habitats. In *Riparian Land Management Technical Guidelines. Vol. 1. Principles of Sound Management*. (Eds S Lovett and P Price) pp. 121–136. LWRRDC, Canberra.
- McCraib GJ, McDonald BJ and Hennoste LM (1993) Lamb birthweight in sheep differently acclimatized to a hot environment. *Australian Journal of Agricultural Research* **44**, 933–943.
- McNaughton KG (1988) Effects of windbreaks on turbulent transport and microclimate. *Agriculture Ecosystems and Environment* **22/23**, 17–40.
- Nageli W (1964) On the most favourable shelterbelt spacing. *Scottish Forestry* **18**, 4–15.
- Percival N and Knowles R (1986) Relationship between radiata pine and understorey pasture production. In *Agroforestry Symposium Proceedings*. 24–27 November. *FRI Bulletin* **139**, 152–164.
- Pitt AJ (1981) A study of the land in the catchments of the Otway Range and adjacent plains. Soil Conservation Authority, Victoria. <<http://www.catchment.crc.org.au/pdfs/industry199709.pdf>>.
- Pollard JC (1999) Shelter benefits for lamb survival in southern New Zealand. 1. Postal survey of farmers' opinion. *New Zealand Journal of Agricultural Research* **42**, 165–170.
- Power I (2002) Tree/pasture interactions with blackwood. In *Blackwood Workshop: Field Day, 23 November 2002*. (Ed. ID Nicholas) pp. 59–64.
- Power IL, Dodd MB and Thorrold BS (1999) A comparison of pasture and soil moisture under *Acacia melanoxylon* and *Eucalyptus nitens*. *Proceedings of the New Zealand Grassland Association* **61**, 203–207.
- Prinsley RT and Swift MJ (1986) *Amelioration of Soil by Trees: A Review of Current Concepts and Practices*. Commonwealth Science Council, London.
- Prosser I, Bunn S, Mosisch T, Ogden R and Karrsies L (1999) The delivery of sediment and nutrients to streams. In *Riparian Land Management Technical Guidelines. Vol. 1. Principles*

- of *Sound Management*. (Eds S Lovett and P Price) pp. 37–60. LWRRDC, Canberra.
- Reid R and Bird PR (1990) Shade and shelter. In *Trees for Rural Australia*. (Ed. KW Cremer) pp. 319–334. Inkata Press, Melbourne.
- Reid R and Burk L (nd) A web of trees: reconnecting the landscape and the community. Otway Agroforestry Network. <<http://www.mtg.unimelb.edu.au/publications/Web%20of%20trees-72.pdf>>.
- Reid RF and Wilson G (1985) *Agroforestry in Australia and New Zealand*. Goddard & Dodson, Melbourne.
- Roberts G (1984) Plotting a better future for lambs. *Queensland Agricultural Journal* **110**(1), 25–26.
- Salisbury FB and Ross CW (1992) *Plant physiology*. 4th edn. Wadsworth Publishing, California.
- Shashua-Bar L and Hoffman ME (2000) Vegetation as a climatic component in the design of an urban street: an empirical model for predicting the cooling effect of urban green areas with trees. *Energy and Buildings* **31**, 221–235.
- Stanton J and O'Sullivan J (2006) *Stock and Waterways: A Manager's Guide*. Land and Water Australia, Canberra.
- Stirzaker R, Vertessy R and Sarre A (2002) *Trees, Water and Salt: An Australian Guide to Using Trees for Healthy Catchment and Productive Farms*. Joint Venture Agroforestry Program, Rural Industries Research and Development Program, Canberra.
- Taylor DW, Dunn GM and Nester MR (1996) Agroforestry in southern Queensland. In *Managing and Growing Trees Training Conference*. (Ed. A. Grodecki) vol. 2, pp. 352–356. Department of Natural Resources, Brisbane.
- Tsitsilas A, Stuckey S, Hoffmann AA, Weeks AR and Thomson LJ (2006) Shelterbelts in agricultural landscapes suppress invertebrate pests. *Australian Journal of Experimental Agriculture* **46**, 1379–1388.
- Williams DG, Wallance P, McKeon GM, Hall W, Katjiua M and Abel N (1999) 'Effects of trees on native pasture production on the Southern Tablelands'. Rural Industries Research and Development Program, Canberra. Publication no. 99/165.
- Wilson SM, Whitham JAH, Bhati UN, Horvath D and Tran YD (1995) Survey of trees on Australian farms: 1993–94. ABARE, Canberra. ABARE Research Report 95.7.

Saltbush for forage production on saltland

EG Barrett-Lennard and HC Norman

Introduction

The growth of saltbush (*Atriplex* species) provides a revegetation option suited to saltland in the 300–450 mm rainfall zones of southern Australia. The major species currently used are the Australian native species old man saltbush (*A. nummularia*) and river saltbush (*A. amnicola*), and the exotic wavy-leaf saltbush (*A. undulata*). Further information on these species is given in Box 14.1.

Saltbushes have a long history of use as forage plants in the drier areas of Australia. Originally the focus was on the use of native stands of saltbushes. On the riverine plains of the Murray-Darling Basin, stands of old man saltbush and bladder saltbush (*A. vesicaria*) were grazed (and in many cases grazed out) after the outset of European settlement in the early 1800s. Pastoral industries were based on the exploitation of saltbush stands in the Murchison and Gascoyne River catchments of Western Australia after the 1860s (Curry *et al.* 1994). In agricultural regions, the focus has been on the use of saltbush plantations as forage banks to be exploited in times of drought or as forage for salt-affected land (Teakle and Burvill 1945; Malcolm and Swaan 1989). This chapter focuses on the latter use of saltbush, although some of the comments will be relevant to the value of saltbush in other applications.

Saltland in Australia

Land affected by salinity falls into two categories: primary salinity (land that is naturally saline) and

secondary salinity (land that has become saline due to human activities).

Australia has about 32 million ha of salt-affected land, most of which has primary salinity and is located in rangeland areas (Standing Committee on Soil Conservation 1982). Secondary salinity usually affects agricultural or irrigated land of higher value.

Two factors are required for land to become affected by secondary salinity – a source of salt stored in the soil and a hydrological disturbance that mobilises the stored salts and transports them to the surface.

Salt stores

Most of the salt stored in Australia's ancient soil profiles originated as air-borne saline dust blown inland from the sea and dissolved in rain. The concentration of salt in rainfall decreases with increasing distance from the coast. In Western Australia, Hingston and Gailitis (1976) showed that large quantities of salt (>200 kg/ha) are precipitated annually at coastal centres in the south-west of the state. This annual amount decreases to ~100 kg/ha approximately 30 km inland, and to 60–80 kg/ha approximately 200 km inland. Drill cores taken from soil profiles of the Belka Valley show these soils contain an average of about 650 t of salt per hectare between the soil surface and the basement rock (Bettenay *et al.* 1964). Since the rainfall contains about 6 mg of salt per litre and the annual rainfall is about 300 mm, it can be calculated that these salts have accumulated over about 36 000 years (Barrett-Lennard and Nulsen 1989). This is a

BOX 14.1

Three major saltbush species grown on saltland in Australia

Old man saltbush (*A. nummularia*) is Australia's iconic saltbush species, native to the semi-arid and arid zones of southern and central Australia. It grows well on saline and rangeland soils and is deeper-rooted (down to ~4 m) than many other saltbushes (Jones and Hodgkinson 1969). Given its deeper root system it can be sensitive to waterlogging, particularly at high temperatures (Galloway and Davidson 1993). Symptoms of waterlogging damage include bleaching of the leaves (Barrett-Lennard *et al.* 2003).

Old man saltbush lives for long periods and can remain productive for decades. The species has a relatively poor ability to produce volunteer seedlings, so it does not self-regenerate successfully in commercial plantings. The main disadvantages as forage for livestock are its low biomass production (<1 kg of leaves and edible stems/plant/yr⁻¹), salt accumulation in leaves (up to 28% of dry matter), low to moderate energy concentration and variable palatability (Norman *et al.* 2004). It is a good source of crude protein and recovers well from grazing. Its erect growth habit (up to 2 m) offers shelter for stock but puts some of the leaves above grazing height for sheep. It has been advocated as a drought reserve in New South Wales and has shown good survival after severe frosts.

In South Australia, a cloned variety, 'Eyes Green' (PBR), has been selected for its low growth habit and palatability. It is propagated vegetatively.

River saltbush (*Atriplex amnicola*) comes from the floodplains of the Murchison and Gascoyne Rivers of Western Australia. Its habit can vary from prostrate to erect and individual plants vary in size from 1 m across and 1 m high to 4 m across and 2.5 m high (Runciman and Malcolm 1989). Established plants have good waterlogging tolerance and can survive partial inundation in winter.

River saltbush has excellent long-term survival, recovery from grazing and palatability (Malcolm and Swaan 1989) and has been widely grown in mixed plantings in the Western Australian wheatbelt. Disadvantages include low biomass production (<1 kg of leaves and edible stems/plant/yr⁻¹), salt accumulation in leaves (up to 24% of dry matter) and low to moderate energy concentration. Establishment from seed can be difficult, especially if correct establishment procedures are not followed. Germination is improved by exposure to light (Vlahos 1997; Stevens *et al.* 2006), hence the need for shallow sowing. River saltbush is a subtropical species and best suited to the northern agricultural areas.

Two ecotypes, 'Meeberrie' and 'Rivermor', which are both public varieties, were selected for ease of establishment.

Wavy-leaf saltbush (*A. undulata*) comes from the semi-arid rangelands of central Argentina and, as the name suggests, has crinkly or wavy leaves. Established plants can reach 1 m high and 2 m across, and stems touching the ground can form roots. It establishes readily from seed using the niche seeder. It has a lower waterlogging tolerance and prefers cooler climates than does river saltbush (Hearn 1991).

comparatively short period in an environment where soil formation has been occurring for millions of years.

Hydrological disturbance

This arises with the introduction of irrigation or the removal of native vegetation and replacement by annual crops and pastures. In the original landscape, the native vegetation systems used virtually all the rainfall. Irrigation or the replacement of perennial with annual plants has increased percolation into the groundwater aquifers, causing a rise in watertables, mobilisation of salt stored in the soil and, where watertables rise to within 2 m of the soil surface, a loss in growth of crops and pastures (Nulsen 1981).

Australia has a substantial secondary salinity problem, but the exact area of land at risk is unclear. In 2001, the National Land and Water Resources Audit estimated that southern Australia had 5.7 million ha at high risk of secondary salinity, comprising 77% in Western Australia, 12% in Victoria, 7% in South Australia, 3% in New South Wales and less than 1% in Tasmania. Furthermore, the total area at risk by 2050 could increase to 17 million ha (National Land and Water Resources Audit 2001). These estimates are now regarded as excessive, but only one state has revised its estimates of areas at risk. In Western Australia it is now believed that there are 1–1.2 million ha of severely salinised land and 2.8–4.4 million ha of land with a high hazard of secondary salinity (McFarlane *et al.* 2004).

Variation in the severity of salinity will affect farmers' incentives to adopt saltland revegetation. For farmers affected by small amounts of salinity, the most powerful motivation may be to cover up and green areas that have become eyesores. However, for farmers with much larger salt-affected percentages of the farm, the incentives for adoption would be more economic: revegetation solutions would need to be profitable in their own right, or farmers would need subsidies to implement the option.

Salinity, waterlogging and inundation

In salt-affected areas such as the margins of salt-lakes in natural (uncleared) landscapes, there is an

ecological transition from the inundated edge of the lake (often bare) to the unaffected land higher in the landscape (which often grows eucalypt woodland with a shrubby or grassy understorey). In such landscapes there is variation in soil productivity; near the lake fringe productivity is negligible but higher in the landscape it increases. This variation is largely caused by differences in the levels of three soil constraints – salinity, waterlogging and inundation (Barrett-Lennard *et al.* 2003).

Salinity

Saline soils affect the growth of plants mainly because of high concentrations of dissolved sodium and chloride ions in the soil. Soils may also contain significant concentrations of magnesium, sulphate, carbonate, bicarbonate and boron.

Salinity can affect plants in a number of ways (Greenway and Munns 1980; Marschner 1995). First, it makes it more difficult for roots to take up water due to the decreased osmotic potential. Plants may have difficulty withdrawing water from what appear to be moist soils. Second, a build-up of salt in the leaves, especially old leaves, can lead to necrosis (Barrett-Lennard *et al.* 1999). The overall effect on the plant depends on the rate of new growth compared with the rate of leaf necrosis. Third, high sodium and chloride concentrations in the soil may affect the uptake of other nutrients, e.g. potassium, magnesium, nitrogen and phosphorus, which are essential for plant growth.

The most common way of assessing the salinity of a soil is to extract the salt in water and measure its electrical conductivity (EC). Salt solutions are conductive because of the electrical charges on the ions. For most practical purposes, the conductivity of soil extracts is proportional to the salt concentration. Electrical conductivities of soil extracts are most commonly reported in deci-siemens per metre (dS/m). For sodium chloride solutions, conversions can be made between units on the basis that 1 dS/m is approximately equal to 584 ppm.

Plants can be broadly divided into three groups according to their growth response to salinity (Figure 14.1).

- Halophytes (salt plants) – halophytes actually have increased growth at mildly saline soils (compared with non-saline soils) but have

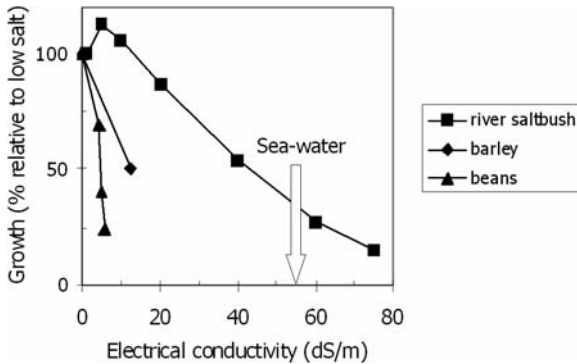


Figure 14.1: Growth response of three plant species to salinity. Barley and beans are typical non-halophytes, while river saltbush is a typical halophyte (data from Gauch and Eaton 1942; Greenway 1965; Eaton 1942; Aslam *et al.* 1986).

decreased growth at much higher concentrations. River saltbush is a typical example (Aslam *et al.* 1986). It has a 10% increase in shoot dry weight at 5 dS/m (a salt concentration equivalent to ~9% of seawater), a 50% decrease in growth at 40 dS/m (equivalent to ~70% of seawater) and is still alive at 75 dS/m (equivalent to ~140% of seawater).

- Salt-tolerant non-halophytes – these plants maintain growth at low salt concentrations, but have decreased growth at higher concentrations. Barley (*Hordeum vulgare*) is a typical example (Gauch and Eaton 1942; Greenway 1965). It has a 50% reduction in shoot growth at 13 dS/m (equivalent to ~20% of seawater).
- Salt-sensitive non-halophytes – the growth of these plants is sensitive even to low concentrations of salt. Beans (*Phaseolus vulgaris*) are typical (Eaton 1942), with a 50% decrease in growth at salt concentrations of 5 dS/m (equivalent to ~9% of seawater).

Waterlogging

Waterlogging refers to the saturation of the root zone with excess water. This inhibits gaseous exchange between soil and atmosphere, leading to a dramatic decrease in the concentration of oxygen in the soil and an accumulation of ethylene and various products of anaerobic metabolism such as carbon dioxide and ethanol (Drew 1983b, 1997). Roots normally require oxygen for the optimal production of energy from sugars. Waterlogging

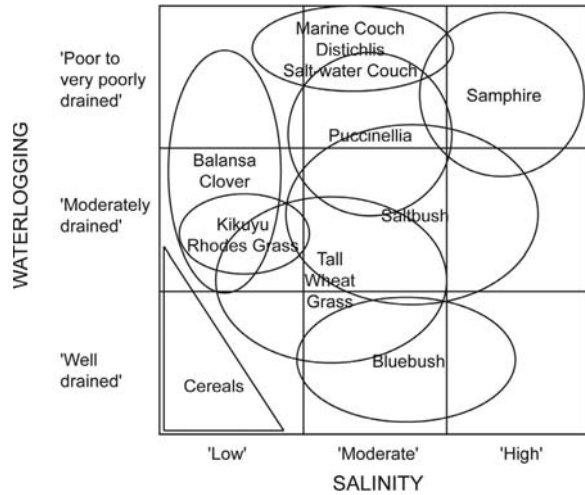


Figure 14.2: Relative tolerances of different saltland pasture species to salinity and waterlogging (after Barrett-Lennard *et al.* 2003).

therefore causes immediate decreases in the growth of roots and subsequently of shoots, rapid death of root tips and eventually of previously developed roots, and decreases in the activity of all processes associated with active ion transport across membranes, such as the uptake of inorganic nutrients.

Most importantly, under saline conditions, waterlogging causes plants to increase their rate of salt uptake, increasing the concentrations of salt in the shoots and jeopardising growth and survival (Barrett-Lennard 2003).

Much of Australia’s saltland is subject to waterlogging because of the presence of shallow groundwater and/or shallow duplex soils with impermeable clay subsoils. The importance of waterlogging is often underestimated, since it is not often visible at the soil surface and can be ephemeral (McFarlane *et al.* 1989).

For saltland pastures, one of the keys to profitability is to grow the right plant in the right place. Waterlogging on saltland will affect the growth of all but the most tolerant plants. The matrix in Figure 14.2 shows where different plants have a competitive advantage in soils of differing levels of salinity and waterlogging.

Inundation

Inundation refers to water ponding on the soil surface. The effect on plants is severe because inundated plants cannot photosynthesise and few plants

survive if they are completely submerged. Flooding is similar but refers to water flowing outside its usual channel, whether that is a river or a small drainage line.

As salinity in valley floors increases because of shallow watertables, inundation and flooding will become more severe (Bowman and Ruprecht 2000). Less rainfall can infiltrate the soil, so more becomes available for run-off. Even brief periods of inundation appear highly damaging to plants and the environment. There is only limited anecdotal evidence of the tolerance of different plants to inundation. One mechanism by which plants avoid inundation is to grow quickly so that total immersion in water is avoided (Barrett-Lennard *et al.* 2003).

Implications for drainage

Understanding the interactions between waterlogging, inundation and salinity can help with the design of drainage. The level of drainage required to decrease soil salinity can be substantial. Depending on soil texture and rainfall, the watertable may need to be drawn-down to critical depths greater than 2 m from the surface (Nulsen 1981). However, studies of the interaction between waterlogging and salinity show that substantial improvements in plant growth are possible with slight decreases in waterlogging. These kinds of changes may be achievable with relatively cheap structures (banks and surface drains) that improve the control of surface water. Saltland pastures should be established once waterlogging has been slightly alleviated. Further lowering of the watertable may be possible through the transpiration of shallow groundwater by these salt-tolerant plants.

Matching sites to pastures

If profitability is to be maximised, revegetation with saltbush needs to be focused on the saltland of greatest capability. We broadly distinguish between three levels of saltland capability when considering revegetation with saltbush (Barrett-Lennard *et al.* 2003).

- Severely affected land – this is subject to high levels of salinity and waterlogging and may have saline groundwater at depths of less than ~1 m in summer (Nulsen 1981). It may be bare

or have a cover of samphire (*Halosarcia* spp.) and an understorey of curly rye grass (*Parapholis incurva*) or iceplant (*Mesembryanthemum nodiflorum*). Land of this type is not suited to the growth of saltbushes. It should be fenced and allowed to revegetate naturally. If protected from grazing, it will grow samphire species and salt- and waterlogging-tolerant trees such as swamp sheoak (*Casuarina obesa*).

- Moderately affected land – this category is usually found at slightly higher elevations than severely affected land. It has lower levels of salinity and waterlogging, and typically has saline groundwater at depths of 0.8–1.6 m in summer (Nulsen 1981). The typical plant indicator for this land is sea barley grass (*Hordeum marinum*). Land of this capability will support stands of saltbush of ~1000 stems/ha (Malcolm *et al.* 1988).
- Mildly affected land – this occurs at higher elevations in the landscape than moderately affected land, has even lower levels of salinity at the soil surface and typically has saline groundwater at depths greater than 1.2 m from the soil surface in summer (Nulsen 1981). The typical plant indicator for this land is annual rye grass (*Lolium rigidum*). This land is capable of growing wider-spaced rows of saltbush with highly productive understorey of annual salt- and waterlogging-tolerant legumes such as burr medic (*Medicago polymorpha*) and balansa clover (*Trifolium michelianum*).

Saltbushes as pastures

Saltbushes have major benefits as saltland pasture species for mildly and moderately affected saltland.

- Animal nutrition – saltbushes have some advantages as forage (good crude protein and vitamin E concentrations in the leaves). However, they also have disadvantages – high salt accumulation, marginal energy concentrations and secondary compounds such as nitrates, betaines and oxalates in the leaves.
- Increased profitability – saltbush forage can be a profitable maintenance feed for sheep in autumn when other sources of herbage are scarce.
- Increased water use – saltbushes use groundwater in summer, which can lower the watertable

so that understorey species of higher productivity and nutritive value can be grown.

These three areas are discussed below.

Animal nutrition

Productivity of animals in extensive grazing systems is determined by plant dry matter (DM) production (quantity grown and time of production) and its feeding value. Feeding value is defined as 'the animal production response to grazing a forage under unrestricted conditions' and is a function of voluntary feed intake and nutritive value (Ulyatt 1973). Saltbush has a number of unique characteristics compared to many forages that are used in grazing systems.

Biomass production

Published productivity figures for saltbush show considerable variability. For example, old man saltbush stands grown under saline irrigation in Arizona are capable of providing 2.2–5.3 t of edible DM (leaves and small stems) per ha each year (Watson and O'Leary 1993) whereas saltbush stands growing on moderately saline sites in Australia would rarely produce more than 1 t of edible DM/ha/yr⁻¹. Twigs with a diameter >3mm should not be regarded as edible DM.

Time of biomass availability

The cost of carrying sheep and cattle through periods of feed shortage is a major limitation to profitability of mixed farming systems in southern Australia. In Mediterranean-type environments this scarcity occurs during the late summer/autumn/early winter period. Biomass that is available to animals during periods of feed shortage has a higher marginal value than herbage produced in the spring. So, although saltbush may not produce large quantities of biomass, the biomass it does produce has relatively high value. Economic modelling indicates that an additional kilogram of pasture produced in the wheatbelt in May has 10 times the value of an extra kilogram of equivalent quality feed in October (Morrison and Bathgate 1990).

Voluntary feed intake

Variation in voluntary feed intake accounts for at least 50% of the variation observed in feeding value

of forages (Ulyatt 1973). Factors influencing voluntary feed intake include gut fill (Weston 1996), clearance rate of digesta from the rumen (influenced by digestibility), energy, protein content, palatability, feeding behaviour (including time spent grazing), bite weight and rate (influenced by pasture morphology) and class of animal. Digestibility and salt are the factors most likely to restrict voluntary feed intake of saltbush, however, shrub architecture and secondary compounds may also play a role.

Digestibility of herbage has a large influence on voluntary feed intake as it determines the rate at which plant material is cleared through the rumen. Put simply, animals can only eat as fast as the rumen clearance rate will allow. Salt accumulation in the leaves of saltbushes results in ash levels in the forage ranging from 15% to 27% (Warren *et al.* 1990; Norman *et al.* 2004). These levels of salt depress both feed intake and digestibility of the feed (Masters *et al.* 2005). Sheep will stop eating salty forage after they have ingested approximately 200 g salt/day (Masters *et al.* 2007).

Palatability (or feed preference) depends on any characteristic of the feed that increases or inhibits intake of forage whether the forage is offered alone or as a mixed sward. If an animal rejects forage, that forage is of reduced feeding value even if its nutritive value is high. There is a range of secondary compounds, associated with palatability, in saltbushes (Norman *et al.* 2004).

Nutritive value

Nutritive value refers to the responses in animal production per unit of voluntary feed intake and is a function of the digestibility of nutrients and the efficiency with which the nutrients are used for maintenance or growth. Metabolisable energy (ME) and crude protein are important components of the nutritive value of feeds.

ME is the amount of energy available for absorption after digestion and fermentation of the feed consumed. The energy value of feeds can be characterised as the megajoules of ME/kg of DM at the maintenance level of feeding (M/D). The ME content of saltbushes is generally low to moderate and may not be high enough for maintenance of dry sheep without supplements. Saltbush has moderate to high levels of crude protein (11–14%), but much of the nitrogen in saltbush is in the form of non-protein compounds such as glycine betaine (up to

an equivalent of 4% crude protein) and nitrate (up to an equivalent of 2–3% crude protein; Masters *et al.* 2001). This nitrogen can only be converted to protein by microbes in the rumen and therefore an adequate supply of fermentable energy for the microorganisms is required.

What does all this mean in terms of animal production? If we consider typical saltbush-based pasture in a moderately saline area in autumn with 1000 saltbush stems/ha, there will be approximately 450–900 kg of edible saltbush biomass. The saltbush is likely to have an M/D of 7.6, 25% ash (of which 21% is soluble salts) and 13% crude protein. Due to the salt concentration, a 50 kg mature wether will stop eating saltbush biomass after ingesting about 800 g of DM, 250 g short of the 1050 g of DM required to maintain liveweight (based on GrazFeed predictions: Masters *et al.* 2007; Freer *et al.* 1997). In addition, up to 8 g of nitrogen will be excreted as there is not enough energy for conversion to microbial protein in the rumen (Norman *et al.* 2004). Another form of feed is required for the animal to maintain weight. Feed may be in the form of understorey plants, adjacent stubbles or supplements. In autumn, dead understorey plants (curly ryegrass, barley grass and clovers) are likely to have variable energy (M/D 6.1–8.5, H. Norman unpub.) but they do not accumulate high concentrations of salt. They give a 50 kg wether a low-salt alternative in order to achieve maintenance. The understorey may provide enough energy to achieve maintenance for a time, but it is likely that energy will become limiting when the best components have been eaten. At that time, productivity is likely to be increased through high-energy supplements such as cereal grain or high-quality hay.

Saltbush may offer additional benefits to animals, for example by providing vitamin E (α -tocopherol), a powerful antioxidant present in green plants. Deficiency can cause nutritional myopathy in weaner sheep (Steele *et al.* 1980), especially when they have grazed dry feed for an extended period. Subclinical nutritional myopathy is not detrimental to liveweight gain or wool production and can often go unnoticed (Fry *et al.* 1996), but clinical deficiency may cause death. Pearce *et al.* (2005) found that weaner sheep grazing saltbush had much higher vitamin E levels in their muscle and liver tissues than did sheep graz-

ing stubbles. This translated to improved meat quality, as vitamin E slows the rate of browning in fresh meat (Pearce *et al.* 2005).

Research and producer experiences show that there are two main options to the grazing of saltbush-based pastures:

- on moderately affected saltland, grow fairly dense stands of shrubs and provide a supplement of good-quality hay or small amounts of grain;
- on mildly affected saltland, grow more widely spaced rows of shrubs with an understorey of tolerant annual legumes. The understorey is the key to productivity. If grazing in autumn, be prepared to supplement animals after they have eaten the high-energy components of the understorey or intensify the grazing so that animals have less opportunity to select among the plants on offer.

Profitability

Current economic analyses suggest that the main value of saltland pastures is in providing a source of feed in autumn. A recent analysis of a hypothetical 2000 ha property on the south coast of Western Australia suggested that revegetating 2.5% of the farm to saltbush could increase the profitability of the whole farm by 5% (O'Connell *et al.* 2005). Profit could be further improved if both the nutritive value and production of the saltland pasture were increased. Sensitivity analyses suggest that improving the nutritive value of the saltbush-based pasture in summer/autumn by 10% will yield three times more return than increasing the amount of autumn feed on offer by 10% (O'Connell *et al.* 2005).

Water use

One of the major benefits of planting perennial plants into saline landscapes is that they will use groundwater, lower watertables and create an environment in which salt can be leached from the soil profile. This will enhance the growth of less salt-tolerant understorey species.

In general, water moves into root zones through the infiltration of rainfall or the upward movement of groundwater through capillarity. The relative

significance of these two factors depends on the amount and frequency of rainfall, the depth of roots relative to the watertable and soil texture. In landscapes with deep watertables, the bulk of the water accessible to roots arises from the infiltration of rainfall. In landscapes with shallow watertables, groundwater is the most continuously available source of water for plants. In such soils, plants can only dry out the soil profile if they can transpire stored soil moisture faster than it can be restored by capillarity from the watertable.

There is evidence to suggest that saltbushes can both dry out soil profiles and lower watertables.

Drying of soil profiles

Evidence for soil profile drying comes from two sources: salt accumulation in the root zone and neutron moisture metering. In general, plants take up water faster than they take up salt (Sinha and Singh 1974, 1976). Therefore, if there is a mass flow of groundwater into the root zone, the rate of salt accumulation can be used to estimate the rate of groundwater use by plants. This principle was used by Barrett-Lennard and Malcolm (1999) to estimate water use by five species of saltbush. They found that the saltbush stands used (transpiration plus evaporation) 60–100 mm of groundwater over a two-year period (460 mm of rain fell in that period). Groundwater use was proportional to the weight of saltbush leaf per unit soil surface area. With bladder saltbush (the smallest species in the experiment), ventilated chamber measurements showed that evapotranspiration in summer was 1.3–3.3 mm/day (Greenwood and Beresford 1980). More recently, Barrett-Lennard and Altman (unpub.) examined the effects of single rows of saltbush on soil moisture stores using the neutron moisture meter. They found that water use was highly seasonal (far greater in summer than in winter), watertables must be 1.5–2.0 m deep for the drying effects to persist through the winter, and the level of drying was increased by leaf density.

Lowering of watertables

Anecdotal evidence has suggested that watertables can fall in landscapes in which saltbushes have been planted. For example, at a site near Pingaring in Western Australia, watertables were 0.2–2.1 m deep and a stand of saltbush increased their depth

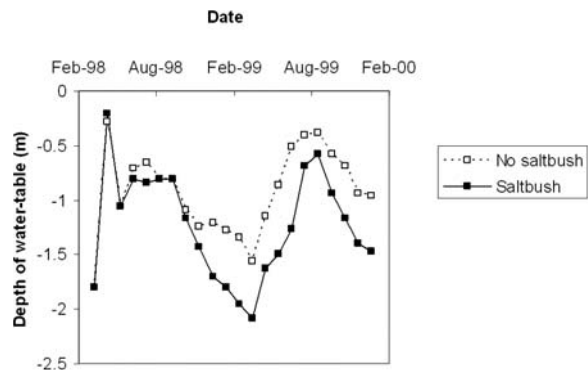


Figure 14.3: Effects of a mixed stand of old man saltbush (*A. nummularia*), river saltbush (*A. amnicola*) and wavy-leaf saltbush (*A. undulata*) on watertable depth at a saline site at Pingaring, Western Australia (Barrett-Lennard 2002).

by 40 cm after 18 months (Figure 14.3). However, it needs to be stressed that these are unreplicated data. More recently, Barrett-Lennard and Altman (unpub.) showed that single rows of saltbushes can cause a 2–5 cm watertable draw-down over a distance of 6 m (four sites, mean of six replicates). In investigations at two sites, stands of saltbush have drawn down watertables in summer over distances of ~15 m by 16 cm (mean of four replicates) and by up to 60 cm (one replicate).

Establishing saltbush

Niche seeding

Saltbushes have dimorphic flowering systems and many of them are dioecious, i.e. they have male and female flowers on separate bushes (Flora of Australia 1984). This reproductive strategy produces high levels of genotypic variation within populations. Female plants produce a fruit that contains a single seed, but fruits will be empty if they develop without a nearby source of pollen (Strawbridge *et al.* 1997). There is a clear warning in this observation – fruit fill must be checked before use in direct seeding.

Seeds on saltland germinate naturally in protected niches such as areas that are protected from drying winds by debris on the soil surface. Niche seeders (Malcolm and Allen 1981) attempt to reproduce such protected sites artificially. Niche seeders deposit fruits of saltbush or bluebush and a covering of vermiculite at 1–3 m intervals on a

raised M-shaped mound. The shape of the mound promotes leaching of salt from the seedbed, while the vermiculite acts as a mulch, retaining moisture around the fruits and decreasing the movement of salt into the seedbed by capillarity. The elevation of the seedbed above the surrounding soil reduces waterlogging.

There are several important factors in successful niche seeding.

- Good site selection – in Western Australia, best results have been achieved on sandy and deeper duplex soils (Vlahos 1997). Avoid grey clays and sites that grow samphire (too saline/waterlogged). Also avoid sites that grow annual legumes and capeweed – even with the use of knockdown herbicides, such low-salinity sites may allow sufficient weed growth to threaten saltbush establishment.
- Good weed control – spraytop the year before establishment and use knockdown herbicides prior to seeding.
- Reduce waterlogging and inundation – reduce overland flow onto saltland by using seepage interceptors, drains and banks. Remove surface water from saltland using W-drains. Plan niche seeding so mounds and furrows direct water into surface drains.
- Use seeding rates appropriate for the seed quality – fruit quality can be highly variable and seed fill is often less than 20%. Seed should be sown at rates high enough to have 50 germinable seeds per placement (Vlahos *et al.* 1991).
- Control insects – the use of systemic insecticides to control red-legged earth mites and other insects is essential if these are present during establishment.
- Good timing – sow late enough to avoid winter waterlogging but early enough to avoid the drying conditions of late spring.
- Control grazing until plants are well-established.

Planting nursery-raised seedlings

Nursery-raised seedlings can be planted using commercial tree planters. This technique is generally more reliable than direct seeding, especially into clayey soils (Barrett-Lennard *et al.* 1991). However, the use of seedlings is relatively expensive as nurseries sell saltbushes for ~\$0.25. On this basis a

stand of 1000 plants/ha would cost \$250/ha, a cost that does not include transport, site preparation and planting.

Bare-rooted seedlings, i.e. seedlings with no soil around the root, can be raised on the farm at low cost. This method can give good results when sown onto non-saline soils, but has had only limited success on saline soils. This is probably due to root damage during planting and osmotic shock from a lack of salt-hardening (Barrett-Lennard *et al.* 2003).

Conclusion

Saltbushes (*Atriplex* spp.) are a viable revegetation option for saltland in the 300–450 mm rainfall zones of southern Australia. Saltbushes use rainfall throughout the year and therefore offer environmental benefits in terms of managing salinity. Profits from saltbush stands are derived through livestock production, particularly during feed gaps associated with autumn and early winter. The high salt content of leaves present management challenges, however, and supplements, in the form of grain or high-quality understorey biomass, should be included in grazing systems. Establishment can be expensive so it is important to choose the target site carefully and use good agronomic practices.

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References

- Anon (2003) 'Salinity investment framework interim report: phase 1'. Salinity and Landuse Impacts, Department of Environment, Perth. Report no. SLUI 32.
- Aslam Z, Jeschke WD, Barrett-Lennard EG, Greenway H, Setter TL and Watkin E (1986) Effects of external NaCl on the growth of *Atriplex*

- ammicola* and the ion relations and carbohydrate status of the leaves. *Plant Cell and Environment* **9**, 571–580.
- Barrett-Lennard EG (2002) Restoration of saline land through revegetation. *Agricultural Water Management* **53**, 213–226.
- Barrett-Lennard EG (2003) The interaction between waterlogging and salinity in higher plants: causes, consequences and implications. *Plant and Soil* **253**, 35–54.
- Barrett-Lennard EG and Malcolm CV (1999) Increased concentrations of chloride beneath stands of saltbushes (*Atriplex* species) suggest substantial use of groundwater. *Australian Journal of Experimental Agriculture* **39**, 949–955.
- Barrett-Lennard EG and Nulsen RA (1989) Dryland soil salinity :cure, containment or catastrophe. In *Proceedings of the 5th Australian Agronomy Conference*, Perth. pp. 212–220.
- Barrett-Lennard EG, Frost F, Vlahos S and Richards N (1991) Revegetating salt-affected land with shrubs. *Journal of Agriculture, Western Australia* **32**, 124–129.
- Barrett-Lennard EG, van Ratingen P and Mathie MH (1999) The developing pattern of damage in wheat (*Triticum aestivum* L) due to the combined stresses of salinity and hypoxia: experiments under controlled conditions suggest a methodology for plant selection. *Australian Journal of Agricultural Research* **50**, 129–136.
- Barrett-Lennard EG, Malcolm CV and Bathgate A (2003) *Saltland Pastures in Australia: A Practical Guide*. 2nd edn. Sustainable Grazing of Saline Lands (subprogram of Land, Water and Wool).
- Bettenay E, Blackmore AV and Hingston FJ (1964) Aspects of the hydrologic cycle and related salinity in the Belka Valley, Western Australia. *Australian Journal of Soil Research* **2**, 187–210.
- Bowman S and Ruprecht J (2000) 'Blackwood river catchment flood risk study'. Surface Water Hydrology Report Series, Water and Rivers Commission, Perth. Report no. SWH 29.
- Curry PJ, Payne AL, Leighton KA, Hennig P and Blood DA (1994) 'An inventory and condition survey of the Murchison River catchment and surrounds, Western Australia'. Department of Agriculture WA, Perth. Technical Bulletin 84.
- Drew MC (1983a) Plant injury and adaptation to oxygen deficiency in the root environment: a review. *Plant and Soil* **75**, 179–199.
- Drew MC (1983b) Oxygen deficiency and root metabolism: injury and acclimation under hypoxia and anoxia. *Annual Review of Plant Physiology and Plant Molecular Biology* **48**, 223–250.
- Eaton FM (1942) Toxicity and accumulation of chloride and sulfate salts in plants. *Journal of Agricultural Research* **64**, 357–399.
- Flora of Australia (1984) *Phytolaccaceae to Chenopodiaceae*. Vol. 4. Australian Government Publishing Service, Canberra.
- Freer M, Moore AD and Donnelly JR (1997) GRAZPLAN: decision support systems for Australian enterprises. II. The animal biology model for feed intake, production and reproduction and the GrazFeed DSS. *Agricultural Systems* **54** 77–126.
- Fry JM, McGrath MC, Harvey M, Sunderman F, Smith GM and Speijers EJ (1996) Vitamin E treatment of weaner sheep. I. The effects of vitamin E supplements on plasma alpha tocopherol concentrations, liveweight and wool production in penned or grazing sheep. *Australian Journal of Agricultural Research* **47**, 853–867.
- Galloway R and Davidson NJ (1993) The interactive effect of salt and waterlogging on *Atriplex amnicola*. In *Productive Use of Saline Land* (Eds N Davidson and R Galloway) pp. 112–114. Proceedings no. 42, Australian Centre for International Agricultural Research, Canberra.
- Gauch HG and Eaton FM (1942) Effect of saline substrate on hourly levels of carbohydrates and inorganic constituents of barley plants. *Plant Physiology* **17**, 347–365.
- Greenway H (1965) Plant response to saline substrates. VII. Growth and ion uptake throughout plant development in two varieties of *Hordeum vulgare*. *Australian Journal of Biological Sciences* **18**, 763–779.
- Greenway H and Munns R (1980) Mechanisms of salt tolerance in nonhalophytes. *Annual Review of Plant Physiology* **31**, 149–190.
- Greenwood EAN and Beresford JD (1980) Evaporation from vegetation in landscapes developing secondary salinity using the ventilated-chamber technique. *Journal of Hydrology* **45**, 313–319.

- Hearn SJ (1991) 'Tackling salinity on the Esperance sandplain'. Division of Resource Management, Department of Agriculture WA, Perth. Technical Report no. 121.
- Hingston FJ and Gailitis V (1976) The geographic variation of salt precipitated over Western Australia. *Australian Journal of Soil Research* **14**, 319–335.
- Jones R and Hodgkinson KC (1969) Root growth of rangeland chenopods: morphology and production of *Atriplex nummularia* and *Atriplex vesicaria*. In *The Biology of Atriplex* (Ed. R Jones) pp. 77–85. Division of Plant Industry, CSIRO, Canberra.
- Malcolm CV and Allen RJ (1981) The Mallen niche seeder for plant establishment on difficult sites. *Australian Rangeland Journal* **3**, 106–109.
- Malcolm CV and Swaan TC (1989) 'Screening shrubs for establishment and survival on salt-affected soils in south-western Australia'. Department of Agriculture WA, Perth. Technical Bulletin 81.
- Malcolm CV, Clarke AJ, D'Antuono MF and Swaan TC (1988) Effects of plant spacing and soil conditions on the growth of five *Atriplex* species. *Agriculture, Ecosystems and Environment* **21**, 265–279.
- Marschner H (1995) *Mineral Nutrition of Higher Plants*. Academic Press, San Diego.
- Masters DG, Norman HC and Dynes RA (2001) Opportunities and limitations for animal production from saline land. *Asian-Australian Journal of Animal Sciences* **14**, 199–211.
- Masters DG, Rintoul AJ, Dynes RA, Pearce KL and Norman HC (2005) Feed intake and production in sheep fed diets high in sodium and potassium. *Australian Journal of Agricultural Research* **56**, 427–434.
- Masters DG, Benes SE and Norman HC (2007) Biosaline agriculture for forage and livestock production. *Agriculture, Ecosystems and Environment* **119**(3/4), 234–248.
- McFarlane DJ, Barrett-Lennard EG and Setter TL (1989) Waterlogging: a hidden constraint to plant growth. In *Proceedings of the 5th Australian Agronomy Conference*. Perth, WA. pp. 74–83.
- McFarlane DJ, George RJ and Caccetta PA (2004) The extent and potential area of salt-affected land in Western Australia estimated using remote sensing and digital terrain models. In *Engineering Salinity Solutions. 1st National Salinity Engineering Conference*. Perth, WA. (Eds S Dogramaci and A Waterhouse) pp. 55–60. Institute of Engineers Australia.
- Morcombe PW, Young GE and Boase KA (1996) Grazing a saltbush (*Atriplex – Maireana*) stand by merino wethers to fill the 'autumn feed-gap' experienced in the Western Australian wheat belt. *Australian Journal of Experimental Agriculture* **36**, 641–647.
- Morrison DA and Bathgate AD (1990) The value of pasture in a dryland farming system. In *Annual Ryegrass Workshop*. Adelaide, SA. p. 13. Waite Agricultural Research Institute.
- National Land and Water Resources Audit (2001) *Australian Dryland Salinity Assessment 2000. Extent, Impacts, Processes, Monitoring and Management Options*. Commonwealth of Australia, Canberra.
- Norman HC, Dynes RA and Masters DG (2002a) 'An integrated approach to the planning, training and management for the revegetation of saline land'. Final Report to State Salinity Council. CSIRO Livestock Industries (in collaboration with the Saltland Pastures Association), Wembley, WA.
- Norman HC, Dynes RA and Masters DB (2002b) Nutritive value of plants growing on saline land. In *Proceedings of the 8th National Conference and Workshop on the Productive Use and Rehabilitation of Saline Lands*. 16–20 September, Fremantle, WA. pp. 59–69.
- Norman HC, Friend C, Masters DG, Rintoul AJ, Dynes RA and Williams IH (2004) Variation within and between two saltbush species in plant composition and subsequent selection by sheep. *Australian Journal of Agricultural Research* **55**, 999–1007.
- Nulsen RA (1981) Critical depth to saline groundwater in non-irrigated situations. *Australian Journal of Soil Research* **19**, 83–86.
- O'Connell M, Young J and Kingwell R (2005) The economic value of saltland pastures in a mixed enterprise farming system in a heterogeneous landscape experiencing a mediterranean climate. *Agricultural Systems* **89**, 371–389.

- Pearce KL, Masters DG, Smith GM, Jacob RH and Pethick DW (2005) Plasma and tissue alpha-tocopherol concentrations and meat colour stability in sheep grazing saltbush (*Atriplex* spp.). *Australian Journal of Agricultural Research* **56**, 663–672.
- Runciman HV and Malcolm CV (1989) 'Forage shrubs and grasses for revegetating saltland'. Department of Agriculture WA, Perth. Bulletin no. 4153.
- Sinha BK and Singh NT (1974) Effect of transpiration rate on salt accumulation around corn roots in a saline soil. *Agronomy Journal* **66**, 557–560.
- Sinha BK and Singh NT (1976) Salt distribution around roots of wheat under different transpiration rates. *Plant and Soil* **44**, 141–147.
- Standing Committee on Soil Conservation (1982) 'Salinity of non-irrigated land in Australia'. Report of the Working Party on Dryland Salting in Australia for the Standing Committee on Soil Conservation of the Australian Agricultural Council. Soil Conservation Authority, Melbourne.
- Steele P, Peet RL, Skirrow S, Hopkinson W and Masters HG (1980) Low alpha-tocopherol levels in livers of weaner sheep with nutritional myopathy. *Australian Veterinary Journal* **56**, 529–532.
- Strawbridge M, Bell RW, McComb JA and Barrett-Lennard EG (1997) The influence of sex ratio and sexual lability on seed production in the dioecious perennial shrub *Atriplex amnicola* (Chenopodiaceae). *Australian Journal of Experimental Agriculture* **37**, 661–666.
- Stevens JC, Barrett-Lennard EG and Dixon KW (2006). Enhancing the germination of three fodder shrubs (*Atriplex amnicola*, *A. nummularia*, *A. undulata*; Chenopodiaceae): implications for the optimisation of field establishment. *Australian Journal of Agricultural Research* **57**, 1279–1289.
- Teakle LJH and Burvill GH (1945) The management of salt lands in Western Australia. *Journal of Agriculture of Western Australia* **22**, 87–93.
- Ulyatt MJ (1973) The feeding value of herbage. In *Chemistry and Biochemistry of Herbage*. (Eds GW Butler and RW Bailey) pp. 131–178. Academic Press, London.
- Vlahos S (1997) Improving the niche seeding method for establishing *Atriplex* spp. (saltbushes) on saline land in south western Australia. MSc thesis. University of Western Australia.
- Vlahos S, Nicholas D and Malcolm C (1991) Variable quality of saltbush seed influences establishment. *Journal of Agriculture of Western Australia* **32**, 130–132.
- Warren BE and Casson T (1994) Sheep and saltbush: are they compatible? In *Proceedings of the 3rd National Workshop on Productive Use of Saline Lands*. Echuca, Vic. (Eds MA Schulz and G Petterson) pp. 125–129.
- Warren BE, Bunny CJ and Bryant ER (1990) A preliminary examination of the nutritive value of four saltbush (*Atriplex*) species. *Proceedings of the Australian Society of Animal Production* **18**, 424–427.
- Watson MC and O'Leary JW (1993) Performance of *Atriplex* species in the San Joaquin Valley, California, under irrigation and with mechanical harvests. *Agriculture, Ecosystems and Environment* **43**, 255–266.
- Weston RH (1996) Some aspects of constraint to forage consumption by ruminants. *Australian Journal of Agricultural Research* **47**, 175–198.

Productive use and rehabilitation of saline land using trees

Nico Marcar

Introduction

It is predicted that, even with major intervention, land and water salinisation will continue to increase (Pannell 2002). Therefore, there is good reason to attempt to turn saline land into a productive resource. Major goals of revegetation management in discharge areas are to lower locally high watertable levels, to make productive use of saline land (often in conjunction with grazing) and to reduce salt transport to streams (especially in the Murray-Darling Basin). Some farmers are already doing this through the use of salt-tolerant pastures, including saltbush as a woody perennial option, for livestock production. Another option for salt-affected land is growing trees for timber, carbon sequestration, shelter and biodiversity enhancement. Other benefits of revegetation may include reduction in soil erosion and improvement of aesthetics and land values.

In some landscapes, a considerable proportion of salt entering streams can come from soil surface runoff, during high-rainfall events and from sub-surface flow of water. Salt transport to streams through these processes may be reduced if planting of trees and other vegetation reduces runoff and lowers watertables, thereby keeping salts at depth. However, some of the salt that accumulates in sub-soils beneath trees may be transported to streams through runoff if the subsoil salinity causes reduced growth and water use of trees and, as a result, the salts are brought to the surface through capillary

rise. Hydrological models are increasingly used to predict outcomes.

Soil and water salinity are significant constraints to establishing trees in dryland areas. The amount and concentration of salt to which trees may be exposed varies with planting location, salt load in the soil regolith, root zone soil water status, site and stand management practices and the extent to which saline soil water and groundwater are used by trees. Saline soils may also be seasonally waterlogged and sodic. Effects of salinity on tree growth are influenced by these factors and how different genotypes react to them, and the techniques used to establish and manage tree plantings.

This chapter deals with:

- the extent and nature of dryland salinity;
- genotypic differences in salt and waterlogging tolerance;
- minimising risks to growth;
- production systems;
- prospects for saline land rehabilitation.

Extent and nature of dryland salinity

Dryland salinity affects over 2.5 million ha of agricultural landscapes throughout Australia (Table 15.1). The prognosis is for worsening of salinity and waterlogging over the next 30–50 years. Predictions have been based on combinations of groundwater trends, field surveys and landscape characteristics. However, the propensity for land to

Table 15.1: Area of land affected by and potentially at risk of dryland salinity in Australia

State/territory	Area of dryland salinity in 1996 (ha) ^a	Area with high potential to develop dryland salinity 1998/2000 (ha) ^b
Western Australia	1 804 000	4 363 000
South Australia	402 000	390 000
Victoria	120 000	670 000
New South Wales	120 000	181 000
Tasmania	20 000	54 000
Queensland	10 000	NA
Northern Territory	minor	minor
Total	2 476 000	658 000

Sources: (a) Hayes (1997); (b) Anon (2000).

become salinised depends on the amount of salt stored in associated soils, the rapidity of groundwater or perched watertable rise and changing climate. Data on areas affected by different degrees of salinity and shallow watertables are available for specific regions but are not readily available on a state-wide basis. The estimates of potential areas at risk must be interpreted with care, because the methods and techniques used to derive these estimates have varied between states. Lower rainfall across much of southern Australia over the last decade has seen a stabilisation or lowering of groundwater levels.

The majority of dryland salinity is in the low-medium rainfall (450–750 mm/yr mean annual rainfall) zone of southern Australia. Overall, dryland salinity affects about 7% and 14% of farms in New South Wales and Victoria respectively (ABS 2002). Outbreaks of salinity in regions, catchments and subcatchments are typically patchy with small proportions (usually <5%) of farmland affected, and salinity tends to be found around drainage lines and lower slopes. Thus, tree planting for salinity management on saline discharge areas is likely to be on a smaller scale than that on non-saline recharge areas. The situation in Western Australia

is quite different, with widespread land salinisation in broad valleys and more than 50% of farms affected by salinity state-wide.

Saline land is typically a harsh environment and imposes multiple stresses on plant survival and growth. These stresses include salinity, sodicity, seasonal waterlogging and water deficits. Soils in saline discharge zones are likely to experience a range of salinity and water states (dry to seasonally waterlogged) that vary in extent and degree both temporally and spatially.

Soil salinity

Soil salinity is usually described in terms of electrical conductivity (EC), measured in a 1:5 soil:water suspension ($EC_{1:5}$). This value can be converted to EC_e (EC of the soil water extract from a saturated soil paste) by applying conversion factors based on soil texture (Marcar and Crawford 2004). Soils affected by salinity are classified according to their severity, e.g. as non-saline ($EC_e < 2 \text{ dSm}^{-1}$), slight ($EC_e 2\text{--}4 \text{ dSm}^{-1}$), moderate ($EC_e 4\text{--}8 \text{ dSm}^{-1}$), high ($EC_e 8\text{--}16 \text{ dSm}^{-1}$) and extreme ($EC_e > 16 \text{ dSm}^{-1}$) (Marcar and Crawford 2004). These classes reflect average conditions in plant root zone depths (typically 0.5 to several metres), not just the surface soil. Electrical conductivity gives an estimate of salt concentration but does not provide information on salt composition, which determines specific ion toxicities.

A broad range of dissolved salts is known to occur in saline soil and water, principally sodium chloride (NaCl). Other ions such as calcium (Ca), magnesium (Mg), sulphate (SO_4) and bicarbonate (HCO_3) may also be found in large amounts, depending on geology and soil types.

Seasonal fluctuations in salinity within the soil profile can also be expected. In saline discharge locations, surface soil salinities are often much higher than those in the subsoil in summer months due to high evaporation and low rainfall, while salinity is lower in winter due to lower surface evaporation and to dilution and leaching of salt from rainfall. Soil salinity is highly variable, both spatially and temporally. For example, surface soil salinities may range from areas with EC_e of 2–6 dSm^{-1} , with corresponding changes from salt-sensitive clovers to salt-tolerant grasses (sea barley

grass, rushes and sedges), to EC_e of 6–15 dSm^{-1} , characterised by bare soil and scalding. At EC_e levels above 15 dSm^{-1} salt crusting can be seen on the soil surface (Semple and Williams 2002).

Saline soils may become seasonally waterlogged during winter and spring due to shallow watertables, seepage from perched watertables or increased sodicity (especially on heavy-textured soils where infiltration at the soil surface is reduced by low permeability). Soil sodicity is often described in terms of the concentration of exchangeable sodium (Na) relative to the total quantity of exchangeable cations (cation exchange capacity) or the exchangeable sodium percentage (ESP). Three sodicity classes are commonly recognised: non-sodic (ESP <6%), sodic (ESP 6–14%) and strongly sodic (ESP >14%).

Genotypic differences in response to salt and waterlogging

The reduction in growth rate in response to increases in soil and water salinity varies among genotypes. Key physiological reasons for reduced growth include:

- reduced water uptake and photosynthesis resulting from decreased stomatal conductance (which may be induced by excessive leaf Na concentrations displacing K);
- increased respiration (extra energy used) associated with the processes of salt exclusion from the root and containment of salt within leaf cells;
- reduced turgor in growing tissues;
- interference with the activity of some enzymes.

As a secondary effect, premature leaf senescence and fall occurs, perhaps as a mechanism for salt removal from plants via leaves. This will reduce leaf area and hence photosynthesis and growth. Apart from halophytic species, salt tolerance is usually a result of the ability of species to exclude salt from the root and restrict transport to the shoot. Waterlogging in the presence of salinity usually reduces the capacity of plant roots to exclude salt. Greater uptake of salt by plants exacerbates the impact of salinity on survival and growth. Excessive amounts of chloride (Cl) in leaf tissue are often

associated with salt damage in trees after some time of exposure, with more salt-tolerant trees often better excluding Cl from leaf tissue.

Salinity also reduces water uptake by trees. For example, Benyon *et al.* (1999) found that salinity reduced stem growth and leaf area development rather than water use per unit of leaf area or sapwood area (sap flux density) in six-year-old *Eucalyptus camaldulensis* trees under moderately saline conditions (EC_e 4–8 dSm^{-1}) at a site near Wellington, New South Wales. Salt-tolerant species probably maintain their sap flow velocity under increasing soil salinity by adaptive processes, including regulation of stomatal function.

Species-level variation

There has been much field testing of tree species, provenances and clones on saline sites in Australia. Slow growth rates of trees on saline sites are usually observed, with rates dependent on genotype (species and provenance) and soil and groundwater conditions. However, the collective information is invaluable for determining the species and provenances with highest growth potential for specific sites. Table 15.2 (based on Marcar and Crawford 2004) is a summary of a broad classification of salt tolerance for species of acacia, allocasuarina, casuarina, eucalyptus, melaleuca and pine potentially suitable for planting on salt-affected sites in southern Australia.

Species can be conveniently grouped into four categories of tolerance, from slight to extreme. This ranking of species is based on general and conservative assessment of their performance for a given category. It would be expected that each group of species would achieve good to very good survival but would grow up to 25% slower than in non-saline soil. It is worth testing the performance of some species and provenances at a level of salinity higher than the one attributed to them in Table 15.2. However, a number of local soil and environmental conditions, such as seasonal waterlogging, would interact to reduce growth, thus confounding interpretation of results. Species highlighted in bold are at least moderately tolerant of waterlogging.

Commercially grown eucalypts, such as *E. globulus* and *E. grandis*, are slightly salt tolerant, with

Table 15.2: Tolerance of selected trees and shrub species to salinity and waterlogging and potential suitability for planting in southern Australia

Size	Average root-zone soil salinity (EC _e dSm ⁻¹)			
	Slight (2–4)	Moderate (4–8)	High (8–16)	Extreme (>16)
Tree	<i>A. mearnsii</i>	<i>A. pendula</i>	<i>A. salicina</i> ^b	<i>A. stenophylla</i>
	<i>A. melanoxylon</i> ^a	<i>All. luehmannii</i> ^a	<i>C. glauca</i>	<i>C. obesa</i>
	<i>Cor. citriodora</i> subsp. <i>variegata</i>	<i>All. verticillata</i>	<i>E. occidentalis</i>	
	<i>Cor. maculata</i>	<i>C. cristata</i> ^b	<i>E. platypus</i> subsp. <i>platypus</i>	
	<i>E. aggregata</i>	<i>C. cunninghamiana</i> subsp. <i>cunninghamiana</i> ^b	<i>E. sargentii</i>	
	<i>E. botryoides</i>	<i>E. astringens</i> subsp. <i>astringens</i>	<i>E. spathulata</i>	
	<i>E. brockwayi</i> ^a	<i>E. camaldulensis</i>		
	<i>E. camphora</i> subsp. <i>humeana</i>	<i>E. campaspe</i> ^b		
	<i>E. cinerea</i> subsp. <i>cinerea</i>	<i>E. largiflorens</i>		
	<i>E. cladocalyx</i> ^a	<i>E. leucoxylon</i> subsp. <i>leucoxylon</i>		
	<i>E. coolabah</i> ^a	<i>E. melliodora</i> ^a		
	<i>E. cornuta</i> ^a	<i>E. moluccana</i>		
	<i>E. crenulata</i>	<i>E. polybractea</i>		
	<i>E. globulus</i> subsp. <i>bicostata</i>	<i>E. raveretiana</i>		
	<i>E. globulus</i> subsp. <i>globulus</i>	<i>E. robusta</i>		
	<i>E. grandis</i> ^a	<i>E. salicola</i>		
	<i>E. loxophleba</i> subsp. <i>lissophloia</i> ^a	<i>E. tereticornis</i> subsp. <i>tereticornis</i>		
	<i>E. microcarpa</i>	<i>E. wandoo</i> subsp. <i>wandoo</i>		
	<i>E. ovata</i> var. <i>ovata</i>	<i>M. styphelioides</i>		
	<i>E. saligna</i>	<i>P. pinaster</i>		
	<i>E. sideroxylon</i> ^a	<i>P. radiata</i>		
	<i>E. tricarpa</i> ^a			
	<i>E. viminalis</i> subsp. <i>viminalis</i>			
	<i>P. brutia</i>			
Shrub	<i>A. implexa</i>	<i>A. acuminata</i>	<i>A. cyclops</i>	<i>M. halmaturorum</i>
	<i>A. iteaphylla</i>	<i>A. retinodes</i>	<i>E. halophila</i>	<i>M. thyoides</i>
	<i>A. longifolia</i> ^a	<i>A. saligna</i>	<i>M. cuticularis</i>	
	<i>E. angustissima</i> subsp. <i>angustissima</i>	<i>A. victoriae</i>	<i>M. lanceolata</i>	
		<i>M. acuminata</i>		
	<i>M. armillaris</i> subsp. <i>armillaris</i>			

Size	Average root-zone soil salinity (EC _e dSm ⁻¹)			
	Slight (2–4)	Moderate (4–8)	High (8–16)	Extreme (>16)
		<i>M. bracteata</i>		
		<i>M. decussata</i>		
		<i>M. ericifolia</i>		
		<i>M. lateriflora</i>		
		<i>M. linariifolia</i>		
		<i>M. squarrosa</i>		
		<i>M. uncinata</i>		

(a): Species which overlap slight to moderate salinity category.

(b): Species which overlap moderate to high salinity category.

Bold type indicates that the species is at least moderately tolerant of waterlogging.

Tree = >5 m, shrub = <5 m.

Cor. = *Corymbia*, All. = *Allocasuarina*.

Source: Based on Marcar and Crawford (2004, Table 2.1).

growth reduction expected at salinity levels above EC_e 2 dSm⁻¹. In contrast, some species with less commercial potential, such as *Acacia stenophylla*, *E. occidentalis*, *E. sargentii* and *E. spathulata*, are highly salt-tolerant, with little growth reduction expected even at EC_e of 10 dSm⁻¹.

Height growth responses to root zone salinity (mean EC_e for the 0–60 cm soil depth) under dry-land conditions at a site near Wellington, central-west New South Wales, which featured a gradient of soil salinity, are summarised for three eucalypt species in Figure 15.1 (examples drawn from Marcar *et al.* 2003). Three types of response to salinity are defined, based on statistical similarity of the slopes of regression equations – tolerance increases from type 1 to 3.

Feikema *et al.* (2005) reported that stem volume growth of *E. globulus* and *E. grandis* at age 10 years was approximately four times more sensitive to soil salinity (mean EC_e over 0–150 cm soil depth) than *E. camaldulensis*. Responses are shown in Figure 15.2. For each species survival was similar under channel and saline water treatments. Thus, lower productivity under saline conditions was not because of differences in mortality.

Species that maintain a relatively high growth rate under saline conditions are likely to have greater water use than those with slower growth under a similar set of conditions. However, the

difference in water use between fast- and slow-growing trees is not necessarily proportional to the difference in their growth rates. For example, Morris and Collopy (1999) found that annual water use by five- to eight-year-old *E. camaldulensis* drawing on saline groundwater (watertable depth 0.7–1.5 m (winter) and 3.0 m (summer) with an EC of 5–10 dSm⁻¹) was 339 mm/yr while that for *C. cunninghamiana*, which produced more than twice the basal area growth of *E. camaldulensis* in that period, was 359 mm/yr. Sap flux density (sap velocity) of the *C. cunninghamiana* trees decreased as their sapwood area increased over the two years of measurement, possibly as a result of limited soil water availability.

Provenance-level variation

There is often marked variation in tree growth between provenances within a species on saline sites. However, differences among provenances in response to soil salinity are usually small. In some cases, significant variation in responses to salinity has been observed for specific provenances and clones of some species, including *A. stenophylla* and *E. camaldulensis* (Marcar and Crawford 2004). Figure 15.3 shows differences among selected provenances of *E. occidentalis* in response to salinity. Differences among most provenances were not significant.

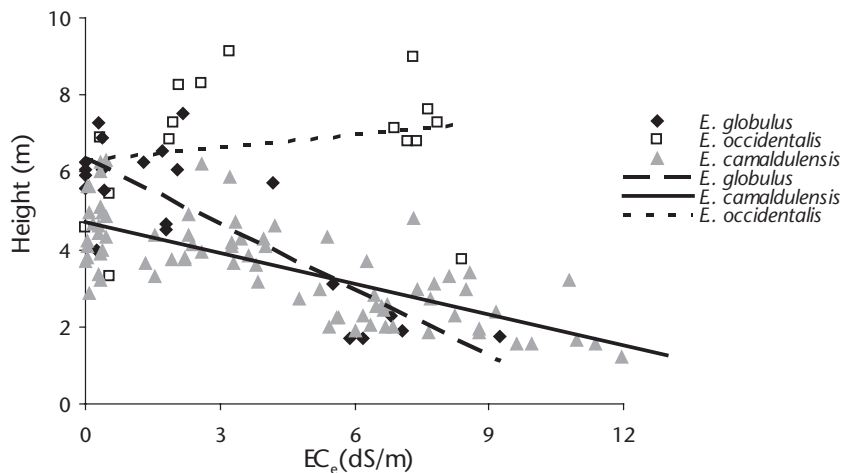


Figure 15.1: Height growth responses to salinity (EC_e) for three eucalypt species aged five years grown at a dryland saline site near Wellington, New South Wales (sandy loam to medium clay, root zone EC_e 0–20 dSm^{-1} , depth to watertable 0.5–5 m, mean annual rainfall 656 mm, potential annual ET 1780 mm). *E. globulus* type 1 response ($R^2 = 0.70$, $p < 0.001$); *E. camaldulensis* type 2 response ($R^2 = 0.57$, $p < 0.001$) and *E. occidentalis* type 3 response ($R^2 = 0.04$, $p =$ not significant). Data from several *E. camaldulensis* provenances have been bulked together (data from Marcar *et al.* 2003).

Minimising risks to growth

Planting stock

Tree genotypes with an appropriate level of salt and waterlogging tolerance should perform better on salt-affected sites than those selected for salt tolerance alone, because soil salinity is often associated with seasonal waterlogging. Selection of bet-

ter-performing trees growing on saline sites has produced clones that grow better on saline sites than clones from unselected trees, for example *E. camaldulensis* and *C. obesa* (Bell *et al.* 1994). Genetic improvement through cloning will be more rapid when the variation between trees attributable to root zone salinity (environmental effects) can be separated from genetic effects.

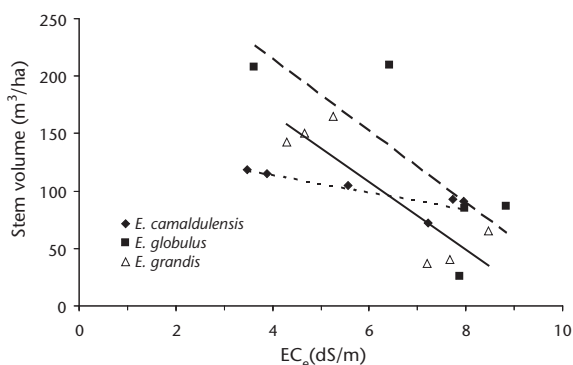


Figure 15.2: Relationships between stem volume (m^3/ha) and soil salinity (average soil EC over 0–150 cm soil depth) for *E. camaldulensis* ($r = 0.85$, $p < 0.05$), *E. globulus* ($r = 0.79$, $p = 0.11$) and *E. grandis* ($r = 0.87$, $p < 0.05$) at age 10 years, when trees were irrigated with good quality channel ($EC \sim 0.2$ dS/m) or saline ($EC \sim 8$ dSm^{-1}) water at a site near Timmering, northern Victoria (data from Feikema *et al.* 2005).

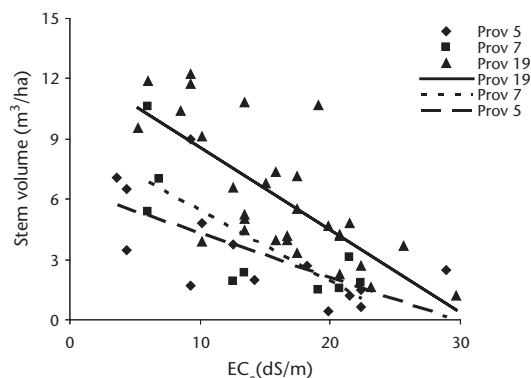


Figure 15.3: Response of selected provenances of four-year-old *E. occidentalis* to salinity at a provenance-progeny trial site near Wakool in southern New South Wales (medium clay, root zone EC_e 3–14 dS/m , depth to watertable 1–2 m, mean annual rainfall 410 mm, potential annual ET 173 mm) (Marcar *et al.* unpub. data).

There is also interest in using eucalypt hybrids which combine the salt tolerance of *E. camaldulensis* with the growth rate, wood quality and form of the commercially grown *E. grandis* and *E. globulus* (Meddings *et al.* 2001). The genetic background of clonal parents and the level of soil salinity and waterlogging at the test site influence the performance of selected hybrid clonal lines. Hybrid clones have not performed consistently well in field trials on saline sites in the Murray-Darling Basin and Western Australia. Trials with *E. camaldulensis* × *globulus* hybrids (Odie and McComb 1996) showed substantial variation in height growth and survival among clones, with responses to salinity intermediate between parent species. However, at a site irrigated with saline groundwater (EC 5–10 dSm⁻¹) near Mt Scobie in Victoria, mean stem volume growth of all the *E. camaldulensis* × *grandis* and *E. camaldulensis* × *globulus* clones exceeded the growth rate of clones of either parent species by 53% and 92%, respectively. The top 10% had more than twice the growth at age two years (Dale *et al.* 2001).

Site selection

Planting sites should be assessed for variability and extent of soil salinity and for depth of the watertable and its salinity. Soil salinity levels are assessed by collecting soil samples that are representative of the site for laboratory analysis (for EC_{1.5} or EC_e determination) and/or using an electromagnetic (EM) induction technique for determining the apparent electrical conductivity (ECa) of soil, as a surrogate for salt concentration (see Figure 15.4). The EM38 device can be a useful means of assessing salinity in the plant root zone up to 1.5 m in depth. It operates by calculating the ratio of an induced electromagnetic field to that of the reflected electromagnetic field. The EM38 is also sensitive to the presence of clay and soil moisture conditions. Calibration of EM38 readings is critical for comparisons among sites. Salinity maps at subcatchment, farm and paddock scales can be produced. Watertable depths are best determined with piezometers or wells installed in a few representative locations and/or by observations in a soil pit. Changes in vegetation composition (e.g. an increase in barley grass cover) and relatively sudden dieback of stands of trees can also be good indicators of increasing salinity.



Figure 15.4: Assessment of soil electrical conductivity near Wellington, New South Wales, by electromagnetic induction using an EM38 meter (photo by Nico Marcar).

Reducing the incidence of waterlogging by removing surface runoff and subsurface flow of water through drains and other means should be a priority. This can be done by pumping of groundwater or through increased drainage, using deep open ditches (trenches), slotted pipe (tile or plastic drains) and mole drains, or both. Caution is required with disposal of saline water within and from farms.

Establishment

Successful establishment of trees on saline sites requires appropriate site preparation, planting and post-planting management. Seedlings should be planted and, if necessary, watered to provide adequate moisture and to assist with flushing out salt in the immediate seedling root environment. Direct seeding is not recommended because high salinity often inhibits germination. Deep ripping with tines will loosen compacted soil and assist root development. Ripping should ideally be carried out about six months before planting if site conditions are suitable, but not when the soil is too wet or too dry. Mounding is required if the sites are prone to waterlogging, either seasonally or due to poor irrigation practices. Where soils have high

clay content and are affected by high salinity and waterlogging, double ridge mounds should be prepared (e.g. Ritson and Pettit 1992). Such mounds are very effective in improving drainage, enabling seedlings to be planted above the watertable and promoting leaching of salt from the root zone to lower depths. Weed control before and after planting is vital for successful establishment of trees on any site, and is best achieved by use of recommended herbicides.

Application of mulch on the soil surface around seedlings helps to reduce soil evaporation and therefore reduces the accumulation of salts at the surface. It also reduces weed competition. Mulch application, alone or in combination with other treatments, often improves tree growth. For example, a combination of fertiliser and mulch improved height growth of *E. camaldulensis* by about 30% at 20 months at a moderately saline site (Marcar *et al.* 2000); improvement continued up to age five years. Common mulches include woodchips, straw (hay), rice hulls, vermiculite, peat, sand and biodegradable plastic film.

Fertiliser application is not usually required for seedling establishment and early growth on farm sites with a history of fertiliser application or legume-based land use. This is despite the fact that nutrients may be less available to seedlings in salt-affected soils than in non-saline soils. However, small applications of fertiliser at or within a few months of planting may promote better early growth.

Management

For timber production at low to medium rainfall or slightly saline sites, initial stockings of 900–1200 stems/ha can be used. To encourage good form and enable the selection of good-quality stems for the final crop trees, the plantation should be thinned early to encourage growth on a smaller number of best stems. However, it may be more cost-effective to plant trees at a lower stocking rate (e.g. 500–800 stems/ha) where trees are planted primarily to increase water use and with only limited prospect of a commercial return, for example in moderately to highly saline discharge areas with shallow watertables. This will lower planting costs per hectare and avoid the cost of non-commercial thinning. Such sites might be suitable for firewood

production, through coppice management. Other sites may be devoted entirely to biodiversity enhancement, using a mixture of local species.

Production systems

Tree planting arrangements

Salt-tolerant trees, shrubs (including *Atriplex* spp.) and grasses can be planted on or adjacent to discharge areas (seeps and scalds). Trees will survive and grow better and use more water if planted adjacent to saline seeps and scalds than if planted directly onto them because soil physical and chemical conditions are more favourable and tree roots may access and use groundwater of lower salinity. Salt-tolerant trees can be introduced to rehabilitate remnant native vegetation and important biodiversity areas subjected to salt damage. An example is the introduction of casuarinas and melaleucas on land surrounding Lake Toolibin near Narrogin, Western Australia (one of the largest lakes in the state to have become salinised), in an attempt to lower saline watertables in conjunction with drainage and pumping schemes (Froend *et al.* 1997).

Trees can be integrated into farming systems in a variety of configurations on or near salt-affected land or shallow watertable sites. They can be planted in woodlots and blocks (typically >500 stems/ha), as shelter belts and alleys (<500 stems/ha), and as belts around saline seeps or scalds or scattered (<500 stems/ha) throughout a saline seep. These arrangements are dictated by factors such as farm layout, desired environmental and commercial benefits, soil and groundwater conditions and landscape configuration and position (Abel *et al.* 1997).

Woodlots

Woodlots are most suited to mid and lower slopes and slight to moderately saline discharge sites where good growth and water use can be expected for commercial production of timber, fence posts, firewood and possibly pulpwood. Planting density is flexible and dependent on rainfall and soil texture, but would be typically 1000–1200 stems/ha in high-rainfall less-saline zones and 500–600 stems/ha in low-rainfall higher-salinity zones. If commercial timber production is not the aim, species that have suitable salt tolerance and are found in remnant vegetation will contribute to the aesthetics and flora and fauna conservation of the area,



Figure 15.5: Blue gums (*E. globulus*) planted on a saline, waterlogged site in south-west Western Australia (photo by Nico Marcar).

and help dry out discharge sites. Perennial salt-tolerant grasses may be established and contribute to grazing value.

Wide-spaced and alley farming

Wide-spaced and alley farming combines trees, shrubs and pastures or crops to maximise productivity and water use. This arrangement can be applied near or on saline land. Tree and pasture growth may be enhanced when combined with surface drainage for waterlogging control. Planting layout and density is flexible; 100–450 stems/ha in multiple rows up to 50 m apart will provide a satisfactory ratio of trees to pasture. Tree belts in alley systems have the potential to use saline groundwater. The widths between and within belts and likely sustainability of the system have been modelled for soils of different texture. The key issues are to maximise the distance between tree belts in order to reduce production losses from crops or pasture, and balance local recharge in the alleys with con-

tinued groundwater use (i.e. enhanced discharge) by the tree belts. For alley cropping to have a hydrological impact, the spacing between belts must be small so that the use of groundwater will be high. However, the challenge is to maintain a high level of water use by trees by minimising salt accumulation in the saturated zone from which groundwater is being drawn, either through salt export or by maintaining the salt at depth.

Windbreaks and shelter belts

Windbreaks and shelter belts can be planted along fence lines and at other appropriate paddock locations. They increase crop and pasture production, provide shade and shelter and use some excess surface and groundwater.

Attempts by farmers in Western Australia to use one or more rows of salt-tolerant trees (e.g. *E. camaldulensis*, *E. loxophleba*, *E. occidentalis*, *E. sargentii* and *E. spathulata*) spaced 15–30 m apart have had some success in lowering saline (EC



Figure 15.6: Experimental planting of *A. stenophylla* near Wellington, New South Wales (photo by Nico Marcar).

up to 30 dS/m) watertables under the trees and in the alleys between the tree rows (Lefroy and Scott 1994). However, pasture growth in the alleys has often been relatively poor due to competition from tree roots, particularly in narrower alleys and on sites which do not permit rapid downward growth of tree roots. Under such site conditions and where trees are drawing on saline groundwater, there may be constraints on the continued growth and water use of trees over the long term (e.g. 15+ years) if salinity increases.

Economic considerations

Trees planted on farmland can produce a broad range of products, depending on the species planted, climate, site conditions and management. These include solid timber, composite wood panels, paper and cardboard, posts and poles, firewood, fodder, oil for solvents, biomass for bioenergy and carbon stored in above- and below- ground tree components. Salinity reduces commercial options by limiting the choice of species and reducing water availability to plants (as salinity increases, plants must expend more energy to remove salt from water) and hence lowering growth rates. Growth rates are likely to be limited by the low to medium rainfall conditions that prevail.

There has been relatively little rigorous investigation of the potential for commercial production of wood and non-wood products from native and



Figure 15.7: Alley planting of *E. spathulata* near Narrogin, Western Australia (photo by Nico Marcar).

exotic tree and shrub species suitable for saline and waterlogged land (OPUS 2001). In general, commercial opportunities for farm forestry in low-medium rainfall zones (<600 mm average annual rainfall) are considerably more limited than those in higher-rainfall zones due to lower growth rates, less forestry infrastructure and usually a greater distance to markets (Zorzetto and Chudleigh 1999). Saline environments have similar restrictions because of the location of saline sites.

Firewood is likely to be one of most sought-after products from woodlots or other agroforestry systems. Many salt-tolerant tree species could provide firewood of adequate quality, especially for modern domestic wood-burning heaters. Very few of these species have proven good-quality pulping characteristics. Unfortunately, firewood and pulpwood are low-priced bulky products and are very sensitive to the high cost of cartage. Even so, much of the firewood sold in Melbourne is transported from red gum stands in New South Wales. Products such as pulp chips (from stem wood), wood fuel chips (from branches and foliage) and cellulose feedstock for industrial purposes such as manufacturing plastics, chemicals and liquid fuels could be considered.

Economic analyses show that fodder, eucalyptus oil and electricity production from tree biomass (byproducts and residues) have reasonable commercial prospects in low to medium rainfall environments (Zorzetto and Chudleigh 1999). These findings also apply to saline environments. Trees

could be planted on saline sites for biomass (for bioenergy), oils and carbon storage (for greenhouse gas abatement) to complement tree planting in recharge sites. Short-rotation tree crops in alley systems based on coppice regrowth (e.g. mallee eucalypts in south Western Australia) may have an economic advantage beyond providing salinity control (Wildy *et al.* 2003).

Some species suitable for low to medium rainfall environments, such as *Citriodora maculata*, *E. occidentalis*, *E. sideroxylon* and *E. cladocalyx*, have wood properties and a recovery of high-quality appearance products suitable for sawn timber, although further genetic improvement for tree form and branching characteristics is needed to improve sawn recovery (Blakemore *et al.* 2003). However, such products from lower-rainfall regions may be uncompetitive with similar products from higher-rainfall zones because of their slower growth and distance from major processing facilities. Slower-growing trees may, however, produce a higher-value product with better recovery and less distortion when dried. *E. cladocalyx*, *C. citriodora*, *E. sideroxylon* and *E. leucoxydon* are naturally durable, and younger faster-grown (plantation or regrowth) material is being tested (McCarthy and Cookson 2004). Salt accumulated in wood of young plantation-grown trees does not appear to affect wood and fibre properties, however, damage could occur if growth is reduced due to salinity caused by processes associated with fibre formation (Catchpole *et al.* 2000).

Special-purpose uses, such as timber for construction, flooring, furniture, cross-arms, poles or fence posts, are possible for selected species (e.g. *C. maculata*, *E. cladocalyx*, *E. moluccana* and *E. tricarpa*). Some species, such as *E. cladocalyx* and *E. camaldulensis*, are well-suited for round timbers. Several salt-tolerant acacias, such as *A. saligna*, *A. stenophylla* and *A. salicina*, have the potential to provide supplementary forage or fodder.

There has been little adoption of farm forestry on salt-affected land. This is most likely due to uncertainty about tree growth rates, lack of established markets, high establishment costs, uncertain prices for products and long time lags between establishment and harvest. Barriers to adoption of farm forestry on productive agricultural land

may include some of these factors as well as the lower-than-expected return compared to conventional agriculture, i.e. the opportunity cost of not using the land for cropping or grazing. In contrast, salt-affected land is of lower value for agricultural production. Therefore the opportunity cost of using that land for farm forestry is generally lower.

Prospects for saline land rehabilitation

The key to rehabilitating saline areas is to lower watertables, to facilitate leaching of salts and provide an improved environment for plant growth. Shallow watertables will be lowered only if trees are planted over large enough areas, the trees can reduce recharge and/or use groundwater, and lateral flows from surrounding areas to the planted areas are relatively small.

George *et al.* (1999) reviewed the effects of tree planting on groundwater at 47 discharge sites in Western Australia. They concluded that:

- changes in watertable ranged from increases of 1 m to decreases of 2.5 m, with the majority of sites showing a decrease;
- tree planting was more effective at lowering groundwater if its salinity was low and where local flow systems, including perched watertables, predominate;
- trees had little or no impact on the watertables more than 10–30 m away from the area planted.

The effectiveness of plantations in using soil water and groundwater will depend on the maximum (or equilibrium) leaf area index (LAI) attained, the time taken to reach that maximum (equilibrium) LAI, the length of time high LAI can be maintained, root growth, and the availability and quality of soil water and groundwater. Factors including species choice, management and site conditions determine the above.

Watertables will be lowered more effectively by trees planted on light-textured than on heavy-textured soils because trees use groundwater more effectively through the unsaturated capillary zone and the rate of water movement in sandier soils is faster. For example, the watertable under an 85 m

wide, 20-year-old *E. grandis* plantation on a heavy-textured soil in northern Victoria was lowered by up to 5 m with an effective zone of influence extending to 30 m away. Modelling suggests that this zone could extend to 100 m on light-textured soils (Silberstein *et al.* 1999). The capacity of different tree species to use groundwater can also vary within a soil type. For example, *C. maculata* growing on a sandy, shallow groundwater site near Deniliquin, New South Wales, derived more of its water from groundwater than did *E. grandis* (Polglase *et al.* 2002).

Salt accumulation and redistribution affect the productivity and water use of plantations so that their long-term effectiveness for lowering shallow groundwater may be less than that observed in younger plantations established on farmland. However, plantations growing over shallow saline watertables may continue to grow provided that equilibrium salt concentrations do not exceed the maximum salinity tolerated by the tree species. The following examples of plantations growing over shallow watertables support this view:

- *E. grandis* (slightly salt tolerant) plantations continued growth over 20 years above a shallow watertable site near Kyabram, Victoria, at about $20 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ (Vertessy *et al.* 2000);
- *E. occidentalis* (highly salt tolerant) showed continued healthy growth at age 14 on a moderately to highly saline site near Stanhope, Victoria (Bandara *et al.* 2002);
- *Melaleuca halimifolium* (extremely salt tolerant) in natural stands draw on saline groundwater in extremely saline swamps in the lower south-east of South Australia (Mensforth and Walker 1996).

Marcar and Morris (2005) indicate that the key factors influencing groundwater use by trees are depth to groundwater and its salinity, root growth characteristics, salt tolerance of tree species and soil properties that influence water availability. Groundwater uptake by trees tends to decrease as the depth to watertable increases. This is due to lower gravitational potential of the water and greater resistance through longer root xylem transport, which limits the tree's capacity to supply respiratory substrate to a deep root system. Soil texture has a significant impact on groundwater use by trees, although the

confounding effects of site and stand management make interpretations from studies difficult (Barrett-Lennard *et al.* 1999). The rate of water uptake per unit of root length will be lower from clay than from loamy and sandy soils, mainly because of reduced rate of water delivery to tree roots.

There is limited information on the ability of different plant species to use groundwater of varying salinity and depth. Based on evaluation of 10 sites planted with trees, Thorburn (1996) concluded that uptake of saline groundwater by plants is often no more than would be expected by discharge from bare soil alone. This is possible because discharge from bare soil will evaporate at potential rate. Nevertheless, trees can use groundwater for growth in the absence of sufficient soil water, under favourable conditions such as when groundwater depth is <5 m and its salinity (EC) is <5–10 dSm^{-1} (George *et al.* 1999).

Best plantation growth and water use occur when species can tolerate soil salinity higher than that likely to occur at some equilibrium in response to saline groundwater use by trees. Most tree species can use groundwater of good quality (EC <2 dSm^{-1}) for growth. Those able to continue using groundwater of increasing salinity require progressively higher salt tolerance. Only highly salt-tolerant species can use highly saline groundwater (EC >15–20 dSm^{-1}).

Saline groundwater use by trees is likely to result in some degree of salt accumulation in the zone of water uptake, because plants exclude most of the salt in the soil solution (Stirzaker 2002). However, equilibrium concentrations are often observed. For example, during a two-year monitoring period in a groundwater-dependent *E. grandis* plantation near Kyabram (Vertessy *et al.* 2000), the salinity (EC) in the 6–8 m soil depth zone fluctuated by 10–20 dSm^{-1} as salts moved down or up with seasonal fluctuations in watertable depth. Such large seasonal changes in root zone salinity indicate that salt accumulation in the soil, as a result of groundwater uptake, is being balanced to some extent by salt removal (e.g. by leaching through rainfall). Based on modelling of upward (capillarity) and downward (leaching, diffusion) salt and water fluxes, Morris and Collopy (1999) showed that the equilibrium soil solution EC may be around 15–25 dSm^{-1} , similar to that observed above.

Conclusion

Salinity is extensive in southern Australia, with outbreaks typically patchy and of varying intensity at catchment, farm and paddock scales. Saline soil and groundwater conditions, and associated stresses of waterlogging and sodicity, reduce tree growth. The extent of growth reduction varies among genotypes and sites. At high soil and groundwater salinities, growth and water use of plantations will be considerably less than at low salinities. Maintenance of adequate long-term productivity requires the use of salt-tolerant species, provenances and/or clones coupled with good site and stand management practices.

Accumulation of salt in the root zone of trees drawing on saline groundwater is likely to reduce long-term growth rates where effective leaching is limited by heavy soils, deep root systems or insufficient rainfall. Although tree water use is also reduced under saline conditions, uptake of saline groundwater and consequent lowering of shallow watertables has been demonstrated on a range of sites. Knowledge of the equilibrium root zone salinities likely to develop and plant genotypes that can grow at acceptable rates under the prevailing site conditions would help better matching of site, species and silviculture.

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References

- Abel N, Baxter J, Campbell A, Cleugh H, Fargher J, Lambeck R, Prinsley R, Prosser M, Reid R, Revell G, Schmidt C, Stirzaker R and Thorburn P (1997) *Design Principles for Farm Forestry: A Guide to Assist Farmers to Decide Where to Place Trees and Forest Plantations on Farms*. Rural Industries Research and Development Corporation, Canberra.
- Anon (2000) *Australian Dryland Salinity Assessment 2000: Extent, Impacts, Processes, Monitoring and Management Options*. National Land & Water Resources Audit, Canberra.
- Australian Bureau of Statistics (2002) *Australian Year Book: Environment, Salinity and Land Management*. Australian Bureau of Statistics, Canberra.
- Bandara G, Morris J, Stackpole D and Collopy J (2002) 'Soil profile monitoring at irrigated plantation sites in northern Victoria: progress report 2001'. Forest Science Centre, Melbourne. CFTT Report no. 2002/025.
- Barrett-Lennard EG, Speijers J, Morris J and Marcar N (1999) Transpiration by trees on land with shallow water-tables: a survey of the literature suggests that transpiration is affected by soil texture. In *Redesign of Australian Plant Production Systems: Deep Drainage and Nitrate Losses in the Mediterranean Climate Region*. Land and Water Resources Research and Development Corporation, Canberra.
- Bell DT, McComb JA, van der Moezel PG, Bennett IJ and Kabay ED (1994) Comparisons of selected and cloned plantlets against seedlings for rehabilitation of saline and waterlogged discharge zones in Australian agricultural catchments. *Australian Forestry* 57, 69–75.
- Benyon RG, Marcar NE, Crawford DF and Nicholson AT (1999) Growth and water use of *Eucalyptus camaldulensis* and *E. occidentalis* on a saline discharge site near Wellington NSW, Australia. *Agricultural Water Management* 39, 229–244.
- Blakemore P, Waugh G, Northway R and Washusen R (2003) 'High value, solid wood products from low rainfall (450–650 mm/yr) farm forestry'. Joint Venture Agroforestry Program, RIRDC/Land & Water Australia/FWPRDC/MDBC. RIRDC Publication no. 03/022.
- Catchpoole S, Downes G and Read SM (2000) 'The effect of salt on wood and fibre formation in eucalypts'. Joint Venture Agroforestry Program, RIRDC/Land & Water Australia/FWPRDC/MDBC. RIRDC Publication no. 00/162.
- Dale G, Sasse J, Hamilton M, Batey T and George B (2001) Commercial plantations for waterlogged

- and saline land. Are trees worth a pinch of salt? In *Wanted: Sustainable Futures for Saline Lands. Proceedings of the 7th National PURSL Conference*. 20–23 March, Launceston, Tas. pp. 231–237. National Committee for the Productive Use and Rehabilitation of Saline Land.
- Feikema PM, Baker TG and Stackpole DJ (2005) Effects of salinity on field-grown *Eucalyptus camaldulensis*, *E. globulus* and *E. grandis*. In *Managing Saline Soils and Water. Proceedings of the International Salinity Forum*. 25–27 April, Riverside, California. CRC for Plant-based Management of Dryland Salinity. CD-ROM.
- Froend RH, Halse SA and Storey AW (1997) Planning for the recovery of Lake Toolibin, Western Australia. *Wetlands Ecology and Management* **5**, 73–85.
- George RJ, Nulsen RA, Ferdowsian R and Raper GP (1999) Interactions between trees and groundwaters in recharge and discharge areas: a survey of Western Australian sites. *Agricultural Water Management* **39**, 91–113.
- Hayes G (1997) 'An assessment of the National Dryland Salinity Program'. R, D & E Program, RIRDC/Land & Water Australia, Canberra. RIRDC Occasional Paper no. 16/97
- Lefroy EC and Scott P (1994) Alley farming: new vision for Western Australian farmland. *WA Journal of Agriculture* **35**, 119–126.
- Marcar NE and Crawford DF (2004) *Trees for Saline Landscapes*. Rural Industries Research and Development Corporation, Canberra.
- Marcar NE and Morris JD (2005) Plantation productivity in saline landscapes. In *New Forests: Wood Production and Environmental Services*. (Eds EKS Nambiar and IS Fergusson) pp. 51–74. CSIRO Publishing, Melbourne.
- Marcar NE, Hossain AKM, Crawford DF and Nicholson AT (2000) Evaluation of tree establishment treatments on saline seeps near Wellington and Young in New South Wales. *Australian Journal of Experimental Agriculture* **40**, 99–106.
- Marcar NE, Crawford DF, Hossain AKMA and Nicholson AT (2003) Survival and growth of tree species and provenances on a saline discharge site. *Australian Journal of Experimental Agriculture* **43**, 1293–1302.
- McCarthy K and Cookson L (2004) 'Natural durability of eucalypt trees from farm forestry and low rainfall areas: a review of the literature'. A report for Joint Venture Agroforestry Program, RIRDC/Land & Water Australia/FWPRDC/MDBC.
- Meddings RLA, McComb JA and Bell DT (2001) The salt-waterlogging tolerance of *Eucalyptus camaldulensis* x *E. globulus* hybrids. *Australian Journal of Experimental Agriculture* **41**, 787–792.
- Mensforth LJ and Walker GR (1996) Root dynamics of *Melaleuca halimifolium* in response to fluctuating saline groundwater. *Plant and Soil* **184**, 75–84.
- Morris J and Collopy J (1999) Water use and salt accumulation by *Eucalyptus camaldulensis* and *Casuarina cunninghamiana* on a site with shallow saline groundwater. *Agricultural Water Management* **39**, 205–227.
- Odie RLA and McComb JA (1996) *Eucalyptus camaldulensis* x *globulus* hybrids for saline land. In *Proceedings of the 4th National Conference and Workshop on the Productive Use and Rehabilitation of Saline Lands*. 25–30 March, Albany, WA. pp. 367–371. Promaco Conventions, Perth.
- OPUS (2001) 'Options for the productive use of salinity'. Report to National Dryland Salinity Program by PPK E & I Pty Ltd. <[http://www.ndsp.gov.au/10_NDSP_projects/05_project_descriptions/30_productive_use_of_saline/reports/PPK1_OPUSpdf](http://www.ndsp.gov.au/10_NDSP_projects/05_project_descriptions/30_productive_use_of_saline_reports/PPK1_OPUSpdf)>.
- Pannell DJ (2002) Loving, losing and living with the environment. *Connections: Farm, Food and Resource Issues* **2**, 25–36.
- Polglase PJ, Theiveyanathan S, Benyon RG and Falkiner RA (2002) 'Irrigation management and groundwater uptake in young tree plantations growing over high watertables'. Rural Industries Research and Development Corporation, Canberra. RIRDC Publication no. 02/146, RIRDC project No CSF-54A.
- Ritson P and Pettit NE (1992) Double-ridge mounds improve tree establishment in saline seeps. *Forest Ecology and Management* **48**, 89–98.
- Semple W and Williams B (2002) Saline seepage scalds: can they be usefully classified? *Natural Resource Management* **5**(1), 13–21.

- Silberstein R, Vertessy R, Morris J and Feikema P (1999) Modelling the effects of soil moisture and solute conditions on long-term growth and water use: a case study from the Shepparton irrigation area, Australia. *Agricultural Water Management* **39**, 283–315.
- Stirzaker R (2002) Planting trees over shallow, saline watertables. In 'Trees, water and salt: an Australian guide to using trees for healthy catchments and productive farms'. (Eds R Stirzaker, R Vertessy and A Sarre). Joint Venture Agroforestry Program, Rural Industries Research and Development Corporation, Canberra. RIRDC Publication no. 01/086.
- Thorburn PJ (1996) Can shallow watertables be controlled by the revegetation of saline lands? *Australian Journal of Soil and Water Conservation* **9**, 45–49.
- Vertessy R, Connell L, Morris J, Silberstein R, Heuperman A, Feikema P, Mann L, Komarzynski M, Collopy J and Stackpole D (2000) 'Sustainable hardwood production in shallow watertable areas'. Rural Industries Research and Development Corporation, Canberra. RIRDC Publication no. 00/163.
- Wildy D, Pate J and Bartle J (2003) 'Silviculture and water use of short-rotation mallee eucalypts'. Joint Venture Agroforestry Program, RIRDC/Land & Water Australia/FWPRDC/MDBC. RIRDC Publication no. 03/033.
- Zorzetto A and Chudleigh P (1999) 'Commercial prospects for low rainfall agroforestry'. Rural Industries Research and Development Corporation, Canberra. RIRDC Publication no. 99/152.

Integrated production systems

John Bartle

Introduction

Agriculture and forestry can be compatible and profitable on the same farm. However, the main motivation for agroforestry is for the agricultural and forestry components to complement each other. Complementarity might be achieved where one of the components uses resources not available to the other, or provides conditions or outputs that benefit the other. For example, combining perennial deep-rooted forestry crops with shallow-rooted annual agricultural crops gives potential for a higher level of capture of water, nutrients and sunlight. In this way agroforestry could achieve better production and environmental performance than agriculture or forestry alone, and could be described as an 'integrated production system'. Integration might target one or more production or environmental objectives and it can be undertaken at various levels of scale and intensity.

In the high-rainfall regions of rural Australia (>700 mm mean annual rainfall, depending on latitude and elevation) both forestry and agriculture may be commercially viable. This weakens the incentive to pursue the benefits of more complex integration and complementarity from agroforestry. It is reflected in the low level of adoption of agroforestry by the major southern Australian forestry industries based on *Pinus radiata* and *Eucalyptus globulus*, even though there is often good potential for complementary benefits. Where agroforestry has been used in high-rainfall areas, it has usually not been ambitious in its pursuit of com-

plementary benefits. This is reflected in a farm woodlot form of agroforestry, where the components remain fairly separate.

In the low-rainfall wheatbelt regions of southern Australia (arable lands with <600 mm mean annual rainfall) land use is dominated by extensive dryland cereal cropping and sheep grazing. Wheatbelt agriculture is economically viable but has serious environmental problems, particularly salinity. The salinity problem could be ameliorated using agroforestry, but there are no forestry industries of the necessary scale in the wheatbelt. Recognised forestry species from the adjacent high-rainfall zone could be extended into the 600–700 mm rainfall region using agroforestry methods, but they fail to achieve commercial performance in the wheatbelt. New large-scale tree crops and industries need to be developed if agroforestry is going to make a contribution to wheatbelt salinity control (Stirzaker *et al.* 2000, 2002).

This chapter focuses on the need to develop new species and industries that might apply the principles of agroforestry in the wheatbelt. It will introduce new concepts. For example, new tree crops suitable for large-scale industries in the wheatbelt are likely to be shrubs not trees, so the term 'woody crop' is commonly used. The main advantages of woody crops are much shorter production cycles (2–5 years) and the opportunity to avoid replanting costs by use of coppicing species (able to regenerate from the cut stump). During their early stages of development, new woody crops

are unlikely to be as profitable as current agriculture. Salinity control benefits are likely to be slow in coming and small when expressed as profit for the farm business. Farm business cannot afford to concede too much of a shortfall in woody crop returns compared to conventional crops. Given the challenge of achieving good commercial returns from new woody crops, there is a strong recognition that development will need to pursue all forms of complementary benefit and achieve very efficient integration.

If new large-scale woody crop industries are to be created, it is likely that the same pressure for multiple benefit and efficient integration will extend down the production chain. It will apply to harvest and handling systems for the supply of biomass to processors, and to processing, where integrated systems for major product and byproduct manufacture will be required. The emerging use of forestry residues for bioenergy strongly indicate what system designs are likely to be successful. Sweden, for example, has a large forestry industry and has implemented policies to foster development of bioenergy, including substantial inducements for 'energy crops' (where the woody crop is grown solely for fuel). However, the only area to achieve a high level of bioenergy output is the utilisation of secondary residues (mill and manufacturing wastes), indicating that if the residue fraction is harvested and centralised in a single integrated operation the prospect for its commercial use is enhanced (Bartle 2006).

These concepts have been applied in the development of mallee as a new woody crop in Western Australia since the mid 1990s. The development has reached the stage of operational testing of processing technologies but is not yet commercially proven. However, it indicates that wheatbelt woody crops have the potential to produce biomass at low cost, which opens several large-scale product opportunities including wood products, chemicals and bioenergy.

This chapter will review the development of mallee in Western Australia and discuss the major issues concerning commercially viable integrated woody crop systems for the wheatbelt and the opportunity to develop additional species and industries.



Figure 16.1: Mallees can have very extensive roots, as illustrated by *Eucalyptus diversifolia* revealed in eroded dunes near Eyre on the Nullarbor coast of Western Australian (photo by John Bartle).

Why mallee?

Natural history of mallee

Low, multi-stemmed mallee eucalypts were a dominant feature of the native vegetation of the 250–400 mm winter rainfall regions of southern Australia before agricultural development. These species have a characteristic large woody lignotuber, or mallee root, at the base of the stem, just below ground level. The lignotuber is the apex of the root system and carries numerous dormant buds that sprout or coppice after damage or loss of the above-ground stems due to fire or drought. This capacity to coppice quickly and be soundly anchored by the lignotuber was a serious obstruction to early agricultural development of mallee lands and gave rise to the invention of the stump-jump plough.

Mallees are well-adapted to drought and infertile soils and are long-lived. They have extensive horizontal and vertical root development (Nulsen *et al.* 1986) (Figure 16.1). In mature stands, they appear very slow-growing. However, coppice regeneration after harvest or fire is rapid given an existing root system rich in starch reserves and a favourable root to shoot ratio (Wildy *et al.* 2003, 2004). Mallee can re-establish from seed under favourable conditions in the wild and is readily propagated by seedlings.

These attributes suggest good potential for productive use within dryland agriculture where extra

water and nutrients might stimulate strong growth rates from plants harvested regularly to maintain them in the coppice growth stage.

Early productive use of mallee in Australia

Of the 800 species in the genus *Eucalyptus* about 180 are mallees (Brooker 2002). The striking aroma of eucalypts comes from a volatile oil carried in small glands in the leaf. Some species, including some mallees, have especially high concentrations of eucalyptus oil.

The Aborigines used eucalyptus oil in traditional medicine and, on arrival in 1788, European settlers quickly followed suit. Eucalypts were harvested on a small scale through the 1800s until the favoured species and oil types became recognised. During this period *E. polybractea* (blue mallee) emerged as a prominent producer of oil (Davis 2002). Production of oil was never a consistently profitable business – the main products were small-volume general household cleaners and folk medicines, and the wide dispersal of eucalypts around the world created competitors overseas. In the post-war period oil from Australian operations became less competitive in world markets and production declined to the current 100 t, valued at about \$1 million/yr. The two major domestic producers vertically integrated their businesses to include processing, product manufacture and trading. The bulk of oil production comes from blue mallee. Native stands and planted crops are harvested in two areas, near West Wyalong in New South Wales and west of Bendigo in Victoria.

Although only a small participant in the traditional industry, Western Australia became home to innovative research on industrial use of eucalyptus oil in the 1980s. Following the oil price escalation of the late 1970s, Associate Professor Allan Barton of Murdoch University discovered that cineole, the major constituent of eucalyptus oil, had chemical properties with potential for large-volume industrial use (Barton 2000). In particular, he identified industrial solvents and stabilisation of petrol/ethanol fuel blends as potential uses. Barton helped develop an efficient, small-sample analytical technique to determine the cineole concentration of eucalypt leaves and applied it to extensive screening of eucalypts, confirming the identity and

distribution of several Western Australian mallee species with high leaf oil concentration.

Subsequent development of mallee drew on the promise of new large-scale markets and the accumulated experience of the traditional industry in New South Wales and Victoria.

Mallee industry design and development

First steps towards a modern mallee industry

In 1992 the then State Department of Conservation and Land Management (CALM) decided to commit substantial resources to developing a tree crop for the wheatbelt of Western Australia. This was motivated by salinity control and biodiversity protection objectives, but it also allowed the use of experience gained in developing the blue gum industry in the adjacent higher-rainfall areas (Bartle and Shea 2002). Initial blue gum development by CALM in the high-rainfall zone (>700 mm annual rainfall) included substantial investment in designing and applying methods for integrating blue gums into agriculture (Bartle 1991). However, little application of integrated planting eventuated because the emerging industry attracted strong corporate investment that favoured conventional plantation forestry. The challenge to achieve a high degree of integration of tree crops remained.

CALM turned its agroforestry ambitions to the wheatbelt. Mallee was an obvious choice of woody crop for the wheatbelt, given its history of commercial use, the diversity and adaptability of local species and the promise of large-scale industrial products. The preference to develop or domesticate native species instead of introducing apparently desirable woody crops from overseas reflected a new determination to reduce the risk of weeds – a problem Australia has long experienced when introducing agricultural plants (Olsen *et al.* 2004).

It was realised from the outset that it was ambitious to create a new crop and associated processing industry options. A large amount of basic research would be required and collaboration with committed farmers would be essential for the practical development of mallee farming systems. The

project successfully attracted a large farmer following. Farmers formed the Oil Mallee Association (OMA), a representative group to provide support for the project and to share knowledge. In 2003 the OMA consolidated all mallee establishment and management information into a detailed code of practice for the industry (OMA 2003).

Oil mallee species selected for domestication

The first step was to select suitable species, including types adapted to the full range of wheatbelt climate and soil types. Figure 16.2 shows two species with contrasting ranges of natural distribution.

The chosen species come from a wide range of taxonomic groups but more than one species was chosen within some groups (Box 16.1). Some detailed taxonomic and molecular genetics work was done to define the degree of difference to determine whether species should be combined or kept separate in breeding programs (Byrne 1999).

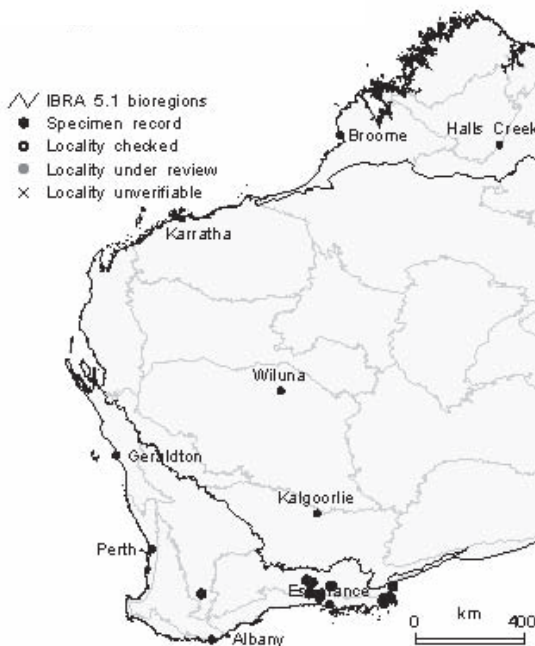
Development plan

The investment in mallee development required strategic decisions about fundamental aspects of

industry design – how the new woody crop industry might be developed, owned and operated. This was done within a conceptual plan designed to maintain coherent development (Figure 16.3; Bartle and Shea 2002). The first step was to select suitable species. Oil mallee species were the obvious choice but this was supported by thorough desktop (pre-feasibility) assessment.

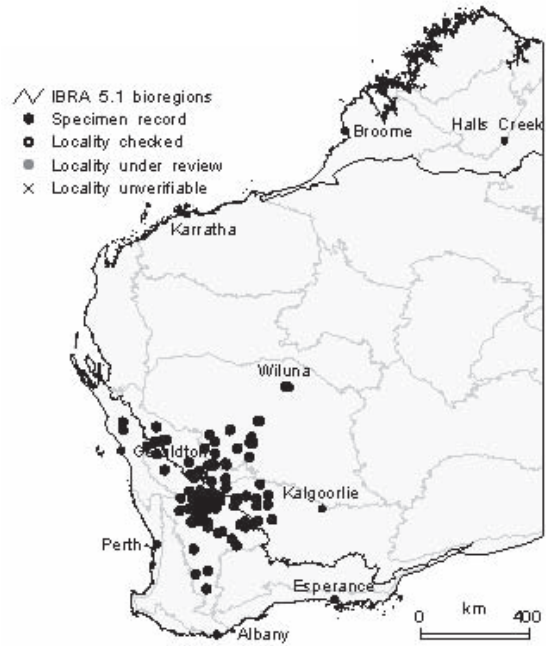
The next step was to invest substantial time and money in industry exploration. This consisted of detailed research and hands-on development. It was pre-commercial (too risky for commercial entrepreneurial investment) and included technical, environmental and socio-economic aspects. A large following of farmer growers was attracted to the project and they built a fledgling resource base (12 000 ha planted to 2004), with some state and Commonwealth government support but mostly at their own expense. At the same time they were doing large-scale practical development of establishment and management techniques. This was complemented where necessary by detailed research (in breeding and seed production, yield prediction and harvest systems). Between 1994 and 1999 the

Eucalyptus angustissima



Map by Paul Gioia, WA Herbarium. Current at June 29, 2005

Eucalyptus kochii subsp. *plenissima*



Map by Paul Gioia, WA Herbarium. Current at November 05, 2004

Figure 16.2: Natural distribution of two mallee species.

BOX 16.1

Mallee species targeted for domestication in Western Australia

- Oleosa series: includes *E. horistes*, *E. kochii* ssp. *kochii* and *E. kochii* ssp. *plenissima*. These are widely distributed in the central and northern wheatbelt and adjacent pastoral areas but their genetic difference is small. They occur on light soils and have a characteristic low spherical plant form.
- Cneorifolia series: *E. angustissima* and *E. angustissima* ssp. *quaerenda* occur in small areas in the south coastal region on low-lying salt-affected sites. The latter is rare and, although classified as a subspecies, is significantly different and will be developed as a separate species. This group also includes the Kangaroo Island narrow-leaf mallee, *E. cneorifolia*, that has been harvested for oil production on a small scale and is widely used as a shelter belt species on Kangaroo Island in South Australia.
- Loxophleba series: *E. loxophleba* ssp. *lissophloia* and *E. loxophleba* ssp. *gratae* are from the central and southern wheatbelt and adjacent pastoral regions and are closely related. They have an erect growth form and occur on medium and heavy soils.
- Section Adnataria: *E. polybractea*, blue mallee, occurs at West Wyalong in New South Wales and west of Bendigo in Victoria. It has an erect growth form and has demonstrated good performance on medium soils in the western and southern wheatbelt regions in Western Australia.

build-up of knowledge and resource was sufficient to attract a commercial investor who was prepared to undertake feasibility investigation of mallee processing (Enecon 2001). The study showed that the use of mallee biomass to produce activated carbon, eucalyptus oil and electricity in an integrated process should be commercially viable.

Mallee management, water use and salinity control

Farmers see annual crops and pastures as the foundation of their business but recognise the need to remedy landcare problems, particularly salinity. This has driven the extensive exploration of mallee by farmers in Western Australia over the past decade. How can mallee, or any other woody crop, be used most effectively?

There is no economic motivation to replace proven commercial annual crops and pastures with unproven permanent woody crops. This might achieve the desired salinity outcome, but woody crop plantation would be limited to rain-fed yield and is not likely to be viable in the wheatbelt in the foreseeable future.

The objective is to use mallee to maximise salinity benefits without reducing farm profit: restated generically in terms of water use, the aim

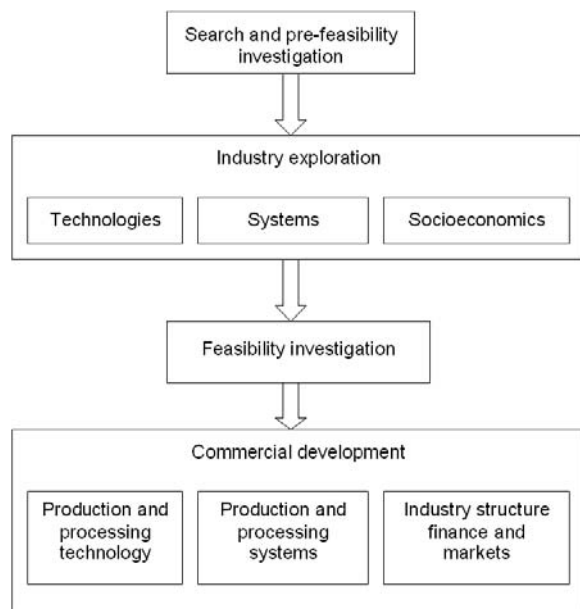


Figure 16.3: Industry development conceptual plan.

BOX 16.2

Box Woody crop types for the wheatbelt

- **Short-cycle coppice crops:** long-lived species that can regenerate or coppice from the cut stump and can be harvested regularly on a short cycle. Harvest frequency might range from 2–5 years, a frequency that strong coppicing species like mallee can sustain indefinitely. Coppicing species make substantial investment in root systems and regenerative organs such as lignotubers and are best suited to belt or alley layouts where the woody crop is planned to be permanent (Wildy *et al.* 2003; Cooper *et al.* 2005).
- **Short-cycle phase crops:** short-lived woody crops suitable for planting on a whole-paddock basis and ready for harvest after 3–6 years. They are quick-growing, readily established (large-seeded, suitable for direct seeding) and deep-rooted. If leguminous (e.g. *Acacia*) they could contribute nitrogen to the crop rotation in addition to dewatering (Bartle *et al.* 2002; Harper *et al.* 2000).
- **Long-cycle tree crops:** long-lived species of trees that require 20–100 years before producing poles or logs of sufficient size for harvest. Best suited to belt planting to provide shelter benefits and have access to extra water.

is to use woody crops (or any perennial) to capture as much of the surplus water from the annual crop and pasture proportion as possible, and to convert it into commercial return. There are two approaches to this. First, the woody crop could be planted in spatial arrangements designed to intercept extra water from adjacent annual crop or pasture. Second, the woody crop could be planted in rotation with annual crops so that there is a water-

accumulating phase under annuals alternating with a dewatering phase of perennials. The first approach is called belt or alley farming, and the second is called phase farming. These approaches and the woody crop types that match them are discussed in Box 16.2, with the conventional long-cycle tree crop method.

Most mallee planting in Western Australia has been in the form of contour belts on sloping land



Figure 16.4: Mallee belts on a farm near Koorda in the Western Australian wheatbelt (photo by John Bartle).

or straight belts on flatter land. Typical distance between belts is a multiple of annual crop machine passes totalling up to 100 m. The belts commonly consist of four planted rows, 2 m apart and with a 1.5 m within-row spacing, although water availability may necessitate narrower belts in future. Mallees are not palatable to sheep and do not need fencing, although care is required with exposure to grazing in the first year of establishment. Farmers have evolved workable methods of integration and management of mallee but more development is required for design of optimum systems of water capture.

Biomass supply chain

There has been considerable theoretical assessment of options for a mallee biomass supply chain (all steps from harvest to delivery to a central processing location) and its efficient integration into activities at the farm and processing plant. The conclusion is that there are no off-the-shelf options, but sugarcane industry handling systems look suitable for adaptation to mallee biomass removal from the paddock and delivery to the processor (Giles and Harris 2003).

Supply chain development is critical due to the demanding economics of mallee. Farmers must receive sufficient return from sale of mallee biomass to justify the cost of establishing and growing the crop. At the same time, processing industries must be able to purchase the biomass at a realistic price. The market value of mallee biomass is anticipated to be about half the value of forestry production of pulpwood chips. The estimate upon which the Enecon feasibility study was based is \$30/green tonne delivered over a 50 km average distance, with a standing in-the-paddock return to the farmer of \$15/green tonne (Enecon 2001). The supply chain must be able to function profitably in the margin between the biomass production cost and its market value.

The harvesting system designed to meet these performance parameters is under development. It consists of a self-propelled harvester travelling continuously along a single row of mallee at about 5 km/h, cutting each stem just above ground level. It firmly grasps and entrains the cut mallees into a continuous stream into a drum chipper, and produces a flowable bulk material at the rate of about 75 t/h. Chipped mallee biomass has sufficient bulk

density for efficient transport. The harvester passes the biomass to trailing haulouts that would deliver to road transport via tipping bins. Research prototypes have been constructed to test specific steps, but operational prototypes will not be made until processing is likely to be commercially viable.

Integrated processing

The feasibility study into integrated mallee processing (Enecon 2001) underpinned the construction of a demonstration plant (operational test scale) at Narrogin, 200 km south-east of Perth. Final results have not been announced. Investigation of this form of mallee processing has cost about \$20 million, indicating the considerable challenge presented by new industry development.

Integrated processing allows the efficient direction of specific biomass fractions to higher-value products while using residues for lower-value services such as bioenergy. The high-value products are activated carbon from the wood fraction and eucalyptus oil extracted from the leaves. All residues and waste heat are used for electricity generation. The demonstration plant is 20% the size of a full-scale plant. The operating parameters for a full-scale plant are given in Table 16.1.

The strength of integrated processing is that it extracts the full revenue potential from a mixed biomass feedstock produced and delivered in a single stream. In this way, costs are minimised and revenue is maximised. The price of woodchips implicit in integrated production and processing appears highly competitive with conventional forestry sources. Likewise, concurrently delivering residue minimises its cost as fuel for bioenergy. The price structure of integrated production and processing gives the option of diversifying into other species, to obtain better-quality biomass components, and into other large-scale products such as panel board, charcoal, transport fuels and fodder (Olsen *et al.* 2004).

Wider application of the mallee model

Predicting yield for woody coppice crops

It is essential to estimate what level of biomass production might be achieved by woody crops in wheatbelt agricultural systems. Yield determines

Table 16.1: Key parameters for full-scale integrated mallee processing plant

Parameter	Capacity
Feedstock required	100 000 green t/yr
Feedstock composition	40% wood, 25% bark/twig, 35% leaf. 50% (including all wood) directed to activated carbon, 50% (including all leaf) directed to oil extraction
Capital cost	A\$28.4 million \pm 15% (steam turbine + air-cooled condenser)
Feedstock cost	A\$15/t standing in paddock, \$30/t delivered to factory
Annual operating expenditure	A\$7.9 million (includes feed purchase and interest payments)
Annual revenues	A\$17.3 million
Activated carbon products	4100 t at A\$2857/t ex works
Eucalyptus oil produced	1050 t at A\$3000/t ex works
Electricity produced	5 MWe green electricity at A\$60/MWh, 8000 hours/yr
Internal rate of return	18.8% (15 yrs)

Source: Enecon (2001)

profitability and potential scale of production, and is the main criterion by which improvement in performance is measured.

The large area of mallee planting in Western Australia provides good opportunity to collect empirical yield data (Grove *et al.* 2007). However, the diversity of species, management inputs, planting configurations and site types mean that large samples are required for representative data and unbiased estimates. The workload is exacerbated by the need to collect data from stands subject to harvest, and to extend this over several coppice cycles so that the influence of initial stored water is dissipated and long-term yield potential is expressed. Biomass supply will require year-round delivery and it is likely that coppice yield will be strongly influenced by the season and frequency of harvest. The first comprehensive experiments to provide empirical data on the effect of season and frequency of harvest on biomass production have only recently been established. The work will gather data on the influence of harvest regime on competition by mallee belts with adjacent annual crops.

There is thus some time before good empirical data become available, so it is necessary to use alternative methods of yield prediction. Cooper *et al.* (2005) developed such a model, based on water sources potentially available to a woody crop belt. It estimates the amount of water available from each source and converts this to biomass yield for mallee, using experimentally derived data on mallee water use efficiency. Figure 16.5 shows potential sources of water that may enter storage in

the water-depleted zone below a woody crop belt and be available for uptake. The water-depleted zone can be broad and deep and operate as a large sink for any lateral water flow (Robinson *et al.* 2006; Sudmeyer and Goodreid 2007).

The model constrains the estimate of area and yield of mallee belt to levels that require the mallee agroforestry component to equal or exceed the profit of the annual plant agriculture that might otherwise occupy the land. The model assumes a biomass selling price of \$15/green tonne (standing on-farm). The Cooper model enables woody crop belt designs to be compared and provides useful indications of priorities for further research. For example, early surveys suggested that the proportion of land that should be planted to perennials to achieve salinity control might be up to 80% (George *et al.* 1999). This work was complemented by catchment-scale hydrogeological modelling. However, such broad-scale work cannot account for the local redistribution of water by surface and shallow subsurface runoff that becomes available to belts of trees (Figure 16.5; Cooper *et al.* 2005, Lefroy *et al.* 2005).

The Cooper model shows why large proportions of planting would not be economically feasible for woody crops. It indicates that woody crop belts would have to be confined to between 1.5% (for 300 mm rainfall/yr) and 8% (for 600 mm rainfall/yr) of farmland to obtain enough runoff from adjacent annual crop and pasture land for commercial yield. At the higher-rainfall end of the range, it appears that passive interception (belts on the contour) will be able to capture enough surplus water.

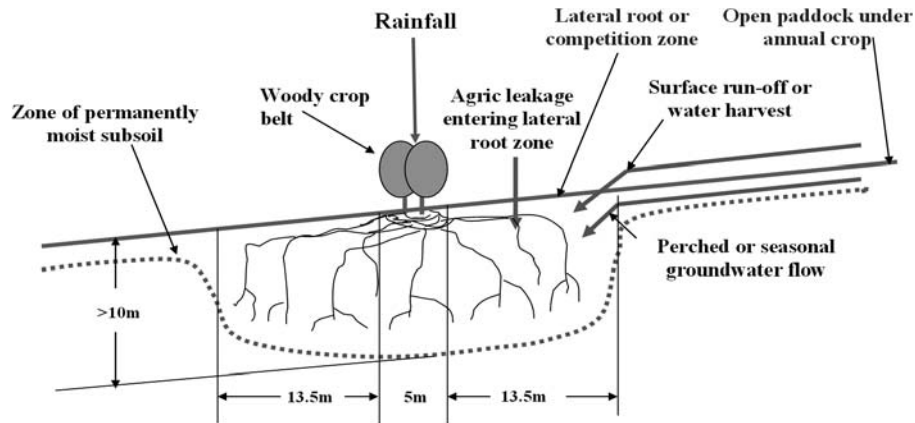


Figure 16.5: Multiple sources of water available to a woody crop in belt layout.

However, in lower-rainfall wheatbelt areas active water harvest systems will be required to complement passive collection, i.e. it will be necessary to harvest runoff from areas that are unsuitable for woody crops and transfer that water to planted areas. This remains an area of active research. Other salinity control practices would also be needed, to achieve a high level of salinity control.

Potential scale of woody crop production

If competitive woody crop yields can only be achieved on 1.5–8% of wheatbelt land, will this produce large enough volumes of biomass to attract processing industries?

Cooper *et al.* (2005) addressed this question. They compared potential mallee biomass production at two locations in the Western Australian wheatbelt, Narrogin (501 mm rainfall) and Merredin (328 mm rainfall). They showed that, with their base assumptions, no commercial yield would be expected at Merredin but that 266 dry kt/yr of biomass could be produced at Narrogin (Table 16.2). However, with small but credible increases in two of the most sensitive parameters, biomass price and water use efficiency (biomass price rise from \$30/green t to \$35/green t and water use efficiency

increase from 1.5 to 1.8 g/L), commercial production would considerably increase.

Scale of production strongly influences the type of industry that might emerge. Industry development at Merredin is likely to be confined to those that would be viable on smaller biomass volumes, e.g. the activated carbon process that needs 55 dry kt/yr (Enecon 2001), whereas Narrogin could support panel board manufacture that requires 800 dry kt/yr. Even at the low-rainfall end of this range, it is clear that the potential planted area and volume of production necessary for salinity control would saturate markets for small-volume high-value specialty products like flowers, fruits, seeds, nuts, bush tucker or aromatic wood. These could form a small but important part of future woody crop industries, but large-volume, lower-value products manufactured from bulk biomass feedstocks will have to carry the base load of new industries.

The Cooper model can be adapted to predict regional biomass productivity. Bartle *et al.* (2007) used Western Australian data to make preliminary estimates of biomass production potential across southern Australian wheatbelt regions.

Figure 16.6 indicates that total Australian wheatbelt production potential is about 40 million

Table 16.2: Biomass production response to increased price and water use efficiency at two locations in dry kt/yr

Location	Base case	Optimistic case		
		Increase price	Increase WUE	Increase both
Narrogin	266	789	608	1630
Merredin	0	42	5	239

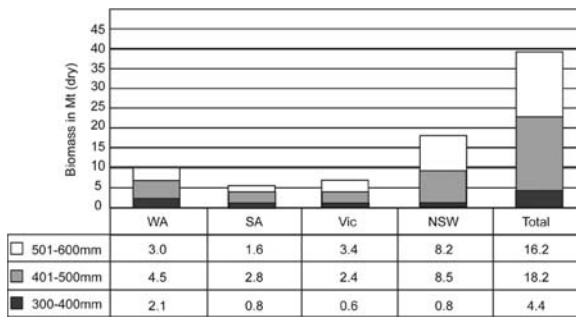


Figure 16.6: Potential biomass production (M dry t/yr) for four southern states of Australia, optimistic scenario for three wheatbelt rainfall zones (reproduced with permission from Bartle *et al.* 2007).

dry tonnes of biomass. In terms of primary energy content, this is equivalent to about 14% of Australia's current consumption (ABARE 2005a). The woodchip fraction (~25% or 10 million dry tonnes) exceeds Australia's current domestic and export woodchip production (12.8 million m³ measured in log volume in 2004/05 (ABARE 2005b), or ~7 million dry tonnes). However, the current export chipwood industry is dominated by high-quality pulp species and mallee would not be suitable. This has stimulated the search to diversify the range of new woody crop species.

Woodchip for panel or paper products is a target product area for wheatbelt biomass development. ABARE (2005b) gives the export woodchip price range: from \$133 (softwood) to \$158 (hardwood) per bone-dry tonne. Depending on conversion rates, water content and quality, this indicates a notional woodchip value of up to \$40 a dry tonne of wheatbelt biomass, or up to \$22 in a green tonne. The Cooper model optimistic scenario uses a biomass price of \$35/green tonne (delivered to a central location). The remaining 75% of biomass after separation of the woodchip fraction may only have to generate revenue of \$13, or \$17.3/green tonne. Other high-value products may be produced from the leaf (eucalyptus oil, fodder) or twig and bark (charcoal), but even without these a landed price of \$17 is an attractive price for a bioenergy feedstock.

Energy balance

Conventional economic analysis does not usually deal with all energy and carbon costs and benefits when evaluating energy production alternatives.

Life-cycle analysis is used to estimate energy and carbon balances to enable comparison of the energy or carbon efficiencies of different systems. To better understand and combat the issues of climate change and fossil fuel depletion, it will be important to add this extra dimension to economic analysis.

Wu *et al.* (2005) conducted a partial life-cycle analysis on mallee. They considered only the balance of energy inputs and outputs in growing, harvesting and delivering mallee biomass to a central location. Mallee biomass production can be sustained indefinitely on regular short cycles of harvesting the entire above-ground parts, with regeneration occurring by coppice from the retained root stock. Since the initial establishment of a mallee crop is expensive and energy-intensive, accounting for this cost can reasonably be distributed across a number of coppice crops. A term of 50 years was chosen as the production period for this assessment. The first sapling crop takes five years to reach harvestable size and subsequent coppice crops take three years. Hence the 50-year production period consists of the initial sapling crop (five years) and 15 coppice crops (45 years), totalling 16 harvests.

All activities during the mallee production period that involve direct non-renewable energy inputs (liquid fuels and lubricants, heat, electricity) and/or indirect energy inputs (fertilisers, agrochemicals, tractors, agricultural machinery, transport equipment, labour, capital) were specified. For each input, the energy amount was converted back to a common base, i.e. the equivalent non-renewable primary energy required to supply the energy used. The energy output is the primary energy contained in all mallee biomass components, i.e. wood, bark and twig, and leaf.

The energy ratio (output of energy in biomass/input of energy in production) was found to be 41.7. This high ratio reflects the strong competitive position of coppice crops in energy capture compared to annual crops such as cereals or canola, that typically have an energy ratio lower than 10. Coppicing avoids regular replanting inputs after every harvest. A high energy ratio helps the complementary position of mallee and annual agricultural crops, i.e. higher mallee yields can be achieved through capture of surplus water and nutrients.

A full life-cycle analysis for biofuels, including the further energy costs of conversion of biomass

Table 16.3: Western Australian species number and region of occurrence for various categories

Category	Region	Number
All native species recorded at State Herbarium	WA	9977
All species excluding priority (rare) taxa	WA	7965
All woody species	WA	6339
All species in the four wheatbelt IBRA regions	Wheatbelt	3664
All species >4 m in more than one wheatbelt IBRA region	Wheatbelt	484
All species >4 m Avon wheatbelt IBRA region	AW	309
All species >4 m Esperance sandplain IBRA region	ES	266
All species >4 m Geraldton sandplain IBRA region	GS	219
All species >4 m mallee IBRA region	M	293
All species >4 m in all four wheatbelt IBRA regions	Wheatbelt	68

IBRA: Interim Biogeographic Regions of Australia

Source: Adapted from Olsen *et al.* (2004)

to fuel, shows an energy ratio of six for mallee compared to a ratio between one and two for the annual crops. The technologies for conversion of woody biomass to biofuels are still in the development stage (Enecon 2002). However, it seems clear that the substantial advantage in energy gain of woody crops will see them dominate biofuels production in the medium to long term.

New species, new products and new industries: FloraSearch

The progress in mallee development gave rise to an obvious question – might there be other native species that would be attractive for development or domestication as wheatbelt crops?

Selection of species for bulk biomass production is far less challenging than selection of species for food crops. Some 80% of the world's food production comes from only 12 species, all of which were domesticated several thousand years ago on the basis of very specific food values (Diamond 2001). Biomass production is a much less specialised target. It means that dominant species in the native flora could provide a good first selection of species suitable for cultivation. This sits comfortably with Australia's increasing reluctance to introduce new plants from overseas. Plant introduction incurs the risk that some will escape from cultivation and become weeds (ARMCANZ *et al.* 1997). This was the rationale for searching only native flora for new woody crops.

Even though biomass production potential is a primary criterion for woody crop prospects, there may be important variation in the quality and range of products for which a particular species might be suited. Species may vary in adaptability to the cropping environment. Hence, a search of the native flora for potential crop species would be based on combined assessment of agronomic and product attributes.

The Natural Heritage Trust sponsored such a search in 1999, screening the ~10 000 flora species in south-west Western Australia for prospective crop species. The CRC for Plant-based Management of Dryland Salinity and the Joint Venture Agroforestry Program also conducted a project, called FloraSearch, to screen the flora of the Murray-Darling basin (~10 000 species) and take initial steps in domesticating selected species from the south-west and south-east.

It was comparatively easy to conduct a broad selection, to reduce the number of species requiring more detailed assessment to a manageable number. The Western Australian Search project used records from the State Herbarium. The process is presented in Table 16.3 and described below.

There were 9977 recorded native species at the time of investigation. Of these, 2012 were designated as extinct, rare, endangered, requiring special protection, or requiring investigation to determine their conservation status. They were excluded from further investigation, reducing the number of species to 7965. Confining the selection

to woody species reduced the list to 6339. Consistent with the objective of minimising weed risk, the selection was limited to species that occur in the four Interim Biogeographic Regions of Australia (IBRA) that approximately coincide with the Western Australian wheatbelt, leaving 3664 species. The largest reduction occurred when an arbitrary height of 4 m was used as a surrogate for productivity, leaving 484 species. The 68 species taller than 4 m that occur in all four of the wheatbet IBRA are of particular interest because their wide distribution suggest good general adaptation.

On the basis of expert opinion, about half the 484 species taller than 4 m and present in at least one of the four IBRA were selected for objective measurements of wood and product attributes. Three levels of testing were done, each accompanied by progressively intensive agronomic assessment. Sample wood products made and performance-tested included paper, medium-density fibreboard and particle board. Additional work was done on combustion properties.

This process identified a list of 11 species to be further investigated when resources permit, and a focus list of three (species that warrant continuing investigation). The focus list for Western Australia consists of *Acacia saligna*, *E. rudis* and *E. loxophleba* spp. *lissophloia*. The first focus species selection from the Murray-Darling Basin search was a potential fodder species (*Atriplex nummularia* – old man saltbush), which was also included in the Western Australia focus species list.

The full report on the Western Australia Search project is available (Olsen *et al.* 2004) and an interim report on the parallel work of FloraSearch has been submitted to the Joint Venture Agroforestry Program (Bennell *et al.* in press). The FloraSearch project is conducting taxonomic and genetic improvement of the focus species, and analysing regional infrastructure across southern Australia for favourable locations for major new industry development.

Conclusion

Mallees have made a remarkable transition, from being considered an obstacle to agriculture during the twentieth century, to contending for a role as an extensive biomass crop in wheatbelt agriculture in

the twenty-first century. Although not yet a commercial reality, mallee has attracted considerable investment and built enough momentum to ensure that its crop potential will be thoroughly examined.

The progress in domestication of mallee springs from its native genetic endowment; it is rich in attributes that find special application in wheatbelt agriculture. There are several species with high leaf oil content. Mallee are impressively tough and quick to get established in the paddock. Unfenced belts are resistant to grazing, causing only minor management inconvenience in the first summer after planting. Their water use efficiency is outstanding and, when grown in belts on conducive soils, they create a zone of water depletion that can act as a reservoir for surface runoff, increasing the crop's hydrologic footprint. Not enough is known about harvest management and biomass yield, but research is underway. Mallee can sustain regular harvest on a three- to five-year cycle. Economic analysis shows that biomass yields are marginal and that efficient passive and active capture of runoff will be important determinants of profitability.

Mallees have won a large farmer following in Western Australia. Farmers like its toughness in the paddock, and the opportunity to achieve substantial on-farm biological diversification and economic diversification in their product range. The experience with mallee has broadened farmers' view of bioenergy options and carbon sequestration. The low ongoing energy expenditure in growing mallee biomass compared to annual crops as a feedstocks for bioenergy is very apparent. This should help create a better national balance between the short-term biofuels opportunities in grain ethanol and biodiesel and the longer-term opportunities for woody crops.

Mallee has been a pioneer large-scale woody crop development. It has shown enough promise to attract interest from other states and for scientists to commence detailed examination of the crop potential of other native species.

References

- ABARE (2005a) *Energy in Australia 2005*. Australian Bureau of Agricultural and Resource Economics, Canberra.

- ABARE (2005b) *Australian Forest and Wood Product Statistics, March and June quarters 2005*. Australian Bureau of Agricultural and Resource Economics, Canberra.
- ARMCANZ, ANZECC and FM (1997) *The National Weeds Strategy: A Strategic Approach to Weed Problems of National Significance*. Agricultural and Resource Management Council of Australia and New Zealand/Australian and New Zealand Environment Conservation Council/Forestry Ministers.
- Bartle JR (1991) Tree crops for profit and land improvement. *WA Journal of Agriculture* **32**, 11–17.
- Bartle JR (2006) New non-food crops and industries for Australian dryland agriculture. In *Proceedings, Green Processing 2006. 3rd International Conference on Sustainable Processing of Minerals and Metals*. Newcastle, NSW. pp. 63–68. Australasian Institute of Mining and Metallurgy.
- Bartle JR and Shea SR (2002) Development of mallee as a large-scale crop for the wheatbelt of WA. In *Private Forestry: Sustainable, Accountable and Profitable. Proceedings of Australian Forest Growers 2002 National Conference*. pp. 243–250.
- Bartle JR, Cooper D, Olsen G and Carslake J (2002) Acacia species as large-scale crop plants in the Western Australian wheatbelt. In *Conservation and Utilisation Potential of Australian Dryland Acacias. Acacia Symposium 2001*. July, Dalwallinu, WA. *Conservation Science Western Australia* **4**, 96–108.
- Bartle JR, Olsen G, Cooper D and Hobbs T (2007) Scale of biomass production from new woody crops for salinity control in dryland agriculture in Australia. *International Journal of Global Energy Issues* **27**(2), 115–137.
- Barton AFM (2000) The oil mallee project: a multifaceted industrial ecology case study. *Journal of Industrial Ecology* **3**(2/3), 161–176.
- Bennell M, Hobbs TJ, Hustable D, Bartle JR, Neumann C, George N and O'Sullivan W (in press). 'FloraSearch species and industry evaluation: low rainfall agroforestry options for southeastern Australia'. Report to the Rural Industries Research and Development Corporation, Canberra. Department of Water, Land & Biodiversity Conservation, Adelaide, SA. Accessed 24 October 2006. <http://www.crc-salinity.com/documents/uploads/RIRDC_FloraSearch_2006_Submitted.pdf>
- Brooker (2002) Botany of the eucalypts. In *Eucalyptus: The Genus Eucalyptus*. (Ed. JJW Coppen) pp. 3–35. Taylor & Francis, London.
- Byrne M (1999) High genetic identities between three oil mallee taxa, *Eucalyptus kochii* ssp. *kochii*, ssp. *plenissima* and *E. horistes*, based on nuclear RFLP analysis. *Heredity* **82**, 205–211.
- Cooper D, Olsen G and Bartle JR (2005) Capture of agricultural surplus water determines the productivity and scale of new low-rainfall woody crop industries. *Australian Journal of Experimental Agriculture* **45**, 1369–1388.
- Davis GR (2002) Cultivation and production of the eucalypts: with special reference to the leaf oils. In *Eucalyptus: The Genus Eucalyptus*. (Ed. JJW Coppen) pp. 183–201. Taylor & Francis, London.
- Diamond J (1997) *Guns, Germs and Steel*. Chatto & Windus.
- Enecon Pty Ltd (2001) 'Integrated tree processing of mallee eucalypts'. Rural Industries Research and Development Corporation, Canberra. Publication no. 01/160. Accessed 1 February 2006. <<http://www.rirdc.gov.au/reports/AFT/01-160.pdf>>.
- Enecon Pty Ltd (2002) Wood for alcohol fuels: status of technology and cost/benefit analysis of farm forestry for bioenergy. Rural Industries Research and Development Corporation, Canberra. Publication no. 02/141.
- George RJ, Nulsen RA, Ferdowsian R and Raper G (1999) Interactions between trees and groundwaters in recharge and discharge areas: a survey of Western Australian sites. *Agricultural Water Management* **39**, 91–113.
- Giles RC and Harris HD (2003) Developing a biomass supply chain for new Australian crops. Paper presented at *IEA Bioenergy Task 30 (Short Rotation Crops for Bioenergy) Conference*. 1–5 December 2003, Tauranga, NZ.
- Grove TS, Mendham DS, Rance SJ, Bartle JR and Shea SR (2007) Nutrient management of intensively harvested oil mallee tree crops. Rural Industries Research and Development Corporation, Canberra. RIRDC Publication no. 07/084.

- Harper RJ, Hatton TJ, Crombie DS, Dawes WR, Abbott LK, Challen RP and House C (2000) 'Phase farming with trees: a scoping study of its potential for salinity control, soil quality enhancement and farm income improvement in dryland areas of southern Australia'. Rural Industries Research and Development Corporation, Canberra. Report no. 00/48.
- Lefroy EC, Flugge F, Avery A and Hune I (2005) Potential of current perennial plant-based farming systems to deliver salinity management outcomes and improve prospects for native biodiversity: a review. *Australian Journal of Experimental Agriculture* **45**, 1357–1368.
- Nulsen RA, Bligh KJ, Baxter IN, Solin EJ and Imrie DH (1986) The fate of rainfall in a mallee and heath vegetated catchment in southern Western Australia. *Australian Journal of Ecology* **11**, 361–371.
- Oil Mallee Association (2003) Mallee cropping code of practice. Rural Industries Research and Development Corporation, Canberra. Accessed 25 October 2006. <http://www.rirdc.gov.au/reports/AFT/code_of_practice_final_version.pdf>.
- Olsen G, Cooper DJ, Huxtable D, Carslake J and Bartle JR (2004) 'NHT Project 973849: Developing multiple purpose species for large scale revegetation'. Search Project Final Report. Available on CD from Department of Environment and Conservation, WA.
- Robinson N, Harper RJ and Smettem KRJ (2006). Soil water depletion by *Eucalyptus* spp integrated into dryland agricultural systems. *Plant and Soil* **286**, 141–151.
- Stirzaker R, Lefroy E, Keating B and Williams J (2000) *A Revolution in Land-use: Emerging Land-use Systems for Managing Dryland Salinity*. CSIRO Land & Water, Canberra.
- Stirzaker R, Vertessy R and Sarre A (Eds) (2002) 'Trees, water and salt: an Australian guide to using trees for healthy catchments and productive farms'. Joint Venture Agroforestry Program, Rural Industries Research and Development Corporation, Canberra. RIRDC Publication no. 01/086.
- Sudmeyer RA and Goodreid A (2007) Short rotation woody crops: a prospective method for phytoremediation of agricultural land at risk of salinisation in southern Australia? *Ecological Engineering* **29**, 350–361.
- Wildy DT, Pate JS and Bartle JR (2003) 'Silviculture and water use of short-rotation mallee eucalypts'. Rural Industries Research and Development Corporation, Canberra. Publication no. 03/033.
- Wildy DT, Pate JS and Sefcik L (2004) Water use efficiency of a mallee eucalypt growing naturally and in short-rotation coppice cultivation. *Plant and Soil* **262**, 111–128.
- Wu H, Qiang Fu, Giles R and Bartle JR (2005) Energy balance of mallee biomass production in Western Australia. In *Biomass for Energy, the Environment and Society. Proceedings of Bioenergy Australia Conference 2005*. December, Melbourne, Vic.

PART III

Implementation of agroforestry

Financial and economic evaluation of agroforestry

David Thompson and Brendan George

Introduction

There are many reasons for planting trees and managing them for wood and non-wood products. Large-scale commercial forestry enterprises focus on financial returns. Publicly owned companies are bound to inform investors of their strategies and financial positions. However, in agroforestry situations, the financial return may be an important but not a primary driver for a farmer to invest in tree planting or the management of native forests. With the changing expectations of society and the development of non-wood markets, there are new incentives for increasing the area and management of trees on farms.

Changing societal expectations and their implications for forestry management involve the need to better understand and manage our natural resources. Despite the willingness of many land managers to adjust their practices to improve natural resource outcomes, there are few markets that allow for the trading of these services, to give a monetary return to the manager. There is, however, a role for planted or existing forests to deliver not only wood products, but also non-wood products such as improved agricultural production from stock shelter and environmental services including improved biodiversity, better water quality and carbon sequestration. There is a relatively clear understanding of the value of wood products via markets. However, there is still much work to be done in quantifying the full range of benefits, and in some cases the costs, of establishing forestry

enterprises on farms and in determining a monetary value which allows economic and financial comparisons with alternative land uses.

Understanding the economic and financial value of farm forestry requires quantification and market development of the mix of values associated with a farm forest. For example, what is the value of an increase in habitat area and quality that leads to an increased number of possums? What is the worth of a tonne of carbon sequestered in a managed forest? What is the value of the timber that can be extracted from the forest? At present, the habitat protection is unquantified and not monetarily valued, the storage of carbon can be quantified but there is uncertainty about its market value, and there are clear, though not always transparent, markets for the wood products.

There are other benefits that agroforestry systems may bring to the farm business. For example, a well-planned and well-implemented agroforestry system may add to the farm's capital value. The use of trees could reduce soil erosion or add to the amenity value of the property. However, these benefits can be difficult to quantify. For example, we may not be able to accurately measure the reduction in soil erosion, and the contribution to maintaining or increasing the resilience of the farming system. But that does not mean agroforestry has no value for this purpose. It means that the value is generally unquantified and therefore not easily included in standard economic or financial analyses. The Australian Bureau of Statistics (Pink 2007) reported on

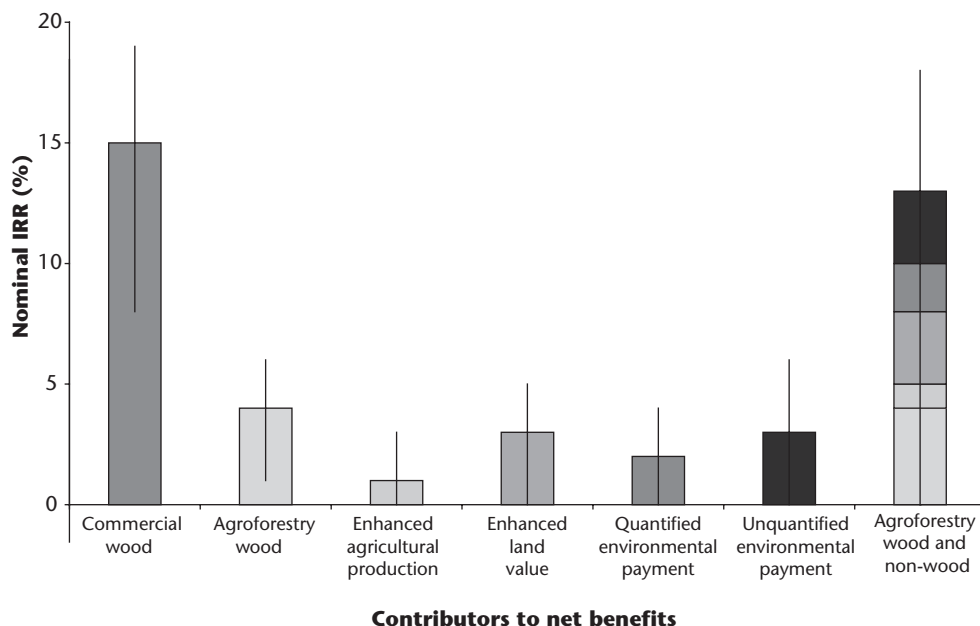


Figure 17.1: Financial returns (represented as the nominal internal rate of return on investment) for large-scale forestry and agroforestry systems. The lines are a schematic representation of the potential variation in the IRR determined from the economic variation of the components.

experimental techniques being considered for a process that can account for the depletion of environmental assets when the stock value is reduced through use in a productive activity (an activity may not be sustainable over a long period). The approach is not yet part of the standard accounting process.

The net economic impact of an agroforestry project may be reflected in the capital value of the farm. When a property is valued by the market (sold) there might be an increased return due to the perceived or real increase in the capital value. Some increases could be real (e.g. healthier soil conditions), others could involve perception (e.g. the aesthetics of a tree-covered property compared to a treeless one).

There are risks associated with these benefits or returns. A hypothetical comparison between a financial return from a plantation aimed solely at wood production (e.g. large-scale plantations established by public companies) and a combined return from wood and non-wood benefits from an agroforestry investment is illustrated in Figure 17.1. This conceptual diagram highlights the issue of traditional economic comparison of activities for known markets (e.g. wood) and developing markets where the values may not be as readily quanti-

fied or traded. The error bars in Figure 17.1 can be used to reflect the risk of particular revenue streams. An agroforestry system may rely on cumulative small returns from different components to reach the threshold returns required for an investment focused primarily on wood production.

It is important to recognise that the standard economic tools used to evaluate large-scale plantation investments aimed primarily at wood production are still valid in the assessment of agroforestry investments. The key difference is that a wider range of benefits and costs might be factored into the agroforestry analysis, and in some cases these are difficult to quantify.

Farmers and landholders rely on various inputs to determine their day-to-day and strategic operational decisions. The landholders' age, health, family circumstances and knowledge could be as important as financial measures in making investment decisions. The capacity to implement land use change such as introducing or increasing agroforestry varies between landholders, but financial considerations usually feature strongly in the decision-making process.

In this chapter we discuss the use of financial and economic tools for assessing forestry invest-

BOX 17.1

Some definitions

- **Financial analysis or investment analysis** describes the analysis undertaken to determine the return on investment in a specific activity or project. It is often focused on enterprise-level (e.g. an agroforestry investment) or farm-level outcomes (e.g. the impact of shelter belts that increase lambing survival rates and overall farm returns).
- **Economic analysis or cost–benefit analysis** generally expands the scope of the analysis to include broader (e.g. societal) considerations. For example, an analysis can be undertaken of the expected costs and returns to society of increasing particular native species and their distribution through tree planting. Unlike financial analysis, economic analysis extends the scope of the investigation beyond the farm boundary to consider off-farm effects and non-productivity-related effects.
- An **externality** occurs when the costs or benefits of an activity affect another entity not party to that activity (e.g. large-scale plantation expansion may have impacts on downstream water quality and quantity). These costs or benefits can be difficult to measure and are often ignored in analysis, for simplification.

ments, and examine how they can be adapted to evaluate agroforestry configurations. We follow a simple example illustrating aspects of economic analysis throughout the chapter, which increases in complexity as issues are introduced.

We discuss the distinction between on-farm financial analysis and broader off-farm economic issues related to agroforestry investments. Analysis at both scales often relies upon investment analysis techniques, and these are summarised. The role of financial and economic analysis is to inform the land manager of the likely outcome of alternative investment options, and allow a more structured decision process for considering the inclusion of trees in a farm business. Similar but wider-ranging cost–benefit analysis can be used to assess the broader social implications of establishing trees in farming systems.

Private and social objectives

Private objectives are often concerned with maximising profit and include consideration of private financial risk. Private objectives are sometimes regarded as something which conflicts with the ‘social welfare’ agenda but, in reality, they are simply a subset of social costs and benefits. The

public can be considered as a collection of many private individuals (Pannell 2004a). The objective of any policy or land use change should be to generate net benefits to society; that is, the sum of the public and private benefits outweighs the sum of the public and private costs.

The situation may arise where a large private benefit outweighs a small public cost. From an economic perspective this is a net benefit and hence an efficient outcome, though philosophically some might view it as a perverse and inequitable situation that is not socially desirable. This issue is addressed in more detail in Chapter 18.

In determining the net private benefit it is important to consider the opportunity cost – the value of the funds in the next best alternative use, such as a change from grazing to wide-spaced agroforestry. In this case, opportunity cost would include assigning a value to the reduction in net grazing returns, not just whether the new activity produces a positive return. The new land use (wide-spaced agroforestry) might be profitable, but could be less profitable than the old land use (grazing). This land use change would thus represent a net private loss, not a benefit.

In relation to land use change, if a net private loss would be offset by a larger net public benefit

there may be a role for government intervention to ensure that the net social benefit is achieved. This issue is discussed in more detail in Chapter 18.

In both financial and economic analysis it is necessary to establish a base case (do-nothing scenario), where it is assumed the project does not go ahead. This is important because the costs and benefits measured in the analysis are nearly always expressed in marginal, or incremental, terms. For example, planting trees on a farm may provide additional shelter which, when compared to an unsheltered farm, increases lamb survival and hence lamb weaning rates by 10%. However, improved livestock husbandry practices for lambing ewes may have already been implemented and produced a 4% increase in lambing rates. The incremental benefit from tree planting may only be an additional 6% improvement. This highlights the difficulty in quantifying the response to changed or improved management decisions. However, to allow for a realistic analysis, these parameters need to be quantified.

Financial investment analysis

In a farm or agroforestry situation, the boundary for financial analysis – often called investment or private analysis – is the individual farm business. Generally, only directly measurable financial elements are considered (i.e. farm costs and revenues). Some components of the analysis may represent a less tangible return, for example ‘amenity value’. A land owner may enjoy having trees on their property though there is no specific financial return. However, this return may become more tangible, and the importance of the trees to the value of the property may be realised, where the property is sold to a buyer who is willing to pay more because of higher aesthetic values.

Essentially, financial analysis is concerned with the organisation’s own financial performance and cash flows. Analysis techniques involve cash-flow budgets and whole-farm financial analysis, and may include risk or bio-economic modelling (a model which simulates biophysical and economic elements of the farm system).

Cash-flow techniques

Cash flow refers to the receipt of revenue or income (cash inflows) and the payment of expenses (cash

outflows) that are a normal part of any business operation. Net cash flow refers to the difference between the two and may be calculated over a range of time frames for business management purposes.

With specific reference to financial analysis, cash-flow calculations involve estimating the revenues and expenses relating to the landholder or business entity who would implement the project. Typically, the factors included in a financial analysis do not involve consideration of externalities, that is, impacts of the project beyond the farm boundary.

We discuss the larger implications of including externalities later in this chapter.

Identifying costs and benefits in a financial analysis

In a financial analysis of an agroforestry enterprise, the benefits represent the returns from agroforestry project sales (e.g. quantity of logs sold multiplied by the price). Benefits may also include returns from synergies with other business activities (e.g. additional livestock gross margin from higher lambing rates due to shelter benefits) and non-wood values such as an increased capital value of a property.

The costs in financial analysis may include variable costs (e.g. cost of ground preparation, tree seedlings, planting, management, pruning, harvesting), overhead costs (e.g. cost of planning and compliance, additional farm labour if required), capital costs (e.g. land purchase, purchase of forestry-specific machinery, depreciation) and opportunity cost (e.g. reduced gross margin from displaced livestock or cropping enterprises on land planted to trees). The cost of labour is an important input for agroforestry systems. Farmers may be able to utilise labour for certain forestry operations on an *ad hoc* basis, thereby increasing the production of otherwise idle labour resources. Further, the landowner may not necessarily value their time in a true economic sense. These changes can dramatically affect the outcomes, especially if the time-value of money is included in the labour assessment. How the costs of inputs are determined is often not clearly understood and it is important that all assumptions be clearly stated.

Only the cash flows that are incremental to the project should be considered in the analysis. In determining incremental costs or benefits, the following must be considered:

- ignore sunk costs as they have already occurred regardless of the project decision and are accounted for in the current financial position;
- opportunity costs can be factored in as negative cash flows. For example, in an agroforestry context, if the plantation replaces grazing, lost grazing net income can be factored into the analysis as a cost;
- tax costs should be factored in as they affect incremental cash flows. However, this is rarely done in practice, possibly due to the complexity of calculating tax implications;
- depreciation costs should be factored in because they affect tax payable and hence incremental cash flows. This would occur only where tax is being factored into the analysis, which is rare;
- consider synergies. For example, agroforestry may boost cash flows in other enterprises, such as increased lambing percentage from shelter, leading to higher income;
- interest payments are excluded because they are catered for in the discounting process.

Pannell (2006) noted that there are usually various simplifications:

- the use of a constant discount rate over time (discussed later);
- tax may be disregarded if we are focusing on social cost–benefit analysis as the payments are effectively transfers of money, not losses to society;

- risk is often ignored or is factored into the discount rate;
- it is assumed that inflation on costs and returns is the same and constant over time;
- productivity growth is usually considered to be zero. For Australian agricultural systems, this has not historically been the case.

Sometimes these simplifications are inappropriate, and judicious selection of parameters to ignore or simplify is required as the simplification process can reduce the usefulness of the analysis, for example use of a constant inflation rate may not account for issues such as the cost–price squeeze where input costs rise faster than product sale prices. Neglecting to quantify risk can lead to over-optimistic or to pessimistic outcomes.

It is often necessary to include the terminal value of an asset in the cash-flow analysis, if the analysis time frame is such that the asset has a remaining useful life and thus value at the end of the analysis period. For example, some pieces of infrastructure purchased specifically for an agroforestry project (timber drying sheds) may have a residual value at the end of the forest rotation. The depreciated or residual value of the asset should be included in the final period of the cash-flow analysis as a salvage value amount (what the structures could be sold for). This means that the initial purchase price of that asset should also be included in the cash flows.

Working Example Part 1

A farmer is contemplating the establishment of a 30 ha softwood plantation for sawlogs on his farm, to supply local sawmills. He intends to plant the entire 30 ha in one year in a paddock which is currently not in productive use. There will be no impact on his other farming enterprises.

Assumptions

A series of key assumptions are made in this example. These hold throughout the chapter, unless stated otherwise.

Costs and timing

- Land preparation and planting costs – \$1800/ha in year 1.
- Planting density – 1000 stems/ha.
- Early weed control – \$150/ha in year 2.

- 1st pruning – \$1.50 per tree in year 5 (1000 trees pruned).
- 1st thinning down to 500 stems/ha – \$500/ha in year 7.
- 2nd pruning – \$1.50 per tree in year 9 (500 trees pruned).
- 2nd thinning down to 250 stems/ha – \$250/ha in year 11.
- Final harvest of sawlogs – \$450/ha in year 25.
- Annual management costs – \$50/ha every year.

Income and timing

- An MAI of 15 m³/ha/yr is assumed up to the first thinning in year 7, and an MAI of 20 m³/ha/yr after that.
- Sales of 1st thinning material for pulp – 50 t/ha at \$10/t in year 7.
- Sales of 2nd thinnings for landscape poles – 56 m³/ha at \$20/m³ in year 11.
- Sales of sawlogs at final harvest – 280 m³/ha at an average \$60/m³ in year 25. This assumes 140 m³/ha is sold as higher-quality pruned sawlogs for \$95/m³ and 140 m³/ha low-quality logs at \$25/m³.

Discount rate

The farmer estimates that the best alternative rate of return that could be achieved if the funds were not invested in the agroforestry project is 5%. This value is used as the discount rate in the analysis. In other words, the opportunity cost of capital is 5%. It is assumed 5% is the real discount rate – the return that could be made on the best alternative investment with inflation factored out of the estimate.

The analysis

Once obtained, this information is readily entered into a spreadsheet to calculate the total costs and returns in each year of the analysis (Figure 17.2).

The results suggest that this agroforestry investment is profitable. It generates a positive net present value (NPV) of \$36 630, indicating that over time the benefits (income) from the project exceed the costs. The internal rate of return is 6.4%, showing the investment is attractive – the cost of capital would have to be 6.4% for the NPV to equal zero (break even). Because the IRR (6.4%) is higher than the discount rate used (5%), the project generates more benefit than its costs. The benefit–cost ratio (BCR) of 1.3 shows that the benefits outweigh the costs by a factor of 1.3.

While this project appears desirable in terms of NPV, IRR and BCR, the net cash position may influence the farmer's decision to proceed. Net cash position shows the typical pattern of cash flows for a forestry project, namely large costs upfront and large returns well into the future (Figure 17.3). This produces a negative net cash position for the first 24 years of the 25-year project, which may deter many farmers from investing as they are unable to fund a negative cash position for such a long period.

Plantation area (ha): 30

Year	Activity	Direct Costs (A)	Revenues (B)	Net Cash Flow (C = B - A)	Net Cash Position (= cumulative C)
1	Establishment	54000	0	-54000	
2	Weed control	6000	0	-6000	-60000
3		1500	0	-1500	-61500
4		1500	0	-1500	-63000
5	1st Prune	46500	0	-46500	-109500
6		1500	0	-1500	-111000
7	1st Thin	15000	15000	0	-111000
8		1500	0	-1500	-112500
9	2nd Prune	24000	0	-24000	-136500
10		1500	0	-1500	-138000
11	2nd Thin	9000	33600	24600	-113400
12		1500	0	-1500	-114900
13		1500	0	-1500	-116400
14		1500	0	-1500	-117900
15		1500	0	-1500	-119400
16		1500	0	-1500	-120900
17		1500	0	-1500	-122400
18		1500	0	-1500	-123900
19		1500	0	-1500	-125400
20		1500	0	-1500	-126900
21		1500	0	-1500	-128400
22		1500	0	-1500	-129900
23		1500	0	-1500	-131400
24		1500	0	-1500	-132900
25	Final Harvest	13500	504000	490500	357600

Establishment cost = 30ha x \$1800/ha
Weed cost = 30ha x \$150/ha
Annual maintenance cost from year 2 onwards is 30ha x \$50/ha

1st prune cost = 30ha x 1000 stems x \$1.50 per stem
1st thin cost = 30ha x \$500/ha
1st thin income = 30ha x 50t/ha x \$10/t
2nd prune = 30ha x 500 stems x \$1.50 per stem
2nd thin = 30ha x \$250/ha
2nd thin income = 30ha x 56m³/ha x \$20/m³

Final harvest income = 30ha x 280m³/ha x \$60/m³

Discount rate = 5%

NPV = \$36,630

IRR = 6.4%

PV benefits (b) = \$179,138

PV costs (c) = \$142,508

BCR = (b/c) 1.3

NPV is calculated from the stream of net cash flows and the discount rate

IRR is calculated from the stream of net cash flows

PV of benefits & costs is calculated from the stream of benefits or costs and the discount rate

Figure 17.2: Spreadsheet showing costs and benefits for each year of the project.

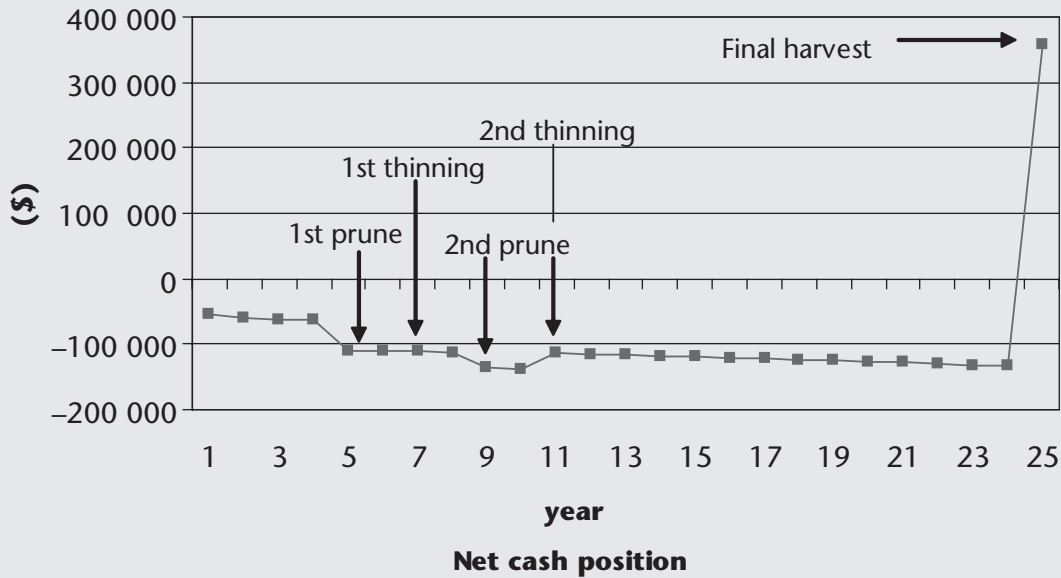


Figure 17.3: Net cash position.

Discounting

Discounting is the technique employed in financial and economic analysis to account for the impact of time or opportunity cost on the magnitude of benefits and costs. The result of discounting is an estimate of the present value of the stream of benefits and costs. Cost–benefit analysis is usually conducted over the life of the project or program.

Timing of costs and benefits

In many agricultural production systems, costs and benefits occur annually – a crop may be sown in late autumn and harvested in a summer. This simplifies the financial analysis. However, for some long-term investments such as agroforestry, the costs and returns occur at very different times in the investment analysis period, for example establishment costs in year 1, timber revenues at harvest in year 25. Consequently, the net benefits of the investment vary, depending on which year of the investment analysis is examined. This creates a need for analytical techniques which cater for the time differences and give the stream of cash flows a common measure that allows comparison with alternative investments.

Discounting is the technique used to deal with the impact of time on the value of projects. Rather than starting with an amount and tracking its growth due to interest, as we do with compounding, we start with a future value – or a stream of future values such as annual cash flows – and determine their worth in current terms. Thus we can compare the costs and benefits of alternative projects with different time horizons and bring them to a single comparable dollar value.

Mathematically, compounding can be calculated as:

$$V_t = V_o \times (1 + i)^t \quad (\text{Eqn 1})$$

Discounting becomes the inverse of this:

$$V_o = \frac{V_t}{(1 + i)^t} \quad (\text{Eqn 2})$$

where V_t is the future value, V_o the current value, i the nominated interest rate and t the number of time periods (usually years). Spreadsheet programs contain built-in functions which allow users to easily apply discounting to a future value or a series of cash flows for a specified discount rate.

Discount rate

There is significant debate in the literature regarding the choice of a discount rate for investment analysis and the issue of the private versus the social discount rate. The concept of discounting and the discount rate involves two key issues.

Time preference discount rates

We assume that most individuals prefer current consumption of benefits to consumption in the future. This is often referred to as the time preference rate, describing most individuals' preference to consume now rather than later. The time preference rate is the real rate of interest on the money borrowed or lent. For example, a person may accept \$105 in a year's time in lieu of receiving \$100 now. This implies their time preference rate is 5%.

Time preference rates can be classified as private (from the individual's perspective) or social (from society's perspective), for present versus future consumption of a benefit. Importantly, the social time preference rate may allow intergenerational equity issues to be considered (allowing consumption to be delayed for the benefit of future generations). Consequently, the social time preference rate is usually lower than the private rate. Under the social time preference rate, future benefits are less heavily discounted and therefore have a larger future value, recognising their benefits to future generations. Discount rates based on time preference are known as consumption discount rates.

Opportunity cost discount rates

Discount rates may also be based on opportunity cost, rather than consumption preferences. These include the:

- opportunity cost of capital, which recognises that an investment involves giving up other investment options. It uses the rate of return on those alternatives as the discount rate against which the proposed investment is assessed;
- project-specific cost of capital, which uses the interest rate of project finance and incorporates market risk as the discount rate to assess the project.

The opportunity cost discount rate is based on the value of the resource used in its next best or

most valuable alternative use. For agroforestry, this generally implies the rate of return on investment from the land use being replaced by agroforestry or other off-farm investments.

For most agroforestry projects, the opportunity cost of capital or the real project-specific cost of

capital is normally used in a financial analysis. The project is assessed on the basis of the expected returns from the most profitable alternative land use or on the real rate at which money can be borrowed to finance the project (Sinden and Thampapillai 1995).

Working Example Part 2: Accounting for opportunity cost in the investment analysis

In Part 1, the assumption was made that adding a new agroforestry enterprise to the farm business had no impact on existing farm enterprises. In reality, this may not be the case as the trees may displace other income-producing activities.

This possibility raises the issue of opportunity cost – the cost of lost income- (or benefit-) generating opportunities as a result of planting 30 ha of the farm to commercial trees.

In Part 1 the concept of the opportunity cost of capital was raised in the context of selecting a discount rate. Here, the opportunity cost of capital was the best alternative return that could be achieved if the funds were not invested in agroforestry. The opportunity cost of capital was then used as the discount rate for the analysis of the agroforestry project.

The opportunity cost illustrated here is a different concept – it is the benefit (or net income) foregone by replacing an existing enterprise with agroforestry. Rather than affecting the analysis through the discount rate, it impacts directly on the cash flows and hence the financial measures used to assess the new investment.

To illustrate, assume the 30 ha planted to agroforestry will replace 30 ha currently used to graze a sheep enterprise which has the following features:

- carrying capacity of the 30 ha is 10 dry sheep equivalents (DSE) per hectare;
- net income (equivalent to the typical gross margin often referred to in agriculture) of the sheep enterprise is \$19/DSE.

Therefore, each hectare replaced by trees means forgoing $10 \text{ DSE} \times \$19/\text{DSE} = \$190/\text{ha}$. Hence, every year of the analysis now includes an additional cost of \$5700 for the 30 ha plantation. It may be rather extreme to assume the entire area is lost to grazing, as the forestry layout is often designed such that stock can be reintroduced after tree establishment, but it provides a simple illustration of opportunity cost.

Note that net income or gross margin is used to calculate the opportunity cost. This is the net benefit (income) that would have been achieved from the sheep enterprise and is calculated as gross income (from wool and cull stock sales) less variable costs. Estimates of these gross margins are regularly published by state Departments of Primary Industries (see www.dpi.nsw.gov.au/agriculture/farm-business/budgets/livestock).

The new analysis with opportunity cost factored is illustrated in Figure 17.4.

Adding opportunity cost to the analysis has reduced the NPV from \$36 630 to -\$43 705 (a negative NPV), the IRR from 6.4% to 3.5% and the BCR from 1.3 to 0.8. The investment has become

unprofitable as the costs now outweigh the benefits, as illustrated by the negative NPV and BCR of less than 1.0. Note that even though the IRR is still positive (3.5%) it is less than the discount rate (5%), indicating that alternative investments provide a better return.

Plantation area (ha): 30

Year	Activity	Direct Costs (A)	Opportunity Costs (B)	Total Costs (C = A + B)	Revenues (D)	Net Cash Flow (E = D - C)	Net Cash Position (= cumulative E)
1	Establishment	54000	5700	59700	0	-59700	-59700
2	Weed control	6000	5700	11700	0	-11700	-71400
3		1500	5700	7200	0	-7200	-78600
4		1500	5700	7200	0	-7200	-85800
5	1st Prune	46500	5700	52200	0	-52200	-138000
6		1500	5700	7200	0	-7200	-145200
7	1st Thin	15000	5700	20700	15000	-5700	-150900
8		1500	5700	7200	0	-7200	-158100
9	2nd Prune	24000	5700	29700	0	-29700	-187800
10		1500	5700	7200	0	-7200	-195000
11	2nd Thin	9000	5700	14700	33600	18900	-176100
12		1500	5700	7200	0	-7200	-183300
13		1500	5700	7200	0	-7200	-190500
14		1500	5700	7200	0	-7200	-197700
15		1500	5700	7200	0	-7200	-204900
16		1500	5700	7200	0	-7200	-212100
17		1500	5700	7200	0	-7200	-219300
18		1500	5700	7200	0	-7200	-226500
19		1500	5700	7200	0	-7200	-233700
20		1500	5700	7200	0	-7200	-240900
21		1500	5700	7200	0	-7200	-248100
22		1500	5700	7200	0	-7200	-255300
23		1500	5700	7200	0	-7200	-262500
24		1500	5700	7200	0	-7200	-269700
25	Final Harvest	13500	5700	19200	504000	484800	215100

Opportunity cost = 30ha x 10 dry sheep equivalents (DSE)/ha x \$19/DSE

Discount rate =	5%	NPV is calculated from the stream of net cash flows and the discount rate
NPV =	(\$43,705)	IRR is calculated from the stream of net cash flows
IRR =	3.5%	PV of benefits & costs is calculated from the stream of benefits or costs and the discount rate
PV benefits (b) =	\$179,138	
PV costs (c) =	\$222,843	
BCR = (b/c)	0.8	

Figure 17.4: Spreadsheet showing financial analysis including opportunity cost.

Treatment of inflation: real vs nominal discount rates

Most analysis utilises current prices, ignoring inflation since inflation is assumed to increase all costs and benefits by a constant percentage each year. Therefore the results of the analysis would be unchanged, even if the inflation rate were applied. This process allows us to determine whether the investment is producing real net benefits over time, and not just increasing in value due to the underlying inflation rate.

There may be instances where prices are expected to change in a manner vastly different from the inflation rate, and this should be accounted for. For example, high-quality hardwood log prices may increase above the inflation rate if access to native forests for timber production is restricted. These changes need to be accounted for in setting the values in the analysis.

For the sake of simplicity, a constant discount rate is usually applied over the time period under

analysis. In arriving at a real discount rate (with inflation factored out), it is usually assumed that the inflation rates for costs and benefits are the same. Pannell (2006) outlines situations where these assumptions may be questionable and require some modification.

Real discount rates have inflation factored out, nominal discount rates do not. The relationship between the real and nominal discount rates is described by:

$$r_n = (1 + r) \times (1 + i) - 1 = (r + i + ri) \tag{Eqn 3}$$

where r_n is the nominal discount rate, r is the real discount rate and i is the inflation rate.

Converting from real to nominal discount rate is generally not a simple matter of adding the inflation rate to the real discount rate. However, $r_n = r + i$ is often used as a reasonable approximation when dealing with small interest (discount) and inflation rates.

Where we have the nominal discount rate, we can turn Equation 3 around to determine the real discount rate, as shown in Equation 4.

$$r = \frac{(1 + r_n)}{(1 + i)} - 1 \quad (\text{Eqn 4})$$

Although most cost–benefit analysis is done in real terms, Pannell (2006) discusses situations where the analysis may need to depart from this simplistic approach. This is to cater for taxation issues or the common situation in agriculture where input prices increase faster than output prices. A sensitivity analysis can be used to assess alternative scenarios, given the difficulty in forecasting inflationary impacts.

Any analysis must be consistent in the use of real or nominal cash flows and real or nominal interest (discount rates). If cash flows are nominal, nominal discount rates are used. If cash flows are real, real discount rates are used.

Investment criteria

Net present value

The calculation of present values is a technique for dealing with the timing of costs and benefits. By applying a discount rate over the time period we can convert a stream of future costs and benefits back to current values. This process allows calculation of the present net value of the project.

Mathematically, the NPV is calculated as:

$$NPV = \sum \left(\frac{B_t - C_t}{(1 + r)^t} \right) = PVB - PVC \quad (\text{Eqn 5})$$

where B_t is the benefit at time t , C_t is the cost at time t , r is the selected discount rate and t is time. Effectively, the NPV is the present value of the benefits (PVB) minus the present value of the costs (PVC). Modern spreadsheets have an NPV function where the user can input a discount rate and a series of net cash flows (benefits less costs in each time period) and the NPV is calculated automatically.

If performed correctly, calculating the NPV in real or nominal terms will produce the same result. However, there may be instances where the costs and benefits are required in nominal terms so that other costs, which can only be estimated on the

basis of nominal cash-flows, can be added to the cash-flow analysis. Such costs include taxation costs (Pannell 2006). Reiterating the earlier point, in conducting the analysis most people use real discount rates and real cash flows. It is rare to see financial analysis of agroforestry investments that includes taxation considerations and is therefore performed in nominal terms so that tax liabilities can be calculated accurately.

Generally, projects with a higher positive NPV are preferred for investment.

Benefit–cost ratio

The benefit–cost ratio provides an estimate of the return for the dollars invested in the project. It is calculated as:

$$BCR = \frac{NPV \text{ benefits}}{NPV \text{ costs}} \quad (\text{Eqn 6})$$

If the ratio is greater than one, the discounted benefits of the project exceed the costs. If it is less than one, the discounted costs exceed the benefits and thus the project needs to be carefully considered (perhaps accounting for other benefits that have not been quantified) before a decision is made to proceed.

Internal rate of return

The internal rate of return for a project shows the investment's actual rate of return. It is the discount rate at which the net present value is equal to zero. The IRR also provides the discount rate, which can then be used for comparing alternative investments.

The IRR is calculated using a process which is repeated until the discount rate returns an NPV of zero. Modern spreadsheets have an IRR function which automates this iterative process and can quickly find the IRR for a series of net cash flows.

The IRR can be compared against the required rate of return for a project to help decide whether the investment is acceptable. Acceptability varies between individuals, depending on their required minimum rate of return (often referred to as the 'hurdle rate').

Ranking projects based on NPV, IRR and BCR

It is important to note that IRR and BCR can give misleading results where projects differ markedly

in time frame or scale. The NPV is usually considered the key criterion (Commonwealth of Australia 2006). It is also important to remember that IRR and BCR are ratios and do not indicate the scale of the investment or return. For example, Project A may have an IRR of 10%, Project B 8% and Project C 7%. Assuming all projects exceed a nominated hurdle rate, the initial reaction would be to invest in Project A. However, the NPV of Project A may be \$40 000, Project B could be \$90 000 and Project

C \$15 000. As such, the return from Project B may be a lower rate of return (represented as a smaller IRR) but it actually returns more money (\$90 000 versus \$40 000). Assuming that Project A could not be scaled up to increase its return or that alternative investments were not available, Project B would be preferable. The key point is that NPV measures the actual net gain from a project whereas IRR and BCR measure relative net gain (see Sinden and Thampapillai 1995).

Working Example Part 3: Impact of timing on the investment analysis

Rather than establishing the entire 30 ha agroforestry project in one year, the farmer may decide to stagger the establishment over six years, planting 5 ha per year, to ease the initial cash outlay. Figures 17.5 and 17.6 show how this modification changes the analysis. Note that the opportunity cost of lost grazing area phases in over six years, in line with the increasing area of forestry.

Plantation area (ha): 30 5 ha established each year for 6 years

Year	Activity	Direct Costs (A)	Opportunity Costs (B)	Total Costs (C = A + B)	Revenues (D)	Net Cash Flow (E = D - C)	Net Cash Position (= cumulative E)
1	Establishment	9000	950	9950	0	-9950	-9950
2	Est & weed	9750	1900	11650	0	-11650	-21600
3	Est & weed	9750	2850	12600	0	-12600	-34200
4	Weed	9750	3800	13550	0	-13550	-47750
5	1st Prune	17500	4750	22250	0	-22250	-70000
6	1st Prune	17750	5700	23450	0	-23450	-93450
7	1st Prune & 1st Thin	11500	5700	17200	2500	-14700	-108150
8	1st Thin	11000	5700	16700	2500	-14200	-122350
9	2nd Prune & 1st Thin	15000	5700	20700	2500	-18200	-140550
10	2nd Prune	15250	5700	20950	2500	-18450	-159000
11	2nd Prune & 2nd Thin	9000	5700	14700	8100	-6600	-165600
12	2nd Thin	9000	5700	14700	8100	-6600	-172200
13	2nd Thin	6500	5700	12200	5600	-6600	-178800
14		6500	5700	12200	5600	-6600	-185400
15		2750	5700	8450	5600	-2850	-188250
16		2750	5700	8450	5600	-2850	-191100
17		1500	5700	7200	0	-7200	-198300
18		1500	5700	7200	0	-7200	-205500
19		1500	5700	7200	0	-7200	-212700
20		1500	5700	7200	0	-7200	-219900
21		1500	5700	7200	0	-7200	-227100
22		1500	5700	7200	0	-7200	-234300
23		1500	5700	7200	0	-7200	-241500
24		1500	5700	7200	0	-7200	-248700
25	Final Harvest 1	2250	4750	7000	84000	77000	-171700
26	Final Harvest 2	2250	3800	6050	84000	77950	-93750
27	Final Harvest 3	2250	2850	5100	84000	78900	-14850
28	Final Harvest 4	2250	1900	4150	84000	79850	65000
29	Final Harvest 5	2250	950	3200	84000	80800	145800
30	Final Harvest 6	2250	0	2250	84000	81750	227550

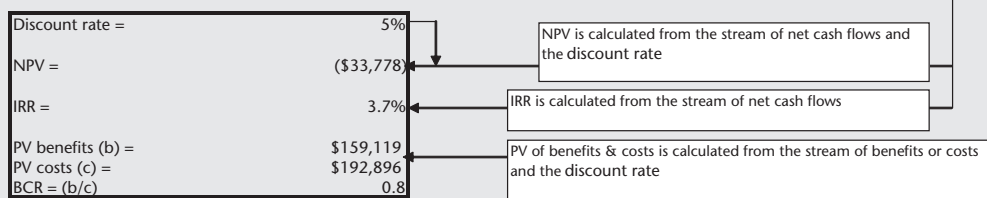


Figure 17.5: Spreadsheet showing financial analysis modified by staggered establishment of plantation.

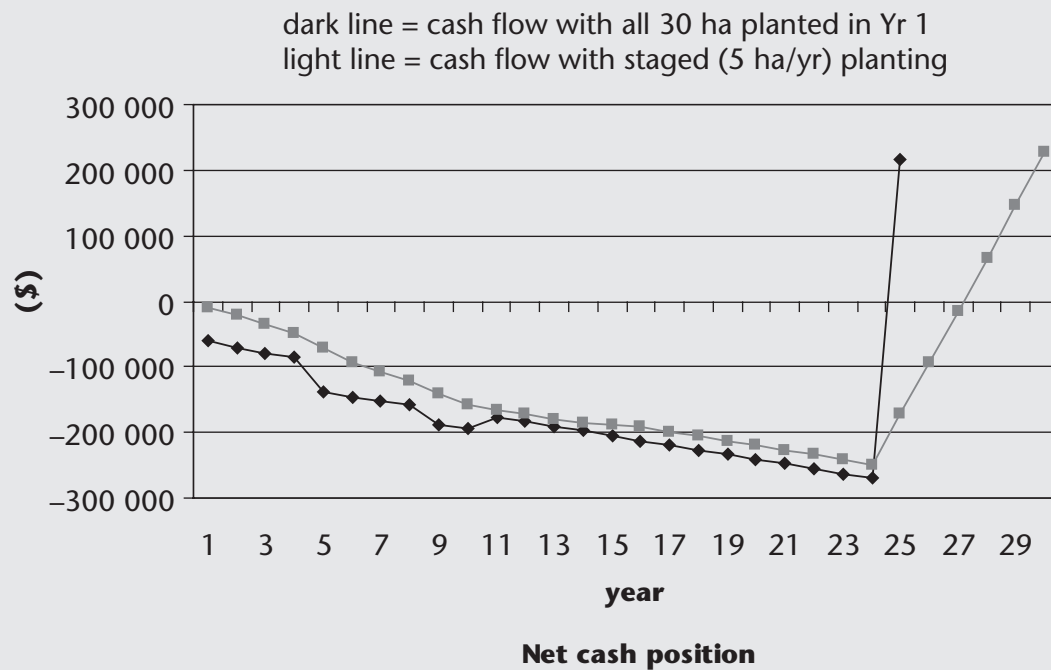


Figure 17.6: Modified net cash position.

Although the essential financial analysis parameters (NPV, IRR and BCA) are similar to Part 2, where all 30 ha were planted in year 1, the net cash position is less negative in the earlier years and thus may be more manageable in terms of cash flows. The net cash position to the time of harvest is also smoother, with fewer large negative dips in the cash-flow pattern.

However, because the planting is staggered over six years, the incomes from thinning and final harvest occur in smaller increments and are pushed into future years. It takes an extra three years before cash flows become positive for the agroforestry investment.

This example helps illustrate the fact that a project investment decision may be determined by practical business management issues such as cash-flow positions and patterns, as much as by financial measures such as NPV, IRR and BCA. However, if the sequence of cash flows has been calculated, it is relatively easy to use a spreadsheet to go a step further and estimate these financial performance measures.

Payback period

The payback period is the time taken for the cumulative stream of project net revenues to pay back (equal) the capital invested in the project. There is no discounting applied to the calculation.

NPV is considered to be the key decision-making criterion. IRR, BCR and payback period can provide useful supplementary information, but if used as the main criteria may lead to the choice of a project with a suboptimal NPV.

Working Example Part 4: Adding non-timber benefits

Depending on the planting configuration (solid blocks of trees vs longer narrower belts), there may be extra benefits from adding a commercial agroforestry enterprise to a farm business.

Consider the situation where the staged planting illustrated in Part 3 was configured to provide shelter for the sheep enterprise. Assume that the configuration does not entirely replace the sheep grazing but allows the area planted to trees to be returned to 50% of its original carrying capacity after two years. Sheep must be entirely excluded for two years after planting to avoid tree damage.

We assume that timber production is not compromised by altering the tree layout. This may not be the case, as trees grown in narrow belts can result in compromised timber quality.

For the sake of simplicity, we assume each 5 ha planting provided shelter for 5 ha of pasture and increased the gross margin by \$1 for each DSE on the sheltered area. The additional shelter benefit has the following features:

- shelter benefit commences five years after planting;
- each hectare planted shelters a hectare of pasture. In reality, it would probably shelter a larger area than this, depending on the tree layout;
- shelter increases the gross margin for the sheep enterprise from \$19/DSE to \$20/DSE due to improved wool production and higher lambing rates etc.;
- the carrying capacity of the pasture remains at 10 DSE/ha. In reality, carrying capacity may increase as shelter lowers sheep maintenance requirements, meaning more sheep can be carried per unit of pasture.

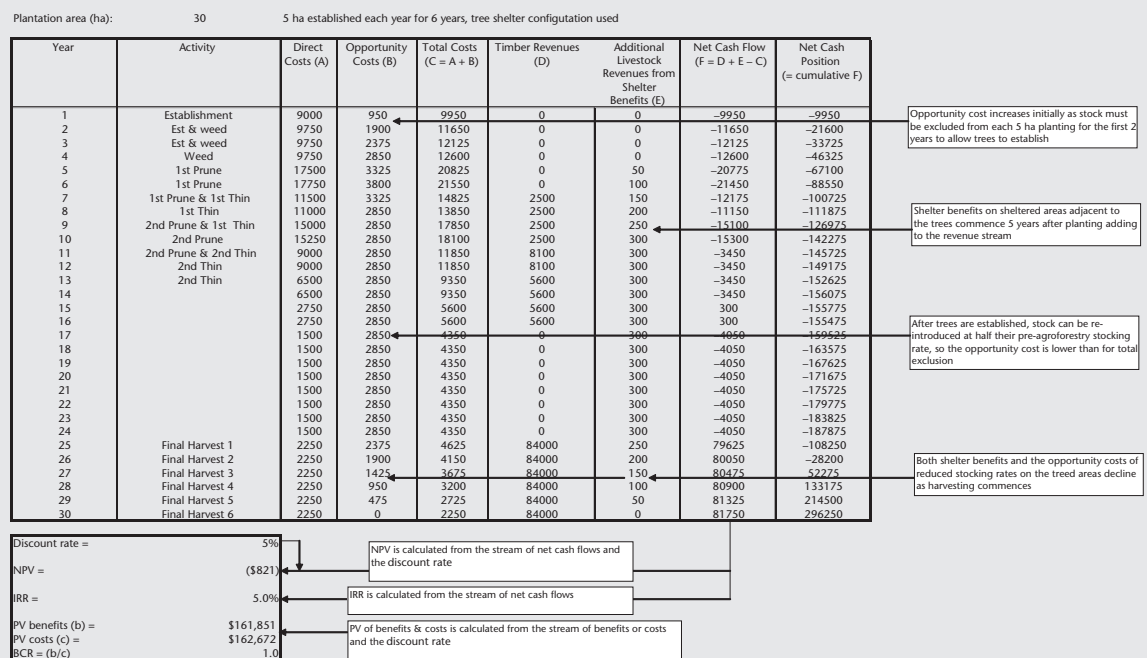


Figure 17.7: Spreadsheet showing financial analysis modified by including shelter benefits.

The additional income (benefit) from stock shelter and the reduced opportunity cost from allowing some restocking of the treed areas is incorporated into the analysis (Figure 17.7).

Including stock shelter benefits and the reduced opportunity costs in the analysis, the financial measures improve relative to Part 3. NPV increases from -\$33 778 to -\$821, IRR from 3.7% to 5.0% and BCR from 0.8 to 1.0. Shelter benefits have brought the investment back to a break-even position against the next best alternative investment option, as observed by the IRR of 5.0%, which is equivalent to the discount rate. The costs and benefits are about equal (BCR = 1.0) and the NPV is only slightly negative.

Working Example Part 5: Land value and terminal values

A non-timber benefit often cited as a reason for planting trees on farms is improved land value at the time of sale, particularly on grazing properties where the trees are configured to provide stock shelter or improve water quality.

Figure 17.8 illustrates how this aspect could be factored into a simple example where the land is sold some time after trees were established on a largely cleared farm block. For simplicity, we use the analysis from Part 2, but assume only 30% of the trees are harvested in year 25 and the rest remain for stock shelter, which adds \$500/ha to the sale value.

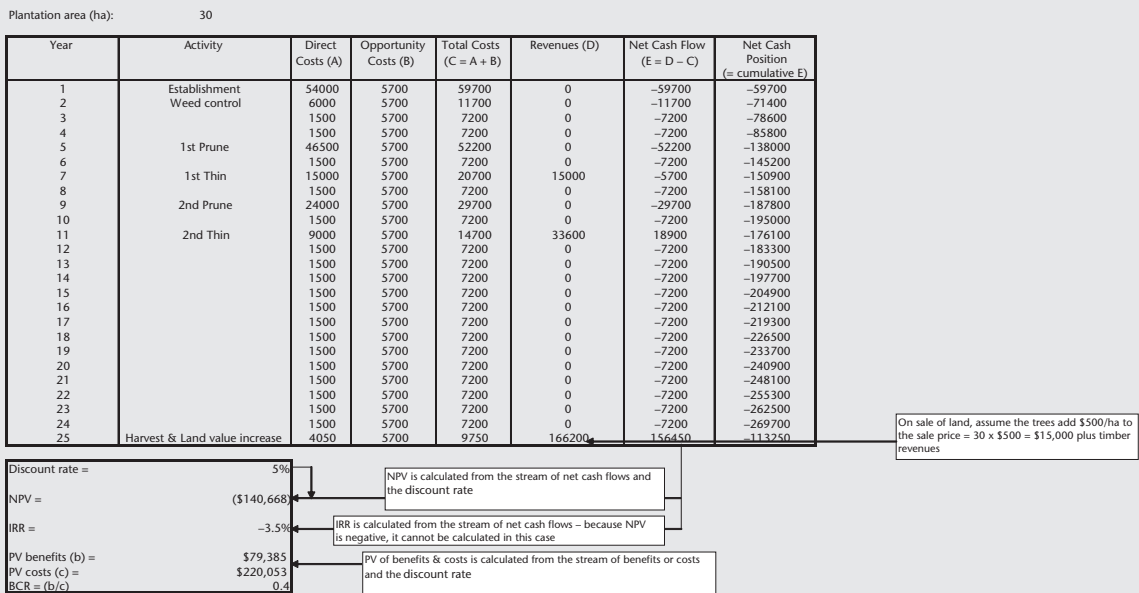


Figure 17.8: Factoring a non-timber benefit into land value.

In previous examples, land purchase was not included as it is assumed the landholder had purchased the farm prior to deciding to invest in agroforestry, hence land purchase is a sunk cost and not included in the analysis. Because land sale was not considered and hence no terminal (sale) value of the land was required in the benefit stream, there was no need to account for its original purchase cost. Some investment analyses include the original purchase cost of capital items

such as land or machinery; if so, a terminal (sale) value must also be included in the final period of the analysis or in the period when the asset is sold.

In Part 5, we exclude the original land purchase value but factor in the increase in land value benefit by assuming the sale price per hectare is higher in year 25 (by \$500/ha) than it would be without the tree plantings. Essentially, we have factored in the marginal increase in the value of the land due to tree planting.

Key assumptions are:

- trees were established with the cost and income timing as in Part 2, except only 30% of the trees are harvested in year 25;
- the 30 ha block is sold 25 years later, straight after tree harvest, and attracts a premium of \$500/ha due to the remaining tree plantings.

In this example, the NPV is negative, the IRR is negative (-3.5%) and the BCR is less than one (0.4), indicating the costs outweigh the benefits. The increase in land value is insufficient to compensate for the lost income (benefit) when only 30% of the trees are harvested. The project should not go ahead unless other benefits can be found.

Uncertainty and sensitivity analysis

With a larger risk there is a need for a greater return to satisfy the investor that the risk is worthwhile. Lower risk can reduce the need for large returns.

The values of most variables in a cost–benefit analysis are likely to be known with varying degrees of certainty. Some variables are well-defined where mature markets are in place to determine their value (e.g. selling timber to a mill). Other variables may be well-quantified but not yet clearly valued (e.g. carbon can be measured but the market is still developing). Finally, especially in relation to agroforestry systems, there are often variables that cannot be easily quantified or for which no markets assign a monetary value (e.g. estimation of threatened species and their monetary value). These uncertainties are illustrated in Figure 17.1, where the risk component is viewed as the changing error associated with different components of the agroforestry system.

Each variable will have an impact on the return to forest and farm managers. The scale of the impact can be determined by conducting a sensitivity analysis. Sensitivity analysis examines how the results of the cost–benefit analysis will change as the values of key calculation input variables change.

For both financial and economic analysis, sensitivity analysis involves assessing average or likely values for costs and benefits (more specifically, the parameters used to calculate costs and benefits, such as log yields and prices). Next, the calculations are rerun using a feasible range of values for those parameters to show how results will change as input variables take on different values within their expected range.

If information is known about the probability of the values that key variables may take, the weighted sum of the value of likely variables can be used to estimate the expected value of the outcome. This process can be automated using software (e.g. @RISK™) which allows model variables to be set up as probability distributions and multiple simulations of the model to be run, to produce a probability distribution of key decision variables. However, as pointed out by Pannell (2004b), the complexity of this approach may make the results more difficult to interpret, detracting from the core message.

Another useful measure which can be estimated is the switching value (cross-over value), which is the value of a variable at which the NPV switches from positive to negative. The decision-maker can assess the likelihood of the switching value occurring, to gain additional information about the riskiness of the project.

BOX 17.2

Sensitivity testing of cash-flow assumption

Because of the long-term nature of many agroforestry investments, access to markets for the products of early thinning operations can have a significant impact on the financial performance of the investment.

Our agroforestry example assumed markets were available for the thinning operations conducted in years 7 and 11 (e.g. sales for pulpwood or small sawlogs). Figure 17.9a–c illustrates what happens to the key financial criteria if those markets are not available and hence no revenue is received until final harvest.

It is clear that the absence of thinning markets and the reduction in early cash flows from thinning sales reduced the financial performance of the investment, though not to a level which would warrant rejection of the agroforestry enterprise as the IRR (5.2%) is still marginally above the discount rate (5.0%).

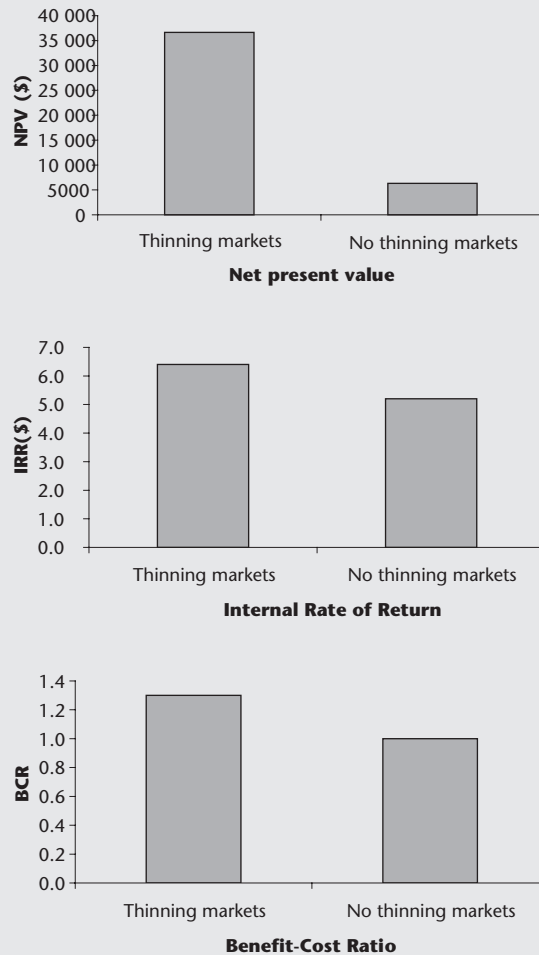


Figure 17.9: (a) NPV with and without thinning markets. (b) IRR with and without thinning markets. (c) BCR with and without thinning markets.

BOX 17.3

Sensitivity testing of discount rates

Consider two projects, A and B, with different net benefit profiles. Project A has high upfront costs followed by higher benefits later in the analysis period. Project B has lower upfront costs and the benefits occur early in the period (Figure 17.10).

A range of discount rates applied to these net benefit streams produces the following results.

Discount rate	NPV (Project A)	NPV (Project B)
4%	\$18 335	\$15 757
8%	\$12 705	\$12 762
12%	\$8944	\$10 572

At lower discount rates, Project A is preferred. At a mid-range discount rate, the project NPVs are comparable and at a higher discount rate Project B is preferred. This switching of the decision criteria result, as the discount rate varies, suggests that there should be further examination of the net benefits of each project to improve the reliability of the decision.

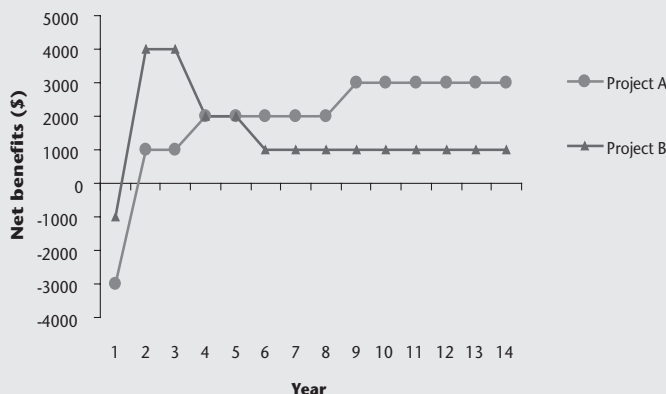


Figure 17.10: Net benefit profiles of two projects.

When conducting sensitivity analysis and changing the value of variables in the analysis, it should be recognised that some variables may be correlated and so should be varied together. For example, in an agroforestry context, ground preparation and weed control are often a major determinant of tree survival and growth rate. Therefore, as assumptions about the costs of these establishment inputs are varied, it may make sense to vary final log volumes and/or the length of time taken to reach a harvestable log size.

Sensitivity testing can also be performed on the discount rate. The magnitude of the discount rate can have important impacts where the timing of

the costs and benefits between different projects varies significantly (Box 17.3). This is particularly important in agroforestry systems, where there can be long lag times between the investment activities and returns, especially when interest rates are considered high.

Economic analysis: the broader social analysis

An economic analysis may include financial analysis, but the boundary is broadened to consider wider public or social issues outside the individual farm system. The concept of externalities

becomes critical: what are the impacts of decisions made within the farm boundary, for example the planting of trees, on society in general (people outside the farm boundary)? The basis of economic analysis is identical to financial analysis, but it often relies on non-market valuation techniques to assign dollar values to intangibles (Department of Heritage and Environment 2005). Economic analysis attempts to measure the value of all the costs and benefits which flow from the project or policy, with the aim of improving the returns to society from using society's limited resources. Consequently, it often involves the estimation of unpriced or non-market costs and benefits that are normally excluded from pure financial analysis.

Cost–benefit analysis

While financial investment analysis is sometimes referred to as cost–benefit analysis, in this section we use the term specifically in the context of broader social analysis.

Cost–benefit analysis is primarily designed to answer the question: 'Does the expenditure of public (or private) money on this project generate a net benefit for society (or the individual)?' The money involved could be used in different projects; cost–benefit analysis is a technique to assess the worth of the current project against the alternatives. From society's perspective, the project may be the introduction of a new policy which leads to land use change (e.g. wide-scale tree planting on farms) that has implications at community, regional, state or national scales.

Cost–benefit analysis is used to answer the following typical questions.

- Does the project/policy provide a net benefit to society?
- Which of the alternative projects/policies should be implemented?
- What are the key assumptions or variables driving the desirability (or otherwise) of the project/policy and is it possible to redesign the project/policy to improve the net benefits?
- Are there key gaps in the information required to make a sound decision?

The process provides a common basis (a dollar value) for comparing alternative projects or poli-

cies. This means that different proposals can be compared.

Because cost–benefit analysis explicitly identifies costs and benefits, it also identifies who gains and who loses if a project is implemented. This tends to be a more important issue for cost–benefit analysis operating at the broader social scale than financial analysis at the individual business level.

Cost–benefit analysis can be used to make decisions about proposed future projects, or used retrospectively to assess the worth of past (or current) projects and determine whether they should be continued in their current form or modified to improve net benefits.

Cost-effectiveness analysis

Where the benefits of a project or policy are difficult to quantify in dollar terms but can be quantified in physical terms, a simplified form of cost–benefit analysis, known as cost-effectiveness analysis, may be used. This method estimates the most cost-effective (lowest-cost) choice for achieving a unit of physical or environmental benefit (e.g. the agroforestry system which has the lowest cost per tonne of CO₂ sequestered from the atmosphere). For cost-effectiveness analysis the alternatives being considered must be similar in nature, that is, alternative methods of achieving the same outcome. Because the benefits are measured in physical rather than monetary terms, discounting is only applied to the costs.

Identifying costs and benefits in an economic analysis

In addition to financial consideration, economic analysis includes, where possible, quantified social costs and benefits. The value of costs and benefits external to the farm system can include parameters such as improved water quality or reduced stream flow. However, in practice it is often difficult to quantify these benefits as they accrue from a small-scale agroforestry investment. Where the scale of the agroforestry project is significant in a catchment context, these benefits (or costs) may be easier to quantify. For more detailed discussion of large-scale changes and impacts on catchments see Nordblom *et al.* (2006) regarding the economic considerations and Zhang *et al.* (2007) concerning the biophysical issues.

BOX 17.4

Cost-effectiveness of carbon sequestration

Climate change is now widely discussed and increasingly, trees are used to remove carbon dioxide from the atmosphere.

Many existing schemes which make carbon credit payments to tree growers in recognition of the CO₂ their trees remove from the atmosphere utilise the Kyoto Protocol assumption that when a tree is harvested, the sequestered CO₂ is released back into the atmosphere. However, recent Australian research indicates that this is not the case: harvested wood products typically store carbon for 50–70 years and even wood-based products which end up in landfill release carbon back into the atmosphere at very slow rates (FWPRDC 2006; CSIRO 2006).

Richardson (2005) examined the cost-effectiveness of carbon sequestration in harvested and unharvested eucalypt plantations. He concluded that plantations harvested on a 20-year rotation are equally effective at removing CO₂ from the atmosphere as unharvested plantations, and are three to four times more cost-effective using a 6% discount rate. The improved cost-effectiveness of harvested plantations results from the additional revenues from the harvested timber products, meaning that the plantation investment generates a small profit. In contrast, the unharvested plantation investment generates a net cost. A managed system will give a better economic outcome and thus increase the likelihood of uptake by landholders.

Commonly, externalities include only negative impacts (e.g. downstream pollution). However, in the case of agroforestry systems there may be positive (benefits) or negative (costs) effects. Externalities could be positive in the case of improved water quality, for example, or negative in the case of reduced water quantity – assuming that reduction in water quantity is reducing the net benefit to society. The biophysical impacts of increasing forested areas in catchments are discussed by Zhang *et al.* (2007), with a case study of the mid-Macquarie catchment in central New South Wales clearly indicating the trade-off between planting and water yield versus water quality. Externalities may not be a problem if they do not result in reduced net benefits to society (discussed in Chapter 18). Economic analysis and the subsequent calculation of cash flows may involve the assessment of costs and benefits which are not traded in formal markets, so their valuation relies on non-market valuation techniques.

Valuation of market and non-market costs and benefits

Many costs and benefits are traded in markets (e.g. the costs of contract tree planting or the stumpage price for hardwood logs), so identifying their value

is relatively straightforward. A common problem for small-scale forestry operations is determining the current local market values, as open and transparent pricing is rare. This is a problem in determining the value of existing plantings or native forests as well as predicting expected market returns.

Other costs and benefits are not traded in regular markets and can be difficult to quantify (e.g. the habitat and biodiversity values of planting trees on farms). Economists utilise two main approaches to assist in the quantification of these non-market values:

- revealed preference methods, where values can be inferred from actions in markets or elsewhere. For example, the cost of travel by visitors to national parks is an estimate of the value society places on habitat conservation;
- stated preference methods, which determine how much in dollar terms people are willing to pay for certain benefits (e.g. restoration of native vegetation). This approach usually involves well-designed surveys that derive the answer from inferred options.

Recently, a range of stated preference tools have been used for non-market valuations of

environmental values relevant to revegetation on farms (e.g. planting native trees to improve habitat). These are discussed briefly below. All these tools attempt to quantify the willingness to pay for various non-market goods and there is a school of thought that these techniques provide more robust estimates than do revealed preference methods.

Valuation of non-market costs and benefits

Contingent valuation

The contingent valuation method involves direct surveys and asking people what they are willing to pay for a particular environmental outcome. Subtraction of the appropriate costs should provide an estimate of consumer surplus or net benefit (Mitchell and Carson 1989).

The mechanisms available for eliciting willingness to pay are outlined by Morrison *et al.* (1997), who observed that the dichotomous choice format is generally considered the most appropriate. This format asks respondents whether they support a change in environmental quality, given a specified additional payment.

In the case of a social cost–benefit analysis, one of the externalities associated with agroforestry may include biodiversity impacts. There have been a number of applications of contingent valuation related to the worth of ecosystems and biodiversity (Jakobsson and Dragun 2001; Bennett 2002, 2003). This is discussed further in Chapter 18.

Choice modelling

Choice modelling is a technique in which respondents choose their preferred resource use option from a number of alternatives. It values different sites and land use options simultaneously, as well as producing site-specific estimates of the value of unit changes in environmental attributes such as native species abundance or recreational opportunities (Bennett and Whitton 2003). The value of multiple use alternatives can thus be estimated.

Contingent rating

Contingent rating involves asking respondents to evaluate a number of alternative environmental outcomes, through the use of a ratings scale. Respondents are not asked to compare the different alternatives, but to consider each separately. The importance of a number of attributes associated

with each alternative can then be determined. Contingent rating allows the estimation of the part-worth as well as the aggregate value of environmental goods. As contingent rating estimates are not conditional on respondents agreeing to purchase a good, estimates of value may be biased (Morrison *et al.* 1997). This technique is not widely used.

Contingent ranking

Contingent ranking involves respondents ranking three or more resource use alternatives from most to least preferred. As with contingent rating, contingent ranking allows the estimation of the part-worth as well as the aggregate value of environmental goods. However, respondents are unable to express opposition to payment for the environmental good, hence their estimates may be biased (Morrison *et al.* 1997).

Paired comparison

In a paired comparison, respondents are presented with two alternatives and asked to rate the difference between them, usually on a five-point scale. The paired comparison method produces estimates of the value of unit changes in attributes as well as estimates of the aggregate value of changes in environmental quality. It has similar bias problems to contingent rating and contingent ranking (Morrison *et al.* 1997).

Biases associated with stated preference techniques

There are several potential biases associated with stated preference techniques.

- An embedding effect is said to occur when it is unclear whether the respondent is valuing the good on its own or as part of a more inclusive category (e.g. preservation of an individual species as opposed to the concept of biodiversity in general).
- Hypothetical bias occurs when respondents do not believe that their answers will have any policy significance and there is thus little incentive to think carefully about their responses.
- Strategic bias occurs when a response is deliberately over- or understated in an attempt to affect the survey outcome.
- Non-response bias occurs when there is a low response rate to the survey, and the answers

may not be truly representative of the population being surveyed.

- Method of payment bias occurs when a respondent is averse to a particular payment vehicle and understates their true willingness to pay when that vehicle is used. In essence, people will say that they are prepared to pay for an outcome but when the opportunity arises they do not take up the offer and incur the extra expense. An example is voluntary green power schemes, where people elect to pay more for electricity generated from more expensive but renewable sources, as opposed to a mandatory green-power tax.
- Starting-point bias may occur when nominated values are used as starting-points. Respondents may consider the starting-point to be an appropriate bid.

These biases are summarised in more detail by Morrison *et al.* (1997), Hanemann (1995) and

Lockwood and De Lacy (1992). They concluded that contingent valuation has been prone to misuse but, although open to bias, with appropriate application it can still be used to produce theoretically valid results.

Morrison *et al.* (1997) noted that the relatively new field of choice modelling has considerable potential for application to environmental valuation. Although difficult to employ, choice modelling provides a more realistic choice setting than other methods so is less likely to encourage biased responses, is less prone to respondents refusing to provide answers and has the potential to validate estimates through the integration of market and non-market goods.

All the methods aim to estimate the value of externalities. When conducting an economic analysis of agroforestry systems, it is important that some value be assigned to these attributes (e.g. biodiversity values or water quality) as this allows a more comprehensive valuation.

Working Example Part 6: Social analysis

Parts 1–5 all involved a private investment analysis which included only costs and benefits within the farm business. Tree planting on farms, if carried out at a sufficient scale, can have a number of off-farm broader social benefits such as improved water quality as trees reduce stream turbidity by stabilising the soil, or enhanced habitat and biodiversity.

Including values for these less-tangible benefits can be a challenge, but economists have devised various survey techniques to estimate the dollar values society is willing to place on these environmental improvements.

Using the information from Part 2, assume that 100 landholders in the region plant 30 ha of commercial native trees, so that 3000 ha is planted. Also assume that surveys have revealed that all households in the region are willing to pay \$200/ha/yr collectively. \$200/ha is a measure of the public (or broader social) benefit derived from the private agroforestry investment.

The key assumptions become:

- 3000 ha of trees planted with the same private cost and revenue pattern for the farmer as in Part 2;
- public benefit is \$200/ha/yr.

The results of expanding the agroforestry project from 30 ha to 3000 ha and including the public benefit are provided in Figure 17.11.

This analysis reveals that NPV, IRR and BCR are all favourable, indicating investment in the project is worthwhile. Note that IRR and BCR have increased relative to Part 2 not as a result of the

increased scale of the project (3000 ha versus 30 ha) but because of the addition of the public biodiversity benefits.

If the project were simply scaled up by a factor of 100 but no public benefits were included, NPV would increase by a factor of 100 but IRR and BCR would remain the same as in Part 2 (3.5% and 0.8% respectively). Scaling up and adding the public benefit has increased these measures to 6.6% and 1.2% respectively.

Plantation area (ha): 3000

Year	Activity	Direct Costs (A)	Opportunity Costs (B)	Total Costs (C = A + B)	Revenues (D)	Public biodiversity benefits (E)	Net Cash Flow (F = D + E - C)	Net Cash Position (= cumulative E)
1	Establishment	540000	570000	5970000	0	600000	-5370000	-5370000
2	Weed control	600000	570000	1170000	0	600000	-570000	-5940000
3		150000	570000	720000	0	600000	-120000	-6060000
4		150000	570000	720000	0	600000	-120000	-6180000
5	1st Prune	4650000	570000	5220000	0	600000	-4620000	-10800000
6		150000	570000	720000	0	600000	-120000	-10920000
7	1st Thin	1500000	570000	2070000	1500000	600000	30000	-10890000
8		150000	570000	720000	0	600000	-120000	-11010000
9	2nd Prune	2400000	570000	2970000	0	600000	-2370000	-13380000
10		150000	570000	720000	0	600000	-120000	-13500000
11	2nd Thin	900000	570000	1470000	3360000	600000	2490000	-11010000
12		150000	570000	720000	0	600000	-120000	-11130000
13		150000	570000	720000	0	600000	-120000	-11250000
14		150000	570000	720000	0	600000	-120000	-11370000
15		150000	570000	720000	0	600000	-120000	-11490000
16		150000	570000	720000	0	600000	-120000	-11610000
17		150000	570000	720000	0	600000	-120000	-11730000
18		150000	570000	720000	0	600000	-120000	-11850000
19		150000	570000	720000	0	600000	-120000	-11970000
20		150000	570000	720000	0	600000	-120000	-12090000
21		150000	570000	720000	0	600000	-120000	-12210000
22		150000	570000	720000	0	600000	-120000	-12330000
23		150000	570000	720000	0	600000	-120000	-12450000
24		150000	570000	720000	0	600000	-120000	-12570000
25	Final Harvest	1350000	570000	1920000	50400000	600000	49080000	36510000

Public benefit = 3,000ha x \$200/ha per year

Discount rate =	5%	NPV is calculated from the stream of net cash flows and the discount rate
NPV =	\$4,085,837	
IRR =	6.6%	IRR is calculated from the stream of net cash flows
PV benefits (b) =	\$26,370,171	PV of benefits & costs is calculated from the stream of benefits or costs and the discount rate
PV costs (c) =	\$22,284,334	
BCR = (b/c)	1.2	

Figure 17.11: Spreadsheet showing economic analysis modified by expansion of agroforestry project and inclusion of public benefits.

Conclusion

Financial and economic evaluation of agroforestry investments are an important component in making decisions about land use change. Many of the concepts and techniques to evaluate financial and economic options are well-established. However, a key issue for agroforestry is that much of the perceived and real value of the investment could be derived from the non-wood values of planting trees on farms.

At the business level, financial analysis allows the decision-maker to think in a structured way about the costs and returns of the investment, and to generate financial decision criteria based on a range of assumptions that guide the investment decision. Many of the values related to wood products that are required to perform the analysis are available in the literature and through local market information. Modern spreadsheet programs help

automate the calculation of key financial measures, and allow for rapid sensitivity testing and comparison of alternative options.

Economic analysis is more relevant to agroforestry policy-making than to individual farm business decisions, as it encapsulates broader social costs and benefits. Quantifying the value of these benefits is more challenging. However, the literature is growing and new techniques have been developed to estimate values for these variables.

There are significant issues in developing robust financial and economic analyses for agroforestry systems. The lack of markets for non-wood products is problematic and limits analysis. Development is occurring in some important areas (e.g. development of carbon trading schemes), but there is still debate and discussion on how to account for important values to society (e.g. biodiversity habitat), especially in privately owned enterprises.

Agroforestry has not been adopted on the scale that some have hoped for. This highlights the need for basic financial and economic analysis to guide farm decisions and policy formulation, to help understand reasons for the low adoption rate and how it might be changed. Further consideration, quantification and valuation of the non-wood benefits generated from agroforestry investments on farms may be required. Essentially, those seeking to increase the role of trees in agricultural systems need to clearly show landholders the benefits of an agroforestry investment. If private financial incentives are insufficient to drive adoption, rewarding landholders for the public benefits of revegetation may need to be part of the policy agenda. However, the commitment of public funds requires clear identification and quantification of the public benefits and a sound basis for the investment – namely, the generation of a net benefit to society.

References

- Bennett J (2002) Investing in ecosystem health: using rivers as a case study. *Ecological Management & Restoration* **3**(2), 104–107.
- Bennett J (2003) Environmental values and water policy. *Australian Geographical Studies* **41**(3), 237–250.
- Bennett J and Whitton S (2003) Duck hunting and wetland conservation: compromise or synergy? *Canadian Journal of Agricultural Economics* **51**(2), 161–173.
- Commonwealth of Australia (2006) *Handbook of Cost-Benefit Analysis*. Commonwealth of Australia, Canberra.
- CSIRO (2006) Wood: another low carbon footprint solution. *ECOS Magazine* **129**, 12–13.
- Department of Heritage and Environment (2005) *Making Economic Valuation Work for Biodiversity Conservation*. Department of Heritage and Environment, Canberra.
- FWPRDC (2006) Forests, wood and carbon balance. *Leading Edge* [newsletter of Forest and Wood Products Research and Development Corporation] **4**(4), 1.
- Hanemann WM (1995) Contingent valuation and economics. In *Environmental Valuation: New Perspectives*. (Eds KG Willis and JT Corkindale). CAB International, Wallingford, UK.
- Jakobsson K and Dragun A (2001) The worth of a possum: valuing species with the contingent valuation method. *Environmental and Resource Economics* **19**, 211–227.
- Lockwood M and De Lacy T (Eds) (1992) *Valuing Natural Areas: Applications and Problems of the Contingent Valuation Method*. Johnstone Centre, Charles Sturt University, Albury.
- Mitchell RC and Carson RC (1989) *Using Surveys to Value Public Goods: The Contingent Valuation Method*. Resource for the Future, Washington DC. Distributed by Johns Hopkins University Press.
- Morrison MD, Blamey RK, Bennett JW and Louviere JJ (1997) A comparison of stated preference techniques for estimating environmental values. Paper presented at *41st Australian Agricultural Economics Society Conference*. Gold Coast, Qld.
- Nordblom T, Hume I, Bathgate A and Reynolds M (2006) Mathematical optimisation of drainage and economic land use for target water and salt yields. *Australian Journal of Agricultural and Resource Economics* **50**, 381–402.
- Pannell DJ (2004a) Thinking like an economist. 5. Public goods and public benefits. In *NRM Pannell Discussions*. Accessed 1 July 2007. <<http://cyllene.uwa.edu.au/~dpannell/pd/pd0022.htm>>.
- Pannell DJ (2004b) Heathens in the chapel? Application of economics to biodiversity. *Pacific Conservation Biology* **10**(2/3), 88–103.
- Pannell DJ (2006) Avoiding simplistic assumptions in discounting cash flows for private decisions. In *Economics and the Future: Time and Discounting in Private and Public Decision Making*. (Eds D Pannell and S Schilizzi) ch. 3. Edward Elgar Publishing, UK.
- Pink B (2007) 'Australia's environment: issues and trends 2007'. Australian Bureau of Statistics, Canberra. Publication no. 4613.0.
- Richardson AJ (2005) The cost-effectiveness of carbon sequestration in harvested and unharvested eucalypt plantations. Paper presented at *Greenhouse 2005 Conference*. November, Mel-

- bourne, Vic. <<http://www.treesmart.com.au/Publications/Greenhouse2005.pdf>>.
- Sinden JA and Thampapillai DJ (Eds) (1995) *Introduction to Benefit Cost Analysis*. Addison-Wesley Longman, Melbourne.
- Zhang L, Vertessy R, Walker G, Gilfedder M and Hairsine P (2007) 'Afforestation in a catchment context: understanding the impacts on water yield and salinity'. Water CRC, Melbourne. Industry report 1/07.

Enhancing the environmental benefits of agroforestry through government policy mechanisms

David J Pannell

Earlier chapters considered the economic and environmental benefits and costs of agroforestry. The market provides a ready mechanism for capturing the available economic benefits but, without additional interventions from governments, the community may miss out on a range of potential environmental benefits from agroforestry. Some of the environmental benefits are relatively intangible and can't be marketed. Resource managers making decisions about agroforestry are unlikely to fully consider the range of environmental benefits accruing to others in the community, since many of those benefits are not experienced or captured by the resource managers themselves.

This chapter focuses on the government's use of policy mechanisms to ensure that environmental benefits are not neglected. This is not to say that environmental benefits would take precedence over economic benefits, but that benefits and costs in both categories would be considered and weighed. We will discuss the circumstances in which government intervention to enhance environmental outcomes from agroforestry would and would not be appropriate. The mere existence of an environmental benefit is not sufficient, as we will see. There is a wide variety of policy approaches and mechanisms. These are briefly described, and some of their pros and cons are discussed. Finally we consider the vexed question of who should pay

for the public environmental benefits generated on private land.

Introduction

It has long been recognised that a range of environmental benefits can result from the introduction of agroforestry systems into extensive farming systems, including benefits related to dryland salinity, biodiversity, carbon sequestration, renewable energy and flood mitigation. A key motivation for government to develop and promote agroforestry is that it can generate these benefits in addition to financial benefits from the sale of commercial products.

Major government programs for environmental protection and natural resource management in Australia have sought to support agroforestry. Recent examples include the Natural Heritage Trust (NHT) and the National Action Plan for Salinity and Water Quality (NAP). They each used various mechanisms to encourage measures, including agroforestry, that would not otherwise be adopted by farmers to the same extent.

This chapter provides a big-picture view on these issues. It outlines ideas from economic theory that provide helpful ways to consider a wide range of questions about the government's policy decisions on agroforestry, focusing on environmental aspects. The questions include the following.

- Under what circumstances should government intervene to enhance environmental outcomes via agroforestry?
- What are the available policy mechanisms that governments can use for this purpose, and what are their strengths and weaknesses?
- Who should pay?

Although some of the material may seem rather conceptual and a long way from the practical reality of growing trees on farms, we should not underestimate its importance in influencing what actually happens on real farms. The theories presented here are very influential high up in government agencies, particularly in departments of finance and treasury, which hold the purse strings for any proposed government policy initiative.

Economic rationale for policy intervention

In the public policy environment that currently dominates in Australia (and many other developed countries), government agencies are increasingly required to ask a difficult question about the policies that they would like to put in place. The question is, in effect, why bother? Why would these issues not be adequately dealt with if the government left decisions about them entirely in the hands of individuals and businesses? Perhaps the best strategy for the government is to do nothing, other than provide the indirect support that comes from an effective legal and economic framework. Economists refer to this 'do nothing' option as the free-market approach, and they have a wealth of evidence showing that in many cases it can be a pretty good option. So much so, in fact, that they often believe that the burden of proof should rest on those who would have the government do something. Many economists start from a position that doing nothing is the best option, until proven otherwise.

The appropriateness of the free market depends on two considerations.

- Does it result in the most efficient outcomes or is there 'market failure'?
- Is the resulting distribution of costs and benefits fair and acceptable?

Later sections deal with market failure and with the issue of who pays – efficiency and fairness. It is

important to remember that an attempt to overcome market failure is aimed at ensuring the efficient operation of the economy (maximising total economic welfare) whereas redistributive activities are attempts to ensure equitable outcomes for all groups in the economy (achieving a fair distribution of the wealth).

Causes of market failure

Economic theory indicates that, in the absence of a number of clear causes of market failure, intervention by governments in human affairs is likely to reduce economic efficiency.

Further, the mere existence of market failure is not a sufficient justification for government involvement. The failure has to be great enough to offset the direct cost of involvement and the risk of 'government failure', that is, the risk that even with the best of intentions, government will formulate laws or undertake measures that make things worse rather than better. The cost of government involvement includes the administrative cost of collecting, holding, distributing and spending taxpayers' money. In Australia, this cost has been estimated at \$0.40 per dollar collected by governments (Findlay and Jones 1982). In other words, to spend \$1.00 the government has to collect \$1.66. This applies generally, not just to environmental programs. To be efficient, the government's use of the money would have to be substantially more productive than the taxpayers' – at least 66% more efficient.

As well as the issue of whether any government involvement is justified, there is also the issue of the optimal level of involvement - the level of government expenditure that maximises benefits to society. This depends on the biological, technical and economic characteristics of each issue and can be very difficult to determine.

There are at least four types of market failure: public goods, externalities, monopolies and ignorance or uncertainty, as outlined below. All are relevant to agroforestry. For further details and theoretical background, see Randall (1981), Pearce and Turner (1990) or Tietenberg (1996).

Public goods

The terms 'public goods' and 'private goods' in economics have very particular meanings that do not always coincide with popular usage. For

BOX 18.1

Non-rival goods related to agroforestry

- **Preservation of a threatened species** that the community values. Agroforestry might contribute to such an outcome in some cases. The fact that one person benefits from (consumes) the knowledge that the species has been conserved does not reduce the benefit to others who care about the issue.
- **Information.** Widely applicable information about agroforestry production methods from research and development may be non-rival. Many producers can make use of the information without reducing its availability or usefulness to others.
- **Aesthetic benefits.** The community may value the aesthetic appearance of a landscape that includes more agroforestry. The enjoyment of these aesthetic benefits by any one community member does not reduce the benefits' availability to others (provided that everyone does not go to enjoy them in the same place at the same time!).

example, a resource may be in private hands but still have public good characteristics. A good may be provided to the broad community (the public) but not have public good characteristics in the economic sense.

There are two broad types of public goods: non-rival and non-price excludable (Randall 1981). In each case the economic problem is that in a free market the good is provided at a lower level than would be socially optimal. Thus there is a prima facie case for government stepping in, in one of a variety of ways (which we will examine later) to ensure that the good is provided at an appropriate level.

Non-rival goods

For a non-rival good, consumption by one person does not reduce the quantity or quality available to others. Most economic goods are rival in nature. Consumption by one person of bioenergy or wood products derived from agroforestry means that they are not available to be consumed by other people, unless the original purchaser is willing to give them up. However, there are examples where outputs from or inputs to agroforestry are non-rival. Non-rivalry applies to relatively intangible outputs from agroforestry, not to tangible products.

The reason a non-rival good results in market failure is that there is no cost of providing the non-rival good to an additional consumer (the marginal cost equals zero). As a consequence, the socially opti-

mal price to charge for the good is zero. The socially optimal price is the price that would maximise overall net benefits to the community. For a rival good, the socially optimal price reflects a balance between the marginal benefits from consumption and the marginal costs of supply. For a non-rival good, at any price above zero there will be consumers who would have consumed and benefited from the good if it were free but who now choose not to do so. Since the benefit they would have experienced would not have cost the community anything, charging a non-zero price for a non-rival good results in an overall loss of benefits to the community.

On the other hand, if government intervenes (e.g. by regulation) to require that private firms must not charge a price for access to the non-rival good, we take away some of their incentive to supply the good. Some of the good may be provided anyway, as a spin-off benefit from commercial decisions (e.g. landholders practising commercial agroforestry may generate aesthetic benefits for which they are not paid), but the point is that because these wider non-rival benefits are not factored into the production decisions of landholders, the agroforestry may not be established over a wide enough area, or in the best places, from the perspective of the community as a whole.

Non-price excludable goods

A non-price excludable good is one that consumers cannot be prevented from consuming, leading to

BOX 18.2

Non-price excludable goods related to agroforestry

- **Off-site benefits from watertable control.** An agroforestry system may help to lower the watertable and reduce off-site impacts from waterlogging and dryland salinity. However, the producer may not be able to charge the off-site beneficiaries for these benefits.
- **Carbon sequestration.** Agroforestry may contribute to preventing adverse changes to global climate by sequestering carbon. Without government intervention, producers cannot charge individual beneficiaries for this service. Beneficiaries are widely dispersed, impossible to identify and may not even be born yet.
- **Flood mitigation.** In Western Australia, rising watertables are increasing the flood risk in large areas of the south-west agricultural region. By lowering watertables locally, agroforestry can reduce runoff and thereby benefit downstream towns and infrastructure. It is not possible for the producers to charge the downstream beneficiaries for this service.

problems of free-riders, underprovision or overexploitation. Because consumers have access to the good without constraint, the provider of the good is unable to charge a fee for access.

Non-price excludable goods can often be considered a problem of poorly defined property rights. If a private firm were able to assert and enforce a right to exclude people who did not pay for the good or service, it would be possible for the private sector to charge a price and consequently efficiently provide the good or service. The assignment and enforcement of property rights gives the holders of the rights an incentive to preserve the resources on which the rights depend.

Note that a good can be both non-rival and non-price excludable. For example, this is true for all three examples of non-rival agroforestry benefits (Box 18.1).

Note also that being non-price excludable is not necessarily an intrinsic characteristic of the good. A good may be non-price excludable in one time or place but price-excludable in another, depending on the laws. For example, consumption of water (rainfall, surface water and groundwater) by trees in the Murray-Darling Basin in eastern Australia is currently non-price excludable, but there have been proposals that tree producers should be required to participate in the water market to purchase water flows that would have ended up in the Murray-

Darling river system. Such a change would effectively convert the water into a price-excludable good, not by physically changing the water but by changing the rules under which it can be used.

Not all goods that are non-price excludable can be converted to price-excludable goods by a change of law. Some of the intangible benefits (aesthetics, conservation) are intrinsically non-price excludable. No change in the legal or administrative system could convert them into a price-excludable good.

Non-rival goods are always intrinsically non-rival and cannot be converted into rival goods by a change of law.

Although the problems of non-rival and non-price excludable goods both relate to zero prices, there is an important difference. For non-price excludable goods, it may be desirable but impossible for suppliers of a good to charge consumers for access, whereas for non-rival goods, it may be possible but not desirable for firms to charge a non-zero fee.

Of the two causes of public goods, non-price excludability is usually the more serious problem. Non-rivalry usually means that a proportion of potential consumers are missing out on modest benefits from access to the good. Non-price excludability, if it results in major overexploitation of a resource, can mean that the entire resource stock is degraded, potentially to the point where it is lost to the whole community.

Externalities

An externality occurs when an activity undertaken by an individual has side effects on others and the first individual does not take these side effects into consideration. There are two types of externality: negative and positive (also called external costs and external benefits).

The classic example of a negative externality is pollution. Suppose that pollution is generated as a side effect of an economic activity. In a free market, a negative externality such as pollution is a problem because the level of the activity chosen by the polluter is too great (in the sense that there exists the potential to improve the welfare of both the polluter and the sufferer). If the external costs could be factored into the polluter's business decision, the polluting activity would not be undertaken or would be undertaken at a lower level. In the absence of regulation or some form of government-imposed incentive, polluters generate more pollution than is socially desirable because they do not consider the costs it imposes on others.

Examples of negative externalities in agricultural production include drift of chemical sprays, failure to prevent the spread of insect pests or weeds, dust or sand deposits from wind erosion, or some cases of dryland salinity. In each case a farmer, whether by action or inaction, increases the costs for neighbours or others in the community. The cost does not have to be a financial cost to be considered an externality. Effects on health or mental well-being are also relevant.

A positive externality is also a problem, but this time it is because the level of activity is too low. For example, if establishing agroforestry on a farm would create off-site benefits (e.g. reduced dryland salinity, habitat for biodiversity, carbon sequestration) for which the farmer is not compensated, the area of agroforestry may be too low from a community-wide perspective. If the off-site benefits were factored into production decisions, the area planted may be increased (although not necessarily, as shown below).

An externality is only a social problem (in the sense of reducing the aggregate community benefits) if it is uncompensated – if the off-site benefits or costs are not taken into account by the decision-

maker. For example, in the case of trees using water that would otherwise be available to downstream users, if the use of such water is free and unregulated (i.e. non-price excludable) then the downstream consequences are unlikely to be considered. The water is being used for lower-value uses than it could be. If tree growers are charged appropriately for the water they use but, having factored in those additional costs, still choose to use the water for tree production, then the fact that the water is not available to downstream users is not a social problem. It is already being allocated to its highest-value use. Randall (1981) pointed out that it is not externalities *per se* that are the problem, but externalities that are associated with a non-rival or non-price excludable good. Public good is the more fundamental problem.

Monopolies

The undesirability of monopolies is well-known. A monopolist faces a strong incentive to exploit its capacity to artificially restrict supply and increase the price it charges. The 'simple' solution is to regulate to curb or avoid monopolies. This is clearly the aim of bodies such as the Australian Competition and Consumer Commission, and is partly relevant to policies such as the National Competition Policy. However, the issue is complicated by the potential for natural monopolies. A natural monopoly occurs in an industry with very high fixed costs and/or very low costs of provision at the margin (e.g. quarantine). In the case of natural monopolies, regulations to prevent monopoly pricing can be counter-productive, because enforcing low sale prices may mean that the monopoly firm is unable to cover its fixed costs and so will shut down. The most common government responses are to take responsibility for provision of the good or to allow the monopolist to charge a price that is higher than their marginal cost.

If agroforestry is used for production of bioenergy, it may become associated with natural monopolies in the form of power suppliers. The fixed costs associated with power generation are so high that there may not be scope for more than viable one supplier within each market (e.g. each state). Fixed costs in establishing processing plants for products from agroforestry may also be high.

Whether this results in natural monopolies depends on the markets into which the products are sold. If they are international markets, competition from overseas suppliers would inhibit the potential for monopoly pricing. New processing firms may struggle to make profits in such cases.

Ignorance and uncertainty

Individuals sometimes behave in a socially undesirable way simply through ignorance. The ignorance may be over damage that they are unwittingly causing to others (e.g. off-site salinity) or over matters that affect them personally (e.g. on-site salinity). If governments feel that they have better information than the individuals they may choose to provide that information as a public service. Examples include public education programs on health, law, pollution, safety and environmental management.

A potential danger is that government officers may be incorrect in their belief that they have better information than the individuals they advising. Agroforestry has been promoted widely in Australia, particularly by programs seeking environmental outcomes (National Landcare Program and Natural Heritage Trust). Uptake has been relatively low. It seems likely that the main explanation has been the economic performance of the agroforestry systems being promoted. Those responsible for promoting agroforestry for environmental benefits have not adequately considered the private economics of their advice before attempting to promote agroforestry.

Net benefit test for market failure

The fact that there are various public good, externality and information problems associated with agroforestry suggests that there may be a case for government intervening to ensure maximum benefits to the community. However, there is an important additional test: are the benefits of intervening greater than the costs? There is a risk, for example, that if the government steps in to reduce an external (indirect or public) cost it may inadvertently cause an even greater internal (direct or private) cost. To avoid this risk, it is important to weigh all the relevant costs and benefits – external and internal, indirect and direct – to check that the proposed change is actually beneficial overall. If it is not ben-

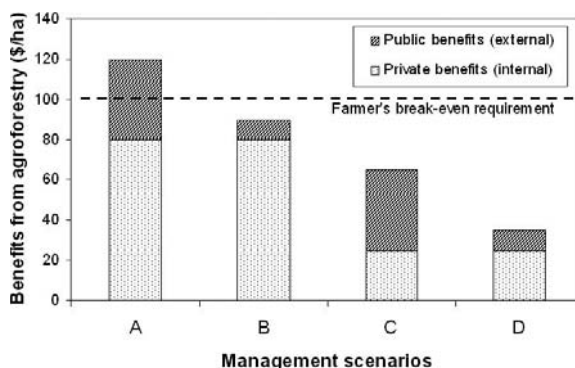


Figure 18.1: The net benefit test for market failure. Conversion of traditional agriculture to agroforestry would generate positive net benefits in scenario A but not in the other scenarios. In scenario A, the unrealised potential for external benefits results in a case of market failure. In the other scenarios, the external benefits are insufficient to cause market failure.

eficial overall then it is not actually addressing a market failure, despite the existence of public goods, externalities, monopoly or ignorance.

To illustrate, suppose that the government wishes to pay incentives to landholders to convert their land from traditional agricultural production to an agroforestry system. Suppose that the agroforestry system is less profitable than traditional agriculture and that the farmers are not willing to make the change voluntarily. The income sacrifice (net private cost) that they would have to bear varies. We will consider examples where it is high or low. Similarly, the net external benefits of making the change to agroforestry may be high or low. Figure 18.1 shows the four relevant scenarios, combining high and low net private cost (reflected in the shortfall of private benefits below the farmer's break-even requirement) and high and low net external benefit. For simplicity, it is assumed that the farmer's break-even requirement is the same in all scenarios.

Scenarios A and B are where agroforestry is somewhat profitable, although insufficiently to be more attractive to farmers than the existing farming systems. In scenarios C and D the practices are much less profitable than existing systems. The levels of non-agricultural (external) benefits resulting from the treatments are relatively high in scenarios A and C and low for B and D. In scenario A, the combination of agricultural and non-agricul-

tural benefits is such that it is possible for the proposed payment to farmers to change the land use and benefit overall. The payment could provide sufficient incentive to exceed the farmer's break-even requirement (mainly determined by the profitability of the existing land use) and prompt a change of management without needing to be so great that it outweighed the resulting external benefits.

In the three other scenarios, either the treatment is insufficiently profitable at the farm level or the non-agricultural benefits are too small, or both. In these scenarios, a payment to farmers sufficient to prompt a change in land use would need to be greater than the value of the resulting external benefits. It clearly makes no sense to pay more for a good than the good is worth. To do so would result in a net reduction in the total benefits that the community gains from this land, even after the external benefits are factored in.

Ideally, proposals for new government policies should be evaluated using a broad cost–benefit analysis, considering public and private benefits and costs. This is particularly difficult where some of the benefits are relatively intangible, but it may still be possible (see Box 18.3).

Evidence for and against market failure related to agroforestry

It is one thing to identify potential causes of market failure for agroforestry, and another to determine that there really is market failure. To do so, we need information about private costs and benefits of agroforestry as well as public external benefits and costs.

In the case of dryland salinity, recent evidence indicates that non-adoption of agroforestry is unlikely to be a general market failure but non-adoption in particular locations probably is a market failure. In much of the landscape, the situation is like scenario B, C or D of Figure 18.1, but in certain locations scenario A probably applies.

This conclusion needs further explanation. Even though the off-farm costs of dryland salinity are obviously high, the off-farm benefits from on-farm treatments are often much smaller than the on-farm costs. Particularly in drier regions, the treatments are often only partly effective at preventing salinity off-site and the positive off-site effects tend to be very long delayed (George *et al.*

1999; Hatton and Nulsen 1999; Heaney *et al.* 2000; National Land and Water Resources Audit 2001; Dawes *et al.* 2002).

We have lost hope that large-scale prevention of salinity can be achieved by clever selection and placement of relatively small-scale plantings of deep-rooted perennial plants (shrubs, perennial pastures or trees). The new consensus is that, in areas where we wish to contain salinity, large proportions of land need to be revegetated with perennials.

Even with major revegetation efforts, the degree of salinity prevention in the long run will probably be less than we would like, particularly in relatively flat landscapes. George *et al.* (1999) presented the results of hydrological modelling for several wheatbelt catchments in Western Australia. The results indicated that if recharge across these catchments were reduced by 50%, implying perennials on more than 50% of the land, the area of land predicted to be salt-affected would be reduced by 3–12% of the catchment. This is not the full story, because there would also be delays in the onset of salinity over a larger area, but the results highlight the relatively low sensitivity of salinity to perennial vegetation in some environments, particularly those with low slopes and/or regional-scale groundwater flow systems.

Applying standard discounting methods to convert distant future benefits into present values further reduces the magnitude of the benefits. The significance for policy interventions is as follows. The level of off-farm benefits from on-farm treatments sets an upper limit on what it could be worthwhile for the community to provide in financial support to encourage farmers' adoption of agroforestry. Small off-site benefits warrant only small financial support. For similar reasons, they warrant only small financial penalties for non-compliance, when a regulatory or tax-based approach is used.

Would small financial support be sufficient? It depends on the on-farm economics of agroforestry. This varies widely from location to location, but there is general agreement that few of the current agroforestry options are economically attractive to farmers other than in high-rainfall regions.

Overall, from a salinity perspective, there is a market failure argument for government intervention to support agroforestry to address dryland salinity, but it requires particular circumstances.

BOX 18.3**Valuation of intangible environmental benefits from agroforestry**

Economists refer to intangible environmental benefits (such as the satisfaction of knowing that a species has been protected from extinction) as non-market benefits, as they cannot be bought or sold in the same way as more tangible products.

Several methods for estimating non-market values have been developed and applied by economists. The best-established techniques include three indirect methods (travel cost recreation demand, hedonic property value (or wage) equation and averting behaviour or household production model) and two direct methods (contingent valuation and choice modelling) (Smith 1996; Bennett and Blamey 2001). Contingent valuation and choice modelling are usually the most relevant techniques for measuring non-market values of agroforestry, particularly non-use values. Both are based on social surveys of population samples. In contingent valuation, people are asked to state their willingness to pay for a hypothetical improvement in environmental quality or their willingness to accept compensation for a hypothetical deterioration in environmental quality. In choice modelling, people are asked to rank hypothetical options that involve trade-offs between environmental and other outcomes. Values attributable to the environmental outcomes are inferred from their responses. In both cases, values are aggregated up to the level of the whole population.

There has been a spirited academic debate about the validity and usefulness of non-market valuation methods, particularly contingent valuation. Arguments put forward by advocates have included the following:

- when done well, the techniques give plausible and realistic results;
- even though the techniques are not perfect, it is important to attempt to measure non-market values using the best available methods because it assists in having them fully and properly considered in public planning and policy-making.

Some economists reject the first argument, particularly for contingent valuation. Much of the debate is technical, mostly based on arguments that results from actual studies are illogical in various ways. Choice modelling avoids some of the problems associated with contingent valuation and its advocates make reasonable claims that it is a superior technique. However, there are some general concerns about contingent valuation that would also affect choice modelling (see Pannell 2004).

To conduct a meaningful non-market valuation study, we need to be able to answer basic (non-monetary) questions such as:

- the effects of different management options on biodiversity;
- the ways in which the biodiversity levels on that land are important or significant (e.g. in ecological terms) and why.

Our knowledge of these areas may be weak, and research to improve these aspects is a priority.

Table 18.1: Pros and cons of different types of policy approaches

Incentive	Examples	Pros and cons
Subsidies and other positive financial incentives	Payments to farmers for adopting agroforestry Carbon credits	Pros: Politically popular; targets specific activities Cons: Financial impact on government budgets; may stimulate too much activity; uncertain effects
Marketable permits	Emissions permits	Pros: Provides clear limits on emissions pollution; effective when sources are numerous and damage per unit of pollution varies with the quantity of pollution; stimulates technological change Cons: Potentially high transaction costs; requires variation among the polluters in the cost of pollution abatement
Pollution charges and taxes	Emission charges for saline discharges	Pros: Useful when damage per unit of pollution varies little with the quantity of pollution; stimulates technological change Cons: Uncertain environmental effects; potentially large distributional effects (winners and losers); high monitoring costs
Input or output taxes and charges	Carbon tax Fertiliser tax Levy on polluting land uses	Pros: Administratively simple; relatively low monitoring costs; effective when sources are numerous and damage per unit of pollution varies little with the quantity of pollution. Cons: Often weakly linked to pollution; uncertain environmental effects; high monitoring costs
Legal liability	Nuisance, trespass Duty of care Natural resource damage assessment	Pros: Can provide strong incentive (if legal recognition of liability and enforcement are high – probably not the case with salinity) Cons: High assessment and litigation costs; large burden of proof
Voluntary programs	Landcare Education and communication	Pros: Low cost. Cons: Uncertain participation (for salinity, participation much too low); assumes viable technologies are available
Support for industry development	Research and development Provision of physical infrastructure Reform of administrative barriers to the industry	Pros: Potentially applicable over very large areas; can generate environmental benefits in cases where direct subsidies would not be warranted; can improve the leverage of public subsidies; if resulting industries are profitable, there will be few problems encouraging adoption; additional social benefits from employment in new industries; relatively low draw on public funds. Cons: Time lags of research and development; can be difficult to control where the new land uses are taken up

- Groundwater systems are most responsive to changes in land management.
- Changing to agroforestry is at low cost to farmers.
- The land in question is physically close to the discharge site affecting the asset that is under threat.

In the case of terrestrial impacts from salinity, a further condition is that there should be downstream impacts on assets of exceptionally high value. In the case of salinity in watercourses, market failure is most likely in locations where salt stores and salt discharge into waterways is outstandingly high.

These problems can be side-stepped if it is possible to identify or develop agroforestry systems that

are profitable in their own right. In many cases, it may be more beneficial to pursue R&D into profitable agroforestry systems than focus on measures to support adoption of unprofitable systems.

There is a further complexity relating to salinity and market failure. In some regions with relatively high rainfall, planting perennials can have a negative impact on the yield of surface water reaching streams and rivers. If the surface water is fresh, it would have diluted salinity already in the waterways. In some cases, this is a more important influence than the reduction in saline discharge that would result from planting the perennials. In addition, the reduction in water yield is itself a problem, as it reduces water availability for downstream users or the environment. If perennials are economically attractive to landholders, there could be

a market failure associated with their adoption rather than their non-adoption.

For the other categories of environmental impacts (biodiversity, carbon sequestration, erosion mitigation), evidence for or against the proposition that lack of adoption of agroforestry reflects market failure is much less clear. It is true that there are ongoing efforts to promote agroforestry for environmental reasons, but there is little clear evidence on whether this is a good use of public funds in the sense of addressing a market failure.

Types of policy intervention

There are many mechanisms that governments can use to encourage farmers to take up agroforestry systems (Pannell 2001). Table 18.1 shows some of the main categories of policy approach relevant to agroforestry and indicates key pros and cons of each. Space does not permit detailed explanation of the many alternatives. The main point is that there are many options available to governments wishing to influence uptake of agroforestry, that their applicability varies widely in different situations, and that care and effort are needed so that the policy approaches used are the most appropriate.

In Australia, the National Action Plan for Salinity and Water Quality supported a pilot scheme investigating a range of innovative policy mechanisms intended to encourage environmental management. One innovative approach draws on the age-old idea of an auction, to ensure that public funds achieve the highest possible environmental benefits per dollar (Box 18.4).

Who should pay?

Mainstream economic theory does not attempt to objectively evaluate the relative merits of different decisions about who pays. For such questions, the contributions of economists are usually limited to:

- quantifying the distributional effects of alternative policies;
- quantifying the efficiency impacts of alternative policies;
- assessing policy performance with regard to general rules that attempt to capture (or shape) community attitudes regarding fairness.

A common rule of thumb for distributional questions is the user-pays or beneficiary-pays principle, under which the beneficiary of a good or service should bear the costs of its provision. It is not a principle in the sense of a scientific principle, but rather a suggestion of what is fair.

Another common system for distributing costs is the polluter-pays principle. Generally, this approach is in direct conflict with the user-pays approach. It lacks any basis in economic theory, but the community may consider it a fair and reasonable norm.

There are problems in trying to rigorously implement either rule. For many environmental issues, it is difficult to accurately identify and quantify the benefits and costs for the polluters or beneficiaries of environmental works. The user-pays approach dictates that community members should pay in proportion to their benefits from establishment of agroforestry. The polluter-pays approach requires costs to be borne in proportion to the damage caused if agroforestry is not established. Meeting the information requirements of either rule is impossible in a practical sense, although approximations may be feasible.

Application of any simple rule may be compromised, as governments' decisions about the distribution of benefits and costs are influenced by a range of considerations. These include political gain, parochialism, the activities of lobby groups or a wish to benefit particular groups due to perceptions of disadvantage.

The market also influences the distribution of benefits and costs, irrespective of the government's wishes. For example, if farmers' production costs go up due to legal requirements to establish agroforestry, the farmers may not be able to pass on the increase to consumers. It depends on how responsive consumers are to price changes. If consumers are too responsive and dramatically cut their consumption as prices rise, farmers lose more than they gain by attempting to pass on the extra costs. In a free market, the distribution of costs between farmers and consumers is completely outside government control as it depends entirely on the responsiveness of supply and demand to price changes; these depend on producers' cost structures and consumers' preferences, not on government policy.

BOX 18.4**BushTender trial of an auction-based policy mechanism**

A variation on the theme of ignorance as a cause of market failure is so-called information asymmetry. Farmers have information about important aspects of the economics of available land use options, but the details are unknown to policy-makers. This limits their powers to design and implement efficient policies. Auction-based systems directly address this problem. Such an approach was trialled in Victoria under the title of BushTender, as a means of allocating public funds to protection of remnant vegetation, (Stoneham *et al.* 2003).

In simple terms, the idea in BushTender is that individual farmers bid for public funds to support environmentally beneficial activities on their farm. They specify the proposed environmental works and the required level of public support. The government agency evaluates the bids and selects those that give the best environmental outcomes per dollar of public funding.

There is an element of competition between bidding farmers that helps ensure that bids offer the best possible value for the public funds. Importantly, bids reflect not only the direct financial costs and benefits facing the farmers, but their personal satisfaction from contributing to environmental protection.

An evaluation of the BushTender trial found that the environmental outcomes per dollar were very substantially increased relative to a more traditional subsidy scheme based on fixed subsidies for particular types of action. There is potential for wider application of this type of policy mechanism, including for agroforestry.

In summary, economics do not offer much help with the question of who should pay. Sometimes there are efficiency aspects to the question, and economics is certainly useful in addressing these. Usually, however, questions of rights and fairness are more important to the community. These are somewhat flexible, driven by community attitudes, politics and power.

Conclusion

‘The government ought to do something about it.’ This chapter has shown that, for a responsible government, issues are not as simple as the sentence makes it sound. A responsible government needs to be concerned about whether a particular policy proposal is warranted. This requires an understanding of the concept of market failure, careful consideration of the public and private benefits and costs, and consideration of the distributional consequences. Environmental benefits from agroforestry are clearly significant in some cases, but the government needs to consider more than that in

examining its policy options. Where policy actions are deemed to be warranted, there is a daunting array of policy mechanisms, with a variety of strengths and weaknesses. The choice of policy mechanism needs careful consideration.

In the specific case of salinity-related benefits from agroforestry, we have seen that the private net costs of existing agroforestry options often exceed the public net benefits, in which case direct policy intervention is probably not warranted. For these situations, the best agroforestry-related use of public funds is probably to support efforts to improve the profitability of agroforestry, such as through research and development into new plants, new products and new systems. However, there may be cases where direct measures to promote agroforestry are justified on the basis of off-site salinity benefits. These would generally be where groundwater systems are most responsive to changes in land management, changing to agroforestry is of low cost to farmers, the land in question is physically close to the discharge site affecting an asset and the asset is of high public value.

BOX 18.5

Should we have an environmental levy?

Governments control the level of public funds allocated to promote and support agroforestry. Public funding for environmental and resource management has increased, but calls by environmentalists for dramatic further increases are common.

The possibility of introducing an environmental levy, either on the price of food or on income tax, is being advocated. For example, the Prime Minister's Science, Engineering and Innovation Council (2002) identified as one of its four priorities for investment, 'Redressing the absence of economic signals, to urban and rural Australians alike, connecting the underlying ecological condition of natural systems to our use of them for products and services' (p. 14). The Wentworth Group of Concerned Scientists suggested a 1% levy on income tax. While laudable in intent, there are a number of problems with these proposals.

- Some may be concerned about the regressive nature of a flat levy and prefer that funds be collected through a more progressive system, such as income tax.
- A hypothecated levy (one whose revenue is allocated to a particular task) would involve greater transaction costs than an approach that makes use of the existing tax system.
- 'Hypothecation may create inefficiencies because the tax rate can be determined on the basis of revenue required, and not on the costs and benefits of the tax. ... Furthermore, it is difficult to determine the appropriate revenue sources for particular expenditures' (Scrimgeour and Piddington 2002, p. 10). The OECD (1997) recommended that hypothecation should be transitory, if used at all, because inefficiency in spending priorities may become locked in.
- Why would the environment, out of all issues in need of public resources, particularly warrant a hypothecated levy? Why not education? The arts? Police? National security? Why not simply use the existing tax system?

References

- Bennett J and Blamey R (2001) *The Choice Modelling Approach to Environmental Valuation*. Edward Elgar Publishing, UK.
- Dawes WR, Gilfedder M, Stauffacher M, Coram J, Hajkowicz S, Walker GR and Young M (2002) Assessing the viability of recharge reduction for dryland salinity control: Wanilla, Eyre Peninsula. *Australian Journal of Soil Research* **40**, 1407–1424.
- Findlay CC and Jones RL (1982) The marginal cost of Australian income taxation. *Economic Record* **58**, 253–266.
- George R, Clarke C, Hatton T, Reggiani P, Herbert A, Ruprecht J, Bowman S and Keighery G (1999) The effect of recharge management on the extent of dryland salinity, flood risk and biodiversity in Western Australia. Preliminary computer modelling, assessment and financial analysis. State Salinity Council of Western Australia. Unpublished report.
- Hatton TJ and Nulsen RA (1999) Towards achieving functional ecosystem mimicry with respect to water cycling in southern Australian agriculture. *Agroforestry Systems* **45**, 203–214.
- Heaney A, Beare S and Bell R (2000) Targeting reforestation for salinity management. *Australian Commodities* **7**, 511–518.
- National Land and Water Resources Audit (2001) *Australian Dryland Salinity Assessment 2000*. National Land and Water Resources Audit, Canberra.

- OECD (1997) *Environmental Taxes and Green Tax Reform*. OECD, Paris.
- Pannell DJ (2001) 'Economic tools to tackle dryland salinity in Western Australia'. Department of Treasury and Finance, Perth. Economic Research Paper.
- Pannell DJ (2004) Heathens in the chapel? Application of economics to biodiversity. *Pacific Conservation Biology* **10**(2/3), 88–105.
- Pearce DW and Turner RK (1990) *Economics of Natural Resources and the Environment*. Harvester Wheatsheaf, New York.
- Prime Minister's Science, Engineering and Innovation Council (1999) 'Dryland salinity and its impact on rural industries and the landscape'. Prime Minister's Science, Engineering and Innovation Council, Department of Industry, Science and Resources, Canberra. Occasional Paper no. 1.
- Randall A (1981) *Resource Economic: An Economic Approach to Natural Resource and Environmental Policy*. Wiley, New York.
- Scrimgeour F and Piddington J (2002) 'Environmental taxation in New Zealand: what place does it have?' Institute of Policy Studies, Victoria University of Wellington. IPS Policy Paper no. 12.
- Smith VK (1996) *Estimating Economic Values for Nature: Methods for Non-market Valuation*. Edward Elgar Publishing, UK.
- Stoneham G, Chaudhri V, Ha A and Strappazzon L (2003) Auctions for conservation contracts: an empirical examination of Victoria's BushTender trial. *Australian Journal of Agricultural and Resource Economics* **47**(4), 477–500.
- Tietenberg T (1996) *Environmental and Natural Resource Economics*. 4th edn. HarperCollins, New York.

Adoption of agroforestry in Australia

Digby Race

Introduction

Forestry continues to be redefined to meet a broad range of economic, environmental and social expectations in many countries, including Australia (Sargent 1992; Brand *et al.* 1993; Grayson 1993; Clark 1995; Kanowski 1995; Ferguson 1996; Humphreys 1996; Myers 1996; FAO 1997; Grundy 1997). A notable feature of this process is the increasing importance given to agroforestry by landholders, industry and government (Pearse 1994; Kanowski 1996). However, despite a considerable increase since the mid 1990s in research into this land use potential, agroforestry is still in a developmental stage in most regions in Australia.

As discussed in earlier chapters, agroforestry is viewed by many as an approach to land management in which trees and shrubs are used to help achieve more sustainable agriculture, diversify farm incomes, improve the aesthetics of farmed landscapes, reduce the national trade deficit in forest products and enhance the viability of regional communities through industry development and employment (McDonald 1993; Commonwealth of Australia 1995; Centre for International Economics (CIE) 1996; MCFFA 1997; Moore and Bird 1997; Herbohn and Harrison 2004).

Aspects of agroforestry have been practised for millennia by agrarian-based societies throughout the world on a relatively localised scale (Dabbert 1995; Dupraz and Newman 1997; Wu and Zhu 1997; Garrity 2006). Despite this long history, the

scale of agroforestry is believed to have remained small and localised, and thus difficult to assess at an international level (Mather 1993) and in Australia (Parsons *et al.* 2006).

Complex opportunities

Partly because of its strong interconnectedness with both agriculture and forestry, agroforestry as an integrated discipline was not studied academically to any notable degree until the late 1960s (Buck 1995; Hawke and Knowles 1997; Williams *et al.* 1997). Today, it is estimated that there are thousands of scientists worldwide working on agroforestry research and development (Wu and Zhu 1997). Its current popularity with some sections of government, industry and rural communities is principally due to the widely held belief that integrated agroforestry is more biologically stable and financially profitable than either agriculture or forestry alone, and creates environmental and management synergies.

However, a critical cost of realising these benefits can be the greater management complexity of optimising agroforestry compared to the management of individual agricultural or forestry systems (Gordon and Newman 1997; Williams *et al.* 1997). Depending on the agroforestry system's design and management, its complexity should not be underestimated – dramatic failures have been reported from many countries. Indeed, the complexity of management has led to the decline of some traditional forms of agroforestry, as land

is developed for modern broadacre farming (Dupraz and Newman 1997). Given Australia's challenges with low-fertility soils, low and erratic rainfall, a narrow range of commercialised plants and uncertain long-term economic returns, it is understandable that agroforestry is still in a developmental stage in most farming communities and viable self-sustaining regional agroforestry industries are still emerging.

Adopting the broad definition of agroforestry promoted earlier in this text, it is relevant to review the emergence of farm forestry – both in parallel and incorporating agroforestry – in the Australian context.

Growth of farm forestry in Australia

Out of a long history of harvesting from native forests and establishing softwood plantations, emerged two segments of farm forestry in the 1980s – plantations through joint ventures with timber companies and government forest departments, and small scattered mixed-species plantings for environmental repair and agricultural benefits (e.g. shelter belts for livestock) (National Plantations Advisory Committee 1991). The emerging interest in farm forestry was scaled up considerably during the 1990s, principally driven by:

- overseas and domestic investment to establish eucalypt woodlots to meet the increased global demand for eucalypt pulp to produce high-quality paper (Japan being a major market) (Turner *et al.* 2004);
- scaling up the activities in line with the Landcare ethic, which popularised trees as a component of 'good' farming (recent estimates indicate that 40% of commercial farmers – 40 000 people – are active members of local Landcare groups) (Vanclay and Lawrence 1995; Campbell 1997; Carr 2002).

The Australian temperate agro-ecological zone of south-west Western Australia, south-east South Australia, southern Victoria and Tasmania is well-suited to growing *Eucalyptus globulus*, a preferred species for high-quality paper products. Investing in eucalypt plantations in this zone had the advan-

tage of the potential availability of large areas of cleared farmland close to deep-sea ports, and the financial returns from forestry were very competitive with most agricultural commodities, particularly wool. Much of the farmland is experiencing or susceptible to dryland salinity.

Investment brokers quickly realised the potential for forestry to meet the needs of overseas and domestic investment funds seeking to achieve a delayed return (e.g. in 10–20 years) but obtain immediate taxation discounts. The upfront cash flow of such investment allowed management companies to purchase farmland (appealing to many farmers wishing to retire from farming) or secure long-term access rights (usually 20–30 years) to farmland by negotiating joint ventures with annuity payments to landholders. During 1995–2005, an average of 70 000 ha/yr were established, the vast majority being eucalypt plantings on farmland by management companies. An estimated 75 000 people own woodlots with managed investment companies, accounting for 23% of Australia's plantations (Parsons *et al.* 2006).

Forestry has added appreciably to the economies of key regional centres where it is concentrated, such as Albany and Bunbury (Western Australia), Mt Gambier (South Australia), Hamilton and Portland (Victoria), and Devonport (Tasmania) (National Forest Inventory 2003; Parson *et al.* 2006). However, the economic benefits of the recent investment in forestry have largely been restricted to medium-high rainfall areas (>700 mm/yr) of the temperate coastal regions with deep-sea ports. Most of Australia's vast wheat-sheep zone with its medium-low rainfall (<700 mm/yr) and long distances to processing and export hubs has failed to attract any appreciable investment in tree-based industries (CSIRO *et al.* 2001). This includes the Murray-Darling Basin, which generates 60% of Australia's agricultural produce yet is under threat of dryland salinity (Murray-Darling Basin Ministerial Council 2001).

Potential farm forestry industries

The National Farm Forestry Roundtable (2000) prepared a preliminary strategy for developing farm forestry industries in Australia's low-rainfall zone, identifying opportunities to:

- extend conventional forestry – encourage existing forestry industries to extend beyond their conventional transport and rainfall limits and extend industry infrastructure as planting expands. With innovative integrated farm forestry designs (where the trees can use surplus water from adjacent agriculture) and extra return from salinity control, viable farm forestry for sawlog production may be able to extend to areas with as little as 400 mm/yr rainfall across southern Australia;
- create new industries – many new tree and woody plant crops will be required as farm forestry options for the low-rainfall zones (250–400 mm/yr rainfall) and to complement sawn timber tree crops in the intermediate rainfall areas (400–600 mm/yr rainfall);
- improve historic low-rainfall timber industries – there are several historic timber industries in the low-rainfall zone that could be upgraded (e.g. *Callitris* woodlands in inland New South Wales and Queensland, goldfields eucalypts and sandalwood in Western Australia and oil mallee in Victoria and New South Wales) (CSIRO *et al.* 2001).

Diversity of farmers and regions

Agroforestry is widely promoted in many regions of Australia, but the prospects for individual farmers and specific regions vary considerably. In many temperate coastal regions, the number of people identifying themselves as farmers is declining but the number of rural landholders is increasing, leading to increasingly diverse rural communities. This social diversity has forced agencies and others to rethink how they engage with landholders, particularly given that an increasing number are not primarily motivated in farm management by economic objectives. The range of agroforestry systems is one expression of the social heterogeneity of Australia's landholders.

There are some signs of success as farm-based forestry is expanding at an unprecedented rate, with 5–20% being established as agroforestry (4000–17 000 ha/yr) (Wood *et al.* 2001). However, successful adoption of agroforestry from a landholder's perspective is often determined by a range of factors – usually far more than simply how

many trees have been established (Guijt and Race 1998; Reid and Stephen 1999; Herbohn *et al.* 2005).

Australian policy context

Considerable government, industry and landholder resources have been committed to developing agroforestry in Australia, most notably since the mid 1990s. For example, the Australian government has increased support for farm-based forestry in pursuit of the multi-functionality that trees in the rural landscape can achieve, including:

- development of forest industries – Australia's forest industries employ 78 400 people and generate an annual business turnover of \$15 billion (Bureau of Rural Sciences 2004);
- arresting land degradation throughout much of Australia's farmland – 3–5 million ha in the Murray-Darling Basin alone are forecast to be at risk of dryland salinity within 50–100 years (Murray-Darling Basin Ministerial Council 2001). At least 40% of farmland must be revegetated if this is to be averted (National Land and Water Resources Audit 2001; <http://www.nlwra.gov.au/archive/full/index.html>);
- helping rejuvenate agriculture by developing an alternative income source for farmers – if 5% of the wheat-sheep zone and 10% of high-rainfall farmland were established to farm forestry, it could generate \$3.1 billion per year once a sustainable harvest is reached and increase incomes up to 20% for tree-growers (CIE 1996).

Increased support for agroforestry is reflected in a series of national policies:

- National Forestry Policy Statement (NFPS) (1992);
- Wood and Paper Industry Strategy (WAPIS) (1995);
- Plantations for Australia: The 2020 Vision (2020 Vision) (1997), which aspires to treble Australia's plantation estate between 1996 and 2020 to more than 3 million ha.

Farm forestry only received a brief mention in the NFPS, but grew in popularity during the 1990s and was given emphasis in the 2020 Vision. In

terms of farm forestry, the policies were implemented and supported most notably by the:

- Commonwealth Farm Forestry Program – managed by the Department of Agriculture, Fisheries and Forestry (DAFF), with \$49.2 million allocated since program inception in 1993;
- Joint Venture Agroforestry Program – a consortium of Commonwealth agencies and industry associations which has allocated \$2–3 million/yr since the early 1990s for research related to farm forestry;
- state government initiatives of varying scales to address a range of natural resource management issues (e.g. salinity, water quality) and stimulate uptake of commercial forestry on farmland (e.g. Farm Forestry Strategy for NSW, launched in 2003).

To help national programs take account of regional characteristics in forestry and numerous other sectors (e.g. natural resource management), the Commonwealth and state governments established and funded Regional Plantation Committees (RPCs) covering 17 forestry regions. The RPCs comprised representatives of regional interests (private and public organisations) and were authorised to facilitate and guide the development of forestry on private land (public forests remain under the sole authority of state governments). The RPCs were renamed Regional Private Forestry Development Committees (RPFDCs) in 2003 (National Forestry Inventory 2003).

Governments' broad intention to increase investment in private forestry is generally supported, but the detail on how policies should be implemented often remains contentious. For example, the conversion of degraded native forests to plantations, harvesting of private native forests and the water use of an expanding plantation estate remain highly contentious among some individuals, non-government organisations, industry bodies and different sections of government (Dargavel 1995; Coakes 1998; Williams *et al.* 2003).

Farm-based forestry: contention and agreement

Despite the support of many government agencies for forestry development, the potential benefits

promoted by forestry advocates are not always accepted by others. For example, some rural communities have claimed that industrial forestry affects a number of factors that support their quality of life (e.g. loss of farmland views, increased heavy transport, increased pest plants and animals, displacement of farm-based business) (Tonts *et al.* 2001; Schirmer 2002). Some people operating in other rural industries are concerned that forestry threatens their viability by reducing the availability of surface water and groundwater, and affordable land. Concerns about the expansion rate and type of forestry are usually voiced through local government (planning appeals process) and the media (Race *et al.* 2004). Agroforestry seeks to offer the farm-based forestry continuum an alternative to industrial plantations – the development of small-scale integrated plantings on family-owned farms, largely designed and managed by landholders themselves (Reid and Stephen 1999).

In general, the more forestry integrates with and supports current agricultural businesses, rather than displacing farming, the less likely it is that widespread community anxiety will arise (Tonts *et al.* 2001). However, this logic becomes complex when people have different interpretations of what type of forestry is supporting agriculture and what type is contrary to agriculture, or what type of forestry generates multiple benefits for landholders and the local community. The definition, design and management options for agroforestry discussed in this text encourage strategies that are integrated with agriculture and enhance our farming landscapes.

The current advice on using trees to ameliorate the effects of dryland salinity is that mapping and analysis of groundwater should occur at a localised level, so that strategies are targeted at specific at-risk areas rather than applied across the landscape (*Australian Forest Grower* 2004). Given the localised design and management of agroforestry, it offers the potential for accurate placement of trees in the landscape to achieve the desired control of dryland salinity. As such, agroforestry is likely to play an important role in the precision land use of Australia's farmland, whereby productive and sustainable solutions are developed at the necessary scale within target areas.

Interest in agroforestry

Farm-based forestry outside that of managed investment funds, such as agroforestry, involves a relatively large number of landholders (estimated at 3000–4000) with a relatively small total forest area (National Forest Inventory 2003). In many respects, agroforestry is different from forestry financed and managed by plantation management companies, reflecting their divergent goals (Reid and Stephen 1999). Agroforestry differs from industrial farm forestry in that it usually:

- is self-financed by the farm family;
- is designed by landholders;
- is of mixed species, predominantly native species;
- is primarily for environmental, shelter and aesthetic benefits;
- has a small proportion of trees selectively managed for high-quality sawn timber;
- includes an intention of selling in speculative profitable markets in the long term (Race and Fulton 1999).

During the 1990s, Commonwealth and state government support through personnel and funding galvanised interest in agroforestry in local interest groups linked to the national agroforestry network. Approximately 4000 landholders pay to receive the quarterly *Agroforestry News* newsletter. The Australian Forest Growers, a national association of small- and large-scale private forest growers, has 60% of its membership (700 members) registered as farm forestry or joint venture members. A larger number of small-scale tree growers have completed eight days of structured training through the Master Tree Grower Program coordinated by the University of Melbourne. Approximately 1500 landholders had completed the program, as of early 2007.

The emergence of farm-based forestry, in many forms on the agroforestry–industrial forestry continuum, has prompted the forestry profession to broaden its thinking about viable forestry and wider community expectations of forestry. As part of this change, farm forestry is now a prominent part of the curriculum at the three universities with undergraduate and post-graduate programs in forestry (Australian National University, University of Melbourne and Southern Cross University).

The growth of agroforestry has brought trees into farm landscapes previously considered unsuitable (e.g. medium-low rainfall areas), under different arrangements (e.g. public-private partnerships) and in search of multiple benefits (e.g. environmental services and commercial tree products). This has increased the challenges for professional foresters, agriculturalists and natural resource managers, and for the companies and agencies who provide strategic and technical advice to landholders.

The Joint Venture Agroforestry Program, managed by the Rural Industries Research and Development Corporation, state agencies and several Cooperative Research Centres have been funding research conducted by their own organisations, CSIRO, universities, private firms and landholder groups to help answer the myriad questions about agroforestry. While there is common agreement that Australia's low-rainfall farmland generally needs more trees, planted at a scale large enough to support a viable self-sustaining industry, uncertainty remains about the best approach for developing such an industry.

Socioeconomics of agroforestry in the wheat-sheep zone

It is widely believed that Australians must make considerable changes to the way we manage farmland in the low-medium rainfall area (400–700 mm/yr), also termed the wheat-sheep zone, in order to:

- move towards sustainable agriculture with new and improved enterprises;
- reduce rates of environmental degradation, for example by arresting dryland salinity;
- manage land-based greenhouse emissions and establish carbon sinks (AGO 2002).

Much of the 100 million ha of Australia's wheat-sheep zone, comprising the largest land use of the medium-low rainfall area, is widely believed to have been overcleared of native vegetation and is showing signs of environmental stress, particularly dryland salinity. The cost of revegetating this agroecological zone to arrest land degradation will far exceed the funds available through the Natural Heritage Trust – to date, the government's largest environmental rehabilitation program. Even the Commonwealth and state governments' \$1.4 bil-

lion seven-year National Action Plan for Salinity and Water Quality, launched in 2001, covered only a small portion of the full costs.

The nature, scale and rate of land use change required in the wheat-sheep zone to develop more sustainable farming systems, arrest land degradation and reduce greenhouse gases, will have important implications for regional communities and individual landholders (CSIRO *et al.* 2001). The opportunities for agroforestry, and the scales at which it is needed, are enormous.

Declining terms of trade for wheat-sheep regions

In terms of land area, cereal cropping (largely wheat production) and sheep farming (largely wool production) are the dominant land uses in Australia's low-medium rainfall (400–700 mm/yr) areas. Areas of irrigated agriculture (cotton, rice) and horticulture (fruit) occur within this agro-ecological zone but occupy far less area. Nevertheless they are highly valuable enterprises. Wheat-sheep farming and associated industries have been experiencing declining terms of trade over the last four decades, and have recently been affected by extended periods of drought. Wool has dropped more than five-fold in value to the nation's economy in real terms since its peak period in the 1950s, now contributing about 0.5% to national GDP (Australian Bureau of Statistics 2001).

Within the wheat-sheep zone, 50–80% of household income is dependent on farming. It is not surprising that there was a steady rate of population decline in this zone during the 1990s, with the median age of farmers increasing. Only 4% of Australia's workforce is employed in the agricultural sector but its importance is great in surrounding regional centres and rural towns, where 30–50% of the local workforce can be employed in the agricultural sector (Australian Bureau of Statistics 1998; Bureau of Rural Sciences 1999).

During the last few decades, grain prices have generally been steady with occasional peaks in market prices. However, wool prices have generally been depressed compared to historical returns; they are now starting to make a slow recovery with the increased economic activity of traditional customers in Asia, Europe and the former Soviet Union. Despite stronger world economic activity and increased consuming markets, retail demand for

wool remains subdued. However, some wool growers are successfully exploiting what many in the industry see as the best long-term chance to remain viable – to produce smaller volumes of high-value (superfine) wool for the luxury market. On such properties, tree-based enterprises need to be competitive with \$180–200/ha, or play a strong supporting role to sustain and improve wool production, if they are to be widely adopted by farmers.

Wheat-sheep producers and their dependent regional industries are unlikely to have sufficient financial reserves to establish agroforestry on any appreciable scale. Changes will require considerable finance from outside the regional economies. Regional economies that depend on wheat and wool have little capacity to self-finance major land use change even if there is an obvious comparative advantage or a pressing imperative, such as salinity in Western Australia's wheatbelt (CALM 2003).

Processing and viable farms

Regional processing is important for converting increased activity in primary production into regional prosperity. The addition and expansion of timber processing in the town of Oberon in New South Wales led to:

- increased economic activity for a range of local businesses;
- population growth due to improved employment opportunities;
- added employment opportunities for farming families;
- higher economic activity and population growth leading to improved health, educational and social services (Dwyer Leslie and Powell 1995).

General figures on profitability of farming in the wheat-sheep zone can disguise the great disparity between individual farming businesses. Many farms within this zone may have been operating marginal or unprofitable businesses in recent years, but most farms still generate a reasonable household income (ABARE 2007). Profitable wheat-sheep farms are characterised as having:

- larger farm sizes (>500 ha);
- lower financial debt;
- continual investment in upgrading technology, equipment or genetics;
- high-quality produce.

Young farmers (<40 years) with large farms (in size and business) and farmers who intend to pass their property on to the next generation, are most commonly associated with farm growth and size-able investment in long-term farm improvements (Tanewski *et al.* 2000). A typical strategy for other wheat-sheep farms is to increasingly gain off-farm income, thereby maintaining the household income. However, this option is only available on an appreciable scale near large regional or urban centres.

As discussed earlier, those with viable wheat-sheep enterprises are more likely to adopt agroforestry if it sustains or improves their current farming systems. That is, agroforestry is more likely to be adopted if it is integrated with wheat-sheep production, rather than replacing it (Race and Fulton 1999; Tonts *et al.* 2001). However, the majority of farmers in the low-medium rainfall zone with unprofitable wheat-sheep farms do not have sufficient finance to invest in widespread land use change, even if change is demonstrably prudent. They may be attracted by agroforestry that provides annuity payments (regular and reliable income) or provides them with the opportunity to sell, and leave agriculture. Many such farmers appear to be deferring their exit from agriculture until wool prices improve so that their farm can be sold at a reasonable price, to afford other opportunities or support their retirement.

If viable agroforestry industries are to develop, a clear understanding of the socio-economic context of landholders and rural communities is required (which regions, which farmers within regions). Regionally specific investigations are also required, that will:

- identify important market specifications;
- develop a process for obtaining and updating market information;
- identify suitable joint venture options;
- assess establishment, management and harvesting costs;
- develop forward marketing opportunities;
- assess the most appropriate mediums for disseminating information to stakeholders.

Earlier research (Curtis and Race 1998) suggested that key principles for effective and mutually beneficial links between small-scale growers and industry include:

- identifying and developing competitive regional agroforestry markets;
- establishing processes that identify and effectively communicate credible information so that stakeholders can make informed decisions;
- industry demonstrating that it is acting in good faith, with growers receiving a fair share of agroforestry profits;
- industry demonstrating a long-term commitment to agroforestry, with infrastructure for processing and/or funding of field staff;
- agroforestry stakeholders being able to negotiate or choose from a range of grower-industry arrangements.

Which landholders might adopt agroforestry

Understanding the socio-economic factors affecting landholders can assist industry and government to identify the landholders most likely to adopt agroforestry. This can make extension, research and development more effective and efficient, and so improve the investment made by industry and government in working with landholders to develop appropriate and viable agroforestry enterprises.

In Australia, the nature of agroforestry (integrating forestry with agriculture) will require most landholders to alter their farming practices (Cernea 1991). Encouraging behavioural change by landholders is often a complex and long-term task, particularly if relying upon voluntary adoption. If new enterprises, such as agroforestry, are expensive, unproven, complicated or contrary to accepted farming ways, adoption of new technologies can be lower than anticipated (Vanclay and Lawrence 1995). Efforts to encourage behavioural change need to address the underlying reasons of why landholders are cautious, unwilling or unable to adopt agroforestry.

Farming communities are typically familiar with timber management for on-farm use, but there are few farming communities in Australia with a strong cultural history of commercial farm-based timber production. Hence, developing agroforestry industries will require industry and government to work out effective communication approaches, as well as address education and skills training, offer financial support, develop marketing arrangements

BOX 19.1

Ingredients for viable agroforestry industries in medium-low rainfall Australia

Wheat-sheep industries and their dependent economies generally lack the necessary finance to invest in profound changes in land use and processing. Finance will have to come from outside the regions. Taxation incentives can be a powerful mechanism for attracting outside investment into a region.

Best-bet regions and industries need to be identified, so that government support for investment can focus on those with a reasonable chance of becoming self-funding or with sufficient community support for ongoing public investment. This includes a need for full environmental, economic and social appraisals.

Rehabilitating saline land is relatively expensive and saline land is unlikely to be useful for growing dynamic trees that will contribute to carbon sinks and have the potential to yield commercial products. However, land that is at risk or at low risk of salinity may be able to support viable long-term agroforestry industries.

Localised processing is important for a range of socio-economic benefits, but if agroforestry industries are to be fully commercial then operations may best be located where business clusters are emerging.

There is a role for government to initiate and nurture innovative industries that have the potential to deliver a range of environmental and socio-economic benefits. However, mixing government support with market opportunities is complex. It is vital to be aware of the effects of government support on the opportunity costs of existing enterprises in that region and neighbouring regions.

Agroforestry enterprises will need to be cost-efficient and price-competitive compared to high-quality wheat and wool, and increased specialist labour (equipment handling and repair, market agent/broker) and mechanisation are likely to be important factors.

Considerable financial injections may be needed to underpin the establishment of agroforestry, sooner rather than later, if there is to be a cost structure that will appeal to the majority of wheat-sheep farmers, who have little financial reserves.

Regions and landholders that offer the best potential have:

- sufficient land, labour or capital to invest in new enterprises/industries;
- productive natural resources, such as suitable soils and rainfall;
- good economies of scale in a given location to allow efficient production for themselves or clusters;
- accessibility with current infrastructure (rail or road);
- low operating and harvesting costs;
- close proximity to processing facilities;

- access to competitive markets for a range of products/services (avoid relying on a single market);
- highly valued assets or natural resources that are threatened by degradation, such as dryland salinity;
- opportunities for integrating agroforestry with current farming enterprises, rather than replacing agriculture.

Source: Adapted from CSIRO *et al.* (2001).

and provide infrastructure. The changing composition of rural communities and the way new landholders manage farmland is another challenge for agencies, particularly those developing policies and programs to encourage agroforestry. The economic incentives for managing farmland do not have the same appeal, particularly for landholders who don't see themselves as farmers. Understanding the willingness and capacity of landholders to adopt agroforestry can be complex, with research across other disciplines indicating that many factors are involved (Vanclay 2004, Pannell *et al.* 2006).

Supporting agroforestry adoption: putting trees on Australian farms

People view 'successful' agroforestry through different eyes, so simplistic assumptions about what model of agroforestry landholders will adopt must be avoided (Race *et al.* 1998; Herbohn *et al.* 2000; Bliss 2001). It is naïve to think that a single extension approach will suit all landholders, and there are not enough resources to provide comprehensive one-to-one extension support for every landholder interested in agroforestry. The challenge is to design and deliver an extension package that effectively and efficiently integrates a mix of approaches, while taking account of the opportunities and issues for a region and for individual landholders. Creating an effective extension package for landholders draws on the transdisciplinary nature of adult education and community development, incorporating elements of communication, facilitation, education and building social capacity (Cernea 1991).

Models of extension

To summarise from a large and expanding body of literature on extension, there are four broad

approaches used to support agroforestry in Australia:

- 1 linear transfer of technology;
- 2 participatory local discussion groups, including participatory research;
- 3 one-to-one advisory service;
- 4 structured education and training.

Rather than accepting a single approach, most agree that there is a role – often a necessity – for a suite or package of all these approaches if agroforestry is to meet the complexities of development. Participatory 'farmer-first' (or 'treegrower-first') extension approaches have grown in popularity worldwide (Chambers 1997) but these should not necessarily be used to the exclusion of other approaches (Race 2002). Furthermore, when there is an overwhelming imperative for land use change over a short period (e.g. addressing sites with critical land or water problems), a comprehensive extension package may need to be accompanied by financial incentives and regulatory controls (Pannell *et al.* 2006).

Technology transfer

The transfer of technological innovations from scientist to farmers (technology transfer) has a long history in Australian agriculture and remains highly relevant, particularly where landholders are seeking to update an established practice, such as adopting the latest crop variety or a newer version of familiar machinery. However, more complex challenges, such as how best to incorporate commercial trees with existing farming operations, may require more than simply the transfer of technology. For instance, viable agroforestry systems may require a package of extension approaches, where technological advice is complemented with

BOX 19.2**Factors affecting landholders' adoption of new practices**

- The links that landholders have with others, such as their engagement in local networks and organisations, proximity to other adopters and the source of information, trusted relationship between landholder and promoter of innovation.
- The demographic attributes of landholders, such as their reliance on off-farm income and their age.
- The relative advantage of new practices, such as improved viability of the business or system, its impact on other aspects of farm business and lifestyle and its consistency with the landholders' lifestyle, beliefs and values.
- The ease of trialling a new practice, including the complexity of innovation, costs and risks of innovation and familiarity of innovation.

Source: Adapted from Pannell *et al.* (2006).

farmer-led research and participation in structured training programs.

When technology transfer is driven by the advocates of change rather than by the needs of farmers, it is sometimes referred to as 'top-down' extension. The common view is that top-down extension can be ineffective. Black (2000, p. 493) explained that the linear top-down approach to extension was based on 'the assumption that new agricultural technologies and knowledge are typically developed and validated by research scientists, and that the task of extension agencies is to promote the

adoption of these technologies by farmers, thereby increasing agricultural productivity'.

The paradigm of technology transfer has evolved beyond the perception that advisers should focus on farmers who are considered early adopters or progressive (Rogers 1983). It should be more precise when linking specific technologies or initiatives to the target group of landholders.

Formerly, farmers who were slow to adopt new practices ('laggards') were disparagingly believed to be personally inadequate and almost undeserving of the benefits of new technology, even though

BOX 19.3**Extension**

Before exploring the range of extension approaches used in rural Australia, it is important to clarify what is meant by 'extension'. In the context of this book, van den Ban and Hawkins' (1996, p. 9) definition appears relevant: 'extension involves the conscious use of communication and information to help people form sound opinions and make good decisions'. The Australasia Pacific Extension Network explains that extension is the 'use of communication and adult education processes to help people and communities identify potential improvements to their practices, then provide them with the skills and resources to effect these improvements' (APEN 1999, in Black 2000, p. 493). Extension is more than simply providing information or slick advertising. It implies a genuine commitment to assisting people make informed decisions (Scoones and Thompson 1994).

such practices might be unproven, expensive, risky, difficult to integrate with existing enterprises or contrary to the farmers' values (Vanclay and Lawrence 1995). Röling (1988) cautioned that top-down extension can reinforce social inequalities within farming communities, as those who benefit most tend to have greater financial and capital resources. During the early 1990s, when some of the more substantive changes in forestry began to take effect, such as the emergence of farm-based forestry, critical thinking about forestry extension for farmers emerged (Reid 1996; Race and Fulton 1999; Reid and Stephen 1999; Black *et al.* 2000).

Participatory local discussion groups

During the 1980s, agricultural extension in Australia and elsewhere underwent a profound change, incorporating a variety of participatory approaches to extension. Drawing on wide experience in international rural development, Chambers *et al.* (1989), Pretty (1995) and others heralded a new era of farmer-first extension. In Australia, this found expression most visibly in the Victorian and subsequently National Landcare Programs – an agenda based on strengthening community–government partnerships to address environmental degradation on private farmland, operating at a local catchment (watershed) scale. Today, the Landcare network with its 4500 groups and nearly 40 000 members is one of Australia's most powerful vehicles for extension within rural communities. It is not, however, without challenges, such as how to maintain landholder engagement (Pannell *et al.* 2006).

Agroforestry emerged in Australia in parallel with, and as a close ally of, Landcare, with a shared goal to increase the integration of trees with farming. Again, first in Victoria in the early 1990s then nationally, Regional Agroforestry Networks provided a social structure for group-oriented extension whereby local groups of landholders could receive government support (administrative assistance, newsletters, information via field days) to explore local opportunities for agroforestry. Regional networks recognise the mix of influences on a forest grower's decision-making, such as the views of family members, other growers and neighbours, government programs and industry incentives, and the latest research findings (Hajek 2001).

Participatory discussion groups implicitly recognise that farming communities are rich in knowledge and practical skills which are valuable even with complex and untested enterprises, such as agroforestry. Such groups acknowledge the value of landholders sharing ideas and information, rather than relying on technical information or management advice from outside the group (Carr 1997; Cary and Webb 2000). Participatory discussion groups intend members to take ownership of problems and solutions, creating viable agroforestry systems that are adapted to the local context rather than simply following generic recipes from elsewhere in Australia (Reid and Stephen 1999).

Landholders can have different perspectives from those in the formal scientific community, towards situation analysis, monitoring progress and change, conducting and adapting research (Millar 1997). Their perspectives are equally legitimate. It is important to discuss and clarify, from the outset, what group members and the extension agent understand by 'participation'. Failure to reach a common understanding of a 'participatory discussion group' can undermine the process that the extension agent is trying to establish (Race and Buchy 2001). It is also vital to clarify whether increased participation by a range of stakeholders in agroforestry extension reflects a genuine change in philosophy, or whether it is simply a strategy to see landholders adopt a prescribed model of agroforestry.

Black (2000, p. 496) cautioned that participatory group extension has limitations:

While participatory and group-based approaches to agricultural extension have various advantages when well implemented, they should not be regarded as the one and only strategy that can or should be used to facilitate the adoption of sustainable farming systems. Belief in a 'participation fix' may be just as naïve as belief in a 'technology fix'.

Also, local community groups largely rely on consensus and so can underestimate or ignore the diversity – and sometimes the considerable differences – in local communities. That is, landholders vary considerably in their socio-economic characteristics and interests, so presumably will vary in the extent to which participatory group-based learning suits their style of learning and local situation (Vanclay and Lawrence 1995). For example, if

a landholder develops an innovative approach to agroforestry which is of little interest to other members of the group, there may be little reason for the landholder to remain an active member of the local discussion group.

One-to-one advisory service

During recent decades the one-to-one advisory service provided by state agricultural agencies has generally declined, with the perception that group-based extension is more efficient or that farmers should pay directly for one-to-one extension that is exclusively focused on private enterprise. However, where the technical advice relates to agroforestry that is likely to generate off-farm benefits, such as where agroforestry acts to control catchment-wide salinity or enhance biodiversity conservation, many argue that governments still have a responsibility to contribute to one-to-one extension. In recognition of the public benefits inherent in many aspects of agroforestry, the Commonwealth and state governments now support a range of farm forestry research and development initiatives, as discussed earlier (Race and Robins 1998). While one-to-one extension does occur through these initiatives (e.g. the Subtropical Farm Forestry Association conducts individual site visits; Novak 2001), the most common extension approach is through local participatory discussion groups such as Landcare groups, Regional Agroforestry Networks or chapters of the Australian Forest Growers.

In parallel with various government forestry initiatives, there has been a rapid expansion of plantations financed by private prospectus and investment companies, most notably with blue gum (*Eucalyptus globulus*) for pulpwood in Tasmania, South Australia, Victoria and Western Australia. It is rare for farmers to be the principal silviculturist in partnership with forestry investment companies. Their responsibilities usually focus on maintaining firebreaks and controlling pest plants and animals (Curtis and Race 1998). Independent forest growers rely on a mix of extension approaches – one-to-one consultations with selected advisers (private consultants, industry representatives, government planners), involvement with local discussion groups and technology transfer of relevant research results or regulatory

information – with their level of use corresponding to their investment in forestry.

Structured education and training

Most farmers are reluctant to undertake formal, long-term educational courses such as those offered by universities (Black 2000), but the opposite applies for agricultural and forestry graduates employed as professionals. The Master Tree Grower program, discussed above, facilitates a structured approach to participatory group-based learning for farmers with a strong interest in farm forestry. Reflecting on why the Master Tree Grower program appealed to landholders, Stephen and Reid (2001) reasoned that the program:

- increased the skills and expertise of landholders;
- encouraged landholders (as growers) to take an active role in farm forestry;
- linked the many forestry stakeholders at the regional level.

There are popular structured accredited courses that improve the critical thinking and knowledge base of extension workers and enhance career prospects. The courses that meet the needs of forestry extension workers are those that analyse contemporary issues, focus on workplace problems and solutions, offer flexible delivery (time and location) and encourage participation.

Extension agents

In addition to Commonwealth and state government programs supporting farm forestry, there are non-government organisations, such as Greening Australia, that have a farm forestry extension service (Race and Robins 1998). These draw on the work of the Australian Tree Seed Centre and Australian Low Rainfall Tree Improvement Group for their extension information (Vercoe *et al.* 2001).

The general approach to extension largely relies on strengthening local partnerships between growers and industry, one-to-one support for farmers establishing demonstration sites, organising field days and seminars, generating articles for newsletters and media outlets, and occasionally producing CD-ROMs (Private Forestry Tasmania's *Farm Forestry Toolbox*; Agriculture Western Australia's *Agro-*

forestry Calculator). There is an emphasis on using a wide range of communication tools and media. Some communication technology, such as the internet, is likely to be of limited value to farmers for some time, as only 20% of Australian farmers have reliable access to the internet (Black 2000). Recently, farmers with considerable agroforestry experience are themselves providing extension services, as individual consultants or as part of a group's extension package (e.g. as offered by the Otway Agroforestry Network, Victoria).

Moore *et al.* (2001), formerly from the Western Australian Farm Forestry Unit, aimed to provide an extension package that allows landholders to learn and innovate with forestry on their own terms. Others have incorporated a similar mix of extension ingredients into a 'participatory holistic approach aimed at empowerment of all involved' (Novak 2001, p. 322). This strategy for agroforestry extension is focused on designing a meaningful process for co-learning, not prescribing the biological composition or silvicultural management of agroforestry. If the aim of agroforestry extension is to encourage landholders to make informed decisions, then it may be of little importance to the design of an extension package whether growers are interested in large-scale plantations, small-scale mixed species timber belts or private native forests.

Maintaining the mix of organisations using a wide range of approaches to extension is not only realistic but preferable, if agroforestry is to benefit from its diversity of stakeholders. In reality, rural landholders are increasingly a heterogeneous group of people even across Australia's wheat-sheep zone, with clear indications that their interest in agroforestry is for diverse objectives (Wilson *et al.* 1995). Landholders seek information from organisations and people whom they perceive can provide credible, feasible, reliable and relevant advice. Even when seeking information and advice from outsiders, they invariably verify it through in-depth discussions with local farmers and advisers. Informal networking among locals is an important stage in developing an agroforestry enterprise that is tailored to a particular context.

There is a high correlation between landholders who have adopted new approaches to farming and their:

- participation in different extension activities;
- contact with extension workers;
- trialling, adaptation and subsequent development that is done incrementally, while communicating with others in a similar context (Röling and Wagemakers 1998).

International experiences and lessons

At an international level, there is a wealth of extension experience in the agricultural and forestry sectors. It is impossible to summarise the breadth of this experience in this chapter, but some of the more valuable ideas are outlined below (Chambers *et al.* 1989; Anderson and Farrington 1996; McKinley *et al.* 1996). Extension support for agroforestry tends to be effective when it:

- follows an analysis of the landholder's context and information needs;
- applies a mix of, and emphasis on, approaches most appropriate to the landholder's learning style;
- builds on local expertise, networks and institutions rather than displaces them;
- accepts that it is as much about listening to individuals and communities as it is about providing information that is easily understood;
- links information from a range of organisations that is credible, reliable and locally relevant;
- acknowledges that agroforestry and its stakeholders exist within a wider context comprising a range of social, economic and environmental imperatives;
- reflects and adapts its approach based on perceptive monitoring and evaluation.

There are many ways to evaluate agroforestry extension. The checklist in Box 19.4 may be a useful way to begin assessing the different levels at which an extension program operates.

Conclusion

In many respects, landholders interested in agroforestry are pioneering a new approach to forestry and agriculture, in search of a productive and sustainable nexus between two otherwise divergent

BOX 19.4**Elements for assessing an extension approach**

- Design of the extension package, for example value of individual activities, mix and sequence of activities, links with other programs.
- Implementation of extension package, for example how and who is involved, quality of service.
- Participation in extension activities by landholders, for example type and extent of participation.
- Landholders' perception of the extension package, for example value of overall and individual activities, aspects for improvement.
- Changes in knowledge, attitude, skills, motivation and confidence by landholders involved in extension package.
- Behavioural changes among landholders involved in extension package.
- Generation of community outcomes of widespread adoption of agroforestry.
- Generation of catchment management outcomes of widespread adoption of agroforestry.

disciplines. Understanding who has established, or is likely to establish, agroforestry enterprises is a challenge for agencies that want it to become a widespread land use, particularly among landholders with farmland facing the risks of dryland salinity. This chapter discussed the:

- complexities of agroforestry for landholders, such as the management of tree-based enterprises outside the traditional regions and paradigms of forestry;
- origins of the interest in agroforestry in Australia;
- increasing diversity among landholders and regions;
- policy context for government support of agroforestry;
- why community support for tree-based industries is not assured;
- organisations and initiatives that support agroforestry;
- socio-economic context of landholders in the wheat-sheep zone;
- landholders most likely to adopt agroforestry, and their decision-making processes;
- extension approaches that support the adoption of agroforestry.

Agroforestry in Australia has moved well beyond being viewed as a potential industry for wood-based products. In line with the broad definition of agroforestry offered in this text, there is no single way to incorporate trees into the farming landscape and no single recipe for landholders to follow. In many regions agroforestry is still in a developmental stage, but it is one of the most exciting options for:

- arresting land degradation;
- supporting existing farm enterprises and offering scope for new enterprises;
- generating considerable off-farm benefits for catchments and communities.

Ultimately, the emergence of self-sustaining regional agroforestry industries will largely depend on how well we support, nurture and learn from today's pioneers – the current practitioners of agroforestry.

References

ABARE (2007) *Australian Farm Survey Results 2004–05 to 2006–07*. Australian Bureau of Agricultural and Resource Economics, Canberra.

- ABS (1998) *Australian Social Trends*. Australian Bureau of Statistics, Canberra.
- ABS (2001) *Year Book Australia*. Australian Bureau of Statistics, Canberra.
- AGO (2002) *Greenhouse Gas Emissions from Land Use Change in Australia: An Integrated Application of the National Carbon Accounting System*. Australian Greenhouse Office, Department of the Environment and Water Resources, Canberra.
- Anderson J and Farrington J (1996) Forestry extension: facing the challenges of today and tomorrow. *Unasylva* 41(184), 3–12.
- Australian Forest Grower* (2004) Australian Forest Growers, Canberra.
- Black A (2002) Extension theory and practice: a review. *Australian Journal of Experimental Agriculture* 40, 493–502.
- Black AW, Forge K and Frost F (2000) 'Extension and advisory strategies for agroforestry'. Joint Venture Agroforestry Program, Rural Industries Research and Development Corporation, Canberra. RIRDC Publication no. 00/184.
- Bliss JC (2001) Extension and the future of family forests: making connections. In *Forestry Extension: Assisting Forest Owner, Farmer and Stakeholder Decision-making. Proceedings of IUFRO Extension Working Party (S6.06–03)*. Lorne, Vic. (Eds D Race and R Reid).
- Brand DG, Roberts RW and Kemp R (1993) International initiatives to achieve sustainable management of forests: Canada's model forests, the Commonwealth Forestry Initiative, and the development assistance community. *Commonwealth Forestry Review* 72(4), 297–302.
- BRS (2004) *Australia's Forests at a Glance 2004*. National Forest Inventory, Bureau of Rural Sciences, Department of Agriculture, Fisheries and Forestry, Canberra.
- Buchy M and Race D (2001) The twists and turns of community participation in natural resource management in Australia: what is missing? *Journal of Environmental Planning and Management* 44(3), 293–308.
- Buck L (1995) Agroforestry policy issues and research directions in the US and less developed countries: insights and challenges from recent experience. *Agroforestry Systems* 30(1/2), 57.
- Campbell A (1997) Facilitating landcare: conceptual and practical dilemmas. In *Critical Landcare*. (Eds S Lockie and F Vanclay). Centre for Rural Social Research, Charles Sturt University, Wagga Wagga.
- Carr A (1997) Innovation of diffusion: landcare and information exchange. In *Critical Landcare*. (Eds S Lockie and F Vanclay). Centre for Rural Social Research, Charles Sturt University, Wagga Wagga.
- Carr A (2002) *Grass Roots and Green Tape: Principles and Practices of Environmental Stewardship*. Federation Press, Sydney.
- Cary J and Webb T (2000) *Community Landcare, the National Landcare Program and the Landcare Movement: The Social Dimensions of Landcare*. Bureau of Rural Sciences, Department of Agriculture, Fisheries and Forestry, Canberra.
- Centre for International Economics, AACM International and Forestry Technical Services (1996) *Contribution of Farm Forestry to Australia: A Quantitative Assessment*. Rural Industries Research and Development Corporation, Canberra.
- Cernea MM (1991) *Putting People First: Sociological Variables in Rural Development*. 2nd edn. Oxford University Press, Washington DC.
- Chambers R (1997) *Whose Realities Count? Putting the First Last*. Intermediate Technology Publications, London.
- Chambers R, Pacey A and Thrupp L (Eds) (1989) *Farmer First: Farmer Innovation and Agricultural Research*. Intermediate Technology Publications, London.
- Clark J (1995) *Australia's Plantations: Industry, Employment, Environment*. Victorian Conservation Council, Melbourne.
- Coakes S (1998) Valuing the social dimension: social assessment in the Regional Forest Agreement process. *Australian Journal of Environmental Management* 5(1), 47–54.
- Commonwealth of Australia (1995) *Wood and Paper Industries Strategy: A Discussion Paper*. Department of Industries, Science and Technology, Canberra.
- CSIRO Land & Water, ANU Forestry, RIRDC and Associates (2001) 'The contribution of mid to low-rainfall forestry and agroforestry to greenhouse and natural resource management outcomes: overview and analysis of opportunities'. Report prepared for Australian Greenhouse

- Office and Murray-Darling Basin Commission, Canberra.
- Curtis A and Race D (1998) 'Links between farm forestry growers and the wood processing industry: lessons from the Green Triangle, Tasmania and Western Australia'. Rural Industries Research and Development Corporation, Canberra. RIRDC Publication no. 98/41.
- Dabbert S (1995) Agroforestry and landuse change in industrialised nations: a case study from northeastern Germany. *Agroforestry Systems* **31**, 157–168.
- Dargavel J (1995) *Fashioning Australia's Forests*. Oxford University Press, Melbourne.
- Dupraz C and Newman SM (1997) Temperate agroforestry: the European way. In *Temperate Agroforestry Systems*. (Eds AM Gordon and SM Newman) pp. 181–236. CAB International, Wallingford, UK.
- Dwyer Leslie Pty Ltd and Powell R (1995) *Oberon Rural Community Development Study*. Dwyer Leslie Consultants, Sydney.
- FAO (1997) *Pluralism and Sustainable Forestry and Rural Development. Proceedings of an International Workshop*. December. Food and Agriculture Organisation, Rome.
- Ferguson IS (1996) *Sustainable Forest Management*. Oxford University Press, Melbourne.
- Garrity D (2006) *World Agroforestry into the Future*. World Agroforestry Centre, Nairobi.
- Gordon AM and Newman SM (Eds) (1997) *Temperate Agroforestry Systems*. CAB International, Wallingford, UK.
- Grayson AJ (1993) *Private Forestry Policy in Western Europe*. CAB International, Wallingford, UK.
- Grundy D (1997) Developing forest policy in the UK. *Commonwealth Forestry Review* **76**(1), 5–10.
- Guijt I and Race D (1998) *Growing Successfully: Australian Experiences with Farm Forestry*. Greening Australia, Canberra.
- Haberkorn G, Hugo G, Fisher M and Aylward R (1999) *Country Matters: Social Atlas of Rural and Regional Australia*. Bureau of Rural Sciences, Department of Agriculture, Fisheries and Forestry, Canberra.
- Hajek CF (2001) Sowing the seeds for change: the use of networks to amplify extension programs. In *Forestry Extension: Assisting Forest Owner, Farmer and Stakeholder Decision-making. Proceedings of IUFRO Extension Working Party (S6.06–03)*. Lorne, Vic. (Eds D Race and R Reid).
- Hawke MF and Knowles RL (1997) Temperate agroforestry systems in New Zealand. In *Temperate Agroforestry Systems*. (Eds AM Gordon and SM Newman). CAB International, Wallingford, UK.
- Herbohn JL and Harrison SR (2004) The evolving nature of small scale forestry in Australia. *Journal of Forestry* **102**(1), 42–47.
- Herbohn KF, Harrison SR and Herbohn JL (2000) Lessons from small-scale forestry initiatives in Australia: the effective integration of environmental and commercial values. *Forest Ecology and Management* **128**, 227–240.
- Herbohn JL, Emtage NF, Harrison SR and Smorfit DB (2005) Attitudes of landholders to farm forestry in tropical eastern Australia. *Australian Forestry* **68**(1), 50–58.
- Humphreys D (1996) *Forest Politics: The Evolution of International Cooperation*. Earthscan Publications, London.
- Kanowski PJ (1995) The complex future of plantation forestry. In *Eucalypt Plantations: Improving Fibre Yield and Quality. Proceedings of IUFRO Conference*. CRC for Temperate Hardwood Forestry, Hobart.
- Kanowski PJ (1996) Australian forestry in transition: towards our brave new world. In *Farm Forestry and Plantations: Investing in Future Wood Supply. Proceedings of the National Conference of the Australian Forest Growers*. Australian Forest Growers, Canberra.
- Mather A (1993) *Afforestation: Policies, Planning and Progress*. Belhaven Press, London.
- McDonald GT (1993) Reafforestation in Australia. In *Afforestation: Policies, Planning and Progress*. (Ed. A Mather). Belhaven Press, London.
- MCFFA, Standing Committee on Forestry, Plantations Australia, Australian Forest Growers and National Association of Forest Industries (1997) *Plantations for Australia: The 2020 Vision*. Department of Primary Industries and Energy, Canberra.
- McKinley CR, Sidebottom JR and Owen JH (1996) The process of forestry extension education:

- speciality tree production in North Carolina, United States. *Unasylva* **184**, 38–43.
- Millar J (1997) The role of farmer knowledge in developing temperate pasture and grazing systems. PhD thesis. Charles Sturt University, Albury, NSW.
- Moore RW and Bird PR (1997) Agroforestry systems in temperate Australia. In *Temperate Agroforestry Systems*. (Eds AM Gordon and SM Newman) pp. 119–148. CAB International, Wallingford, UK.
- Moore R, Jenkins D, Hingston B and Batty G (2001) Putting together the total package: farm forestry extension in Western Australia. In *Forestry Extension: Assisting Forest Owner, Farmer and Stakeholder Decision-making. Proceedings of IUFRO Extension Working Party (S6.06–03)*. Lorne, Vic. (Eds D Race and R Reid).
- Murray-Darling Basin Ministerial Council (2001) *Integrated Catchment Management in the Murray-Darling Basin 2001–2010: Delivering a Sustainable Future*. Murray-Darling Basin Commission, Canberra.
- Myers N (1996) The world's forests: problems and potentials. *Environmental Conservation* **23**, 156–168.
- National Forest Inventory (2003) *Australia's State of the Forests Report 2003*. Bureau of Rural Sciences, Canberra.
- National Forest Policy Statement: A New Focus for Australia's Forests (1992) Department of Agriculture, Fisheries and Forests, Canberra.
- National Plantations Advisory Committee (1991) *Integrating Forestry and Farming: Commercial Wood Production on Cleared Agricultural Land. Appendix A*. Report for the Department of Primary Industries and Energy, Canberra.
- National Strategy for Low Rainfall Farm Forestry in Australia National Farm Forestry Roundtable (2000) December. Department of Agriculture, Fisheries and Forests, Canberra.
- Novak M (2001) Participatory extension by Subtropical Farm Forestry Association: for smaller tree growers, by these growers, with all stakeholders. In *Forestry Extension: Assisting Forest Owner, Farmer and Stakeholder Decision-making. Proceedings of IUFRO Extension Working Party (S6.06–03)*. Lorne, Vic. (Eds D Race and R Reid).
- Pannell D, Marshall G, Barr N, Curtis A, Vanclay F and Wilkinson R (2006) Understanding and promoting the adoption of conservation technologies by rural landholders. *Australian Journal of Experimental Agriculture* **46**(11), 1407–1424.
- Parsons M, Gavram M and Davidson J (2006) *Australia's Plantations 2006*. Bureau of Rural Sciences, Canberra.
- Pearse PH (1994) Farm forestry and agricultural adjustment: opportunities and policy implications. *Organisation for Economic Cooperation and Development Workshop on Forestry, Agriculture and the Environment*. Madrid, Spain. Unpublished summary.
- Plantation 2020 Vision Implementation Committee (1997) *Plantations for Australia: The 2020 Vision*. Department of Primary Industries and Energy, Canberra.
- Pretty JN (1995) *Regenerating Agriculture: Policies and Practices for Sustainability and Self-reliance*. Earthscan Publications, London.
- Race D (2002) Has extension changed to match Australia's dynamic forestry landscape? *Rural Society* **12**(2), 148–159.
- Race D and Buchy M (2001) The twists and turns of community participation in natural resource management in Australia: what is missing? *Journal of Environmental Planning and Management* **44**(3), 293–308.
- Race D and Fulton A (1999) 'Farm forestry in Australia: understanding landholders' decision to adopt'. CRC for Sustainable Production Forestry, Hobart, Tas. Technical Report 19.
- Race D and Robins L (1998) 'Farm forestry in Australia: research and policy update'. Report for SCF's Research Working Group 11 (Farm Forestry) and Rural Industries Research and Development Corporation, Canberra.
- Race D, Guijt I and Kanowski P (1998) Farm forestry: lessons from Australian experiences. *Environmental Conservation* **25**(3), 234–243.
- Race D, Schirmer J and Bail I (2004) 'Company responses to community concerns about plantation expansion: lessons from industrial partners'. CRC for Sustainable Production Forestry, Hobart, Tas. Technical Report 138.
- Reid R (1996) The diagnosis and design of farm forestry systems for Australian landowners

- and farmers. Paper presented to *Outlook '96 Conference*. Canberra, ACT. Australian Bureau Agricultural and Resource Economics.
- Reid R and Stephen P (1999) *The Farmer's Log, 1999*. Department of Forestry, University of Melbourne, Australia.
- Rogers EM (1983) *Diffusions of Innovations*. 3rd edn. Free Press, New York.
- Röling N (1988) *Extension Science: Information Systems in Agricultural Development*. Cambridge University Press, Cambridge.
- Röling NG and Wagemakers MAE (1998) *Facilitating Sustainable Agriculture: Participatory Learning and Adaptive Management in Times of Environmental Uncertainty*. Cambridge University Press, Cambridge.
- Sargent C (1992) Natural forest or plantation? In *Plantation Politics: Forest Plantations in Development*. (Eds C Sargent and S Bass) pp. 16–40. Earthscan, London.
- Schirmer J (2002) 'Plantation forestry disputes: case studies on concerns, causes, processes and paths toward resolution'. CRC for Sustainable Production Management, University of Melbourne, Australia. CRC Technical Report no. 42 (rev.).
- Scoones I and Thompson J (Eds) (1994) *Beyond Farmer First: Rural People's Knowledge, Agricultural Research and Extension Practice*. Intermediate Technology Publications, London.
- Stephen P and Reid R (2001) Innovations in forestry teaching and learning. In *Forestry Extension: Assisting Forest Owner, Farmer and Stakeholder Decision-making. Proceedings of IUFRO Extension Working Party (S6.06–03)*. Lorne, Vic. (Eds D Race and R Reid).
- Tanewski GA, Romano CA and Smyrnios KX (2000) *Determinants of Australian Family Farm Growth: The Role of Owner Characteristics and Strategic Planning*. Rural Industries Research and Development Corporation, Canberra.
- Tonts M, Campbell C and Black A (2001) 'Socio-economic implications of farm forestry'. Rural Industries Research and Development Corporation, Canberra. RIRDC Report no. R01/045.
- Turner J, Wareing K, Flinn D and Lambert M (2004) *Forestry in the Agricultural Landscape: A Review of the Science of Plantation Forestry in Victoria*. Department of Primary Industries, Melbourne.
- Vanclay F (2004) Social principles for agricultural extension to assist in the promotion of natural resource management. *Australian Journal of Experimental Agriculture* 44(3), 213–222.
- Vanclay F and Lawrence G (1995) *The Environmental Imperative: Eco-social Concerns for Australian Agriculture*. Central Queensland University Press, Rockhampton, Qld.
- van den Ban AW and Hawkins HD (1996) *Agricultural Extension*. 2nd edn. Blackwell Science, Massachusetts.
- Vercoe T, Arnold R and Bush D (2001) Seed and information support for farm forestry: farmers as researchers. In *Forestry Extension: Assisting Forest Owner, Farmer and Stakeholder Decision-making. Proceedings of IUFRO Extension Working Party (S6.06–03)*. Lorne, Vic. (Eds D Race and R Reid).
- Williams PA, Gordon AM, Garret HE and Buck L (1997) Agroforestry in North America and its role in farming systems. In *Temperate Agroforestry Systems*. (Eds AM Gordon and SM Newman) pp. 9–84. CAB International, Wallingford, UK.
- Williams K, Nettle R and Petheram RJ (2003) Public response to plantation forestry on farms in south-western Victoria. *Australian Forestry* 66, 93–99.
- Wilson SM, Whitham JAH, Bhati UN, Horvath D and Tran Y (1995) 'Trees on farms: survey of trees on Australian farms 1993–94'. Australian Bureau Agricultural and Resource Economics, Canberra. Research Report no. 95.7.
- Wood MS, Stephens NC, Allison BK and Howell CI (2001) 'Plantations of Australia: a report from the National Plantation Inventory and the National Farm Forest Inventory'. National Forest Inventory, Bureau of Rural Sciences, Canberra.
- Wu Y and Zhu Z (1997) Temperate agroforestry in China. In *Temperate Agroforestry Systems*. (Eds AM Gordon and SM Newman) pp. 149–179. CAB International, Wallingford, UK.

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