TAKAO FUJIMORI

Ecological and Silvicultural Strategies for Sustainable Forest Management

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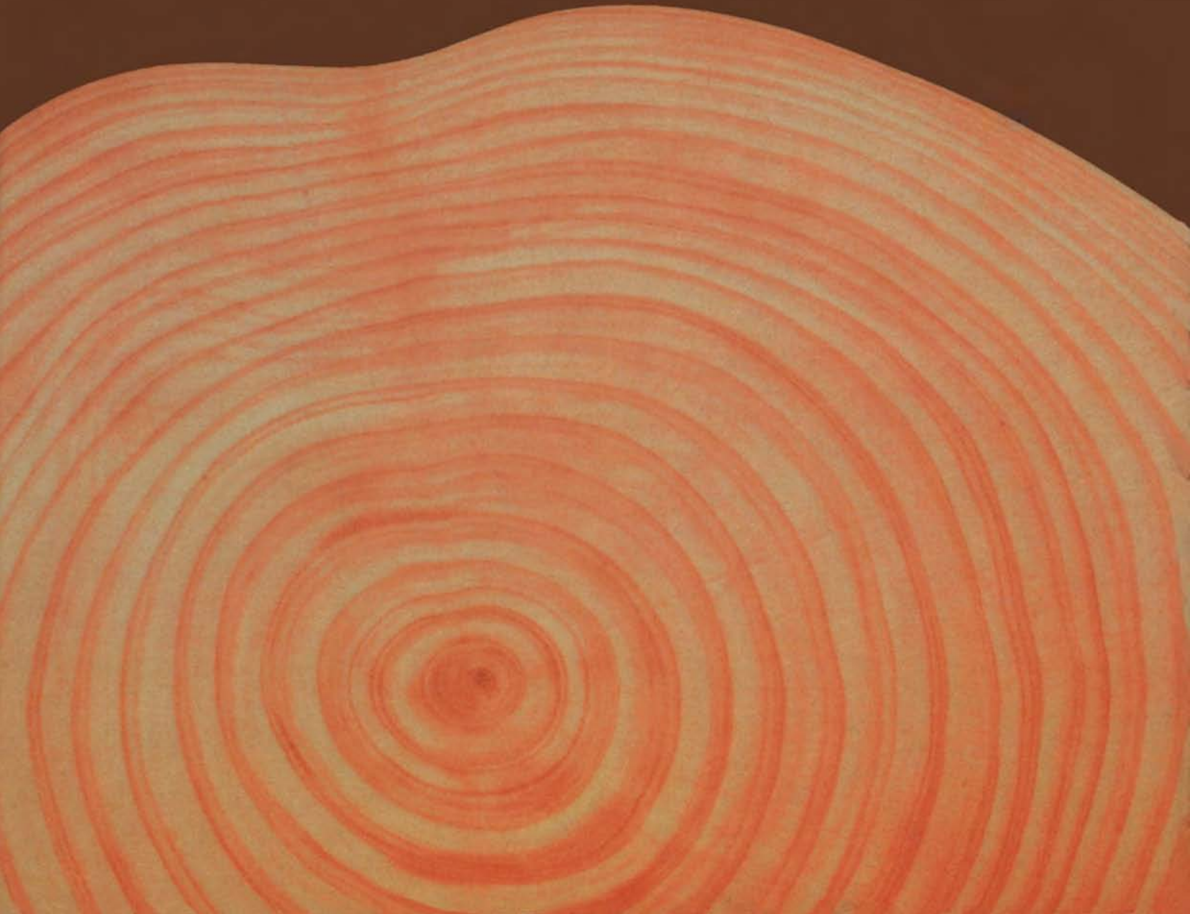

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Preface

Forest ecosystems fulfil a range of functions, including providing environmental and cultural services as well as the production of wood. The paradigm of forest management has shifted across the world from maintaining a sustained yield of forest products to sustained forest ecosystem management. This trend arose in the 1970s and has advanced greatly since the 1990s. Sustainable forest management was emphasized in the Statement of Forest Principles and Agenda 21 which were adopted in the United Nations Conference on Environment and Development (UNCED) held in Rio de Janeiro in 1992. Since then, sustainable forest management has become one of the most important key words of forest management throughout the world.

Sustainable forest management can be defined as management that meets present needs for various forest functions without compromising the ability of the forest to fulfil the needs of future generations. It has been agreed that sustainability must be evaluated by whether management recognizes biodiversity, soils, water, recreation, and forest products. However, silvicultural theories that include strategies to meet this range of functions have not yet been developed. Therefore, this book discusses and proposes new silvicultural approaches for sustainable forest management.

Silvicultural techniques and systems or methods which conserve productivity for forest products have been in use for many years and these can be used to help develop sustainable forest management systems. These traditional methods are summarized and reviewed to evaluate how they can be applied or revised to develop new, sustainable silvicultural methods. Where the traditional methods do not fulfil the requirements of sustainable management, new approaches are proposed. Implementing a combination of the old and new methods should allow a new era of forest management to commence.

Natural and social conditions vary across the world, and silvicultural methods vary accordingly. When discussing silvicultural methods, it is always necessary to consider what is universal and what is specific to local areas. Establishing silvicultural methods that are suitable to the natural and social conditions of a local area, and extending such methods nationally and internationally by continued information exchange will enhance the development of new methods.

Although I have some experience in tropical forests, my knowledge is insufficient to discuss silvicultural techniques and methods for these forests. Therefore, this book is focused on forests of the temperate and boreal zones. The discussion is somewhat biased towards the situation in Japan, where I have done most of my work and am most experienced. However, I have tried as much as possible to analyze information from other temperate and boreal areas around the world, to illustrate that theories developed at a local level can be applied universally. It is my hope that this book will contribute to the development of sustainable forest management methods that will be applied locally and universally.

I heartily appreciate the efforts of Dr. Jo Sasse, who works for Centre for Forest Tree Technology, Australia, for her revision of my English. I also heartily appreciate the valuable knowledge and information contributed by my many colleagues at the National Forestry and Forest Products Research Institute in Japan and Japan Forest Technology Association.

Tsukuba, March, 2001 Takao Fujimori

Contents

Chapter 1

Introduction

The most important challenge for human beings in the 21st century is the establishment of a sustainable society. The most basic condition for a sustainable society is an environment in which we can live healthily and which has ecosystems that provide resources that we can utilize sustainably. Sustainable forest management, both internationally and in each country, is an essential step in achieving a sustainable society.

In 1992, at the United Nations Conference on Environment and Development (UNCED) held in Rio de Janeiro, the Statement of Forest Principles and Agenda 21 were adopted. For the first time, an internationally agreed definition of sustainable forest management was developed and its importance to the establishment of a sustainable society recognized. International working groups were formed under the United Nations to clarify the concept of sustainable forest management. The Helsinki Process and Montreal Process developed frameworks of criteria and indicators of sustainable forest management for boreal and temperate forests (Chapter 9). These frameworks provided a definition of sustainable forest management that included the maintenance, enhancement and recovery of the health and vitality of forest ecosystems to fulfil the needs of the present generation without compromising the ability to fulfil the needs of future generations. Various forest functions were recognized, such as the production of wood, conservation of biodiversity, conservation of soil and water resources, provision of recreational opportunities, and contribution to the global carbon cycle. The main challenge for modern silviculture is how to harmoniously satisfy these various demands of forests, and there is a strong need to develop appropriate ecological and silvicultural strategies.

The current definition of sustainable forest management was preceded by concepts of forest ecosystem management which included sustained yield. The concepts of sustainability have been recognized and implemented in many areas of Europe and elsewhere in the world since Möller (1922) advocated the Dauerwald. Dauerwald means continuous cover forestry (Benecke, 1996) or permanent, perpetual, continuous, or sustainable forestry (Schabel and Palmer, 1999). The Dauerwald concept tends to emphasize sustainable yield, as shown by Möller's (1922) assertion that "the most beautiful forest will be the most productive." If this is the case, old-growth forest is less valuable than forests at other stages of development. Over the last two or three decades, ecological knowledge has advanced and social demands on forests have changed such that there is now value placed on a more diverse range of forest functions.

Since the 1970s, the focus of forest management has shifted worldwide from sustainable wood production to sustainable forest ecosystem management, including conservation of biodiversity, environmental and cultural forest functions. This trend has been especially conspicuous since the beginning of 1990s. Such concepts and practices as new forestry and ecosystem management (Franklin, 1989; Swanson and Franklin, 1992; Franklin, 1997), diversity-oriented forest management (Fujimori, 1991a), nature-oriented silviculture and diversity-oriented silviculture (Lähde, 1992, 1993; Lähde et al., 1999), and ecological silviculture (Benecke, 1996) have become of increasing interest. These concepts and practices are characterized by an emphasis on the diversity of the stand structure and the diversity of ecosystems in a landscape. Declining trees, snags, and fallen logs are recognized as elements of the ecosystem that provide habitats and niches for various organisms and contribute to the conservation of soil and water resources (Franklin et al., 1981; Swanson and Franklin, 1992). The development and maintenance of stand structures that are resistant to destructive agents (such as wind) and remain effective for production of valuable wood is an important silvicultural challenge.

This book recognizes these changes, and confronts the question of how sustainable forest management can be implemented – i.e., what are appropriate ecological and silvicultural strategies? The title "Ecological and silvicultural strategies for sustainable forest management" reflects the strong basis of ecology, including landscape ecology, in the new silviculture.

This book consists of four parts. In Part I, the fundamental components of forest ecology, from individual trees to forest ecosystems, are reviewed as a basis for the development of silvicultural theories for sustainable forest management. Disturbance regimes and forest stand development patterns are discussed in some detail, as they are especially important to the silvicultural theories developed in this book. It is essential for forest managers to understand the forest ecosystem if they are to manage the forest sustainably, but it is also important that those citizens who are interested in forests and forestry also have knowledge of forest ecology and associated forest functions, so that consensus can be reached at a local scale on appropriate ways to implement sustainable forest management.

Part II reviews traditional specific silvicultural techniques and provides a lot of practical silvicultural information. Most techniques were developed for forest products, but some can be applied without modification to enhance other forest functions required for sustainable forest management. Other techniques can be applied to sustainable forest management if they are improved and/or incorporated into new systems.

In Part III, traditional silvicultural methods applying specific silvicultural techniques are reviewed. These traditional methods are reviewed and evaluated according to their capacity to meet new social demands and improved silvicultural methods are proposed for sustainable forest management.

Part IV discusses silvicultural theories and integrated silvicultural strategies which enhance the functions of forests. The strategies are discussed initially in terms of their ability to satisfy the primary functions of biodiversity conservation, protection of soil and water resources, enhancement of recreation, sequestration and pooling of carbon, and growth of forest products. Methods of concurrently satisfying a range of functions are then discussed, in terms of the required stand structures and appropriate silvicultural practices to achieve and maintain these structures.

Part IV also discusses ways of maintaining, enhancing, or recovering the health and vitality of forest ecosystems. The control of natural and anthropogenic disturbances such as wind, fire, insect pests or diseases is an important issue for the implementation of sustainable forest management. It is difficult but important to distinguish between natural disturbances that can be allowed as a part of normal phenomena of forest ecosystems and unusual disturbances that will prevent the implementation of sutainable forest management.

Finally, a summary is provided in Chapter 16.

The status of forests around the world and the natural and social environments surrounding them differ widely, and this provides significant challenges to the implementation of sustainable forestry. In tropical zones, the area of forested land is still decreasing, the degradation of forests continues, and this is clearly not sustainable. In temperate and boreal zones, by contrast, the area of forested land and growing stock have increased in recent decades (Kauppi et al., 1992). However, in many countries in these areas, such as in Europe and Japan, the sustainability of the monoculture plantations that are a widespread feature of expanded forest areas has been questioned (Benecke, 1996; Fujimori, 1997a, 1997b; Lähde et al., 1999; Piussi and Farrell, 2000).

Changes in the area of forested land are the result of changing land use. In many tropical areas and developing countries, forest lands have been converted to farmland or other purposes, but in advanced countries, farmlands and pastures have been converted to forests, either naturally or artificially. Changes in land use are the result of socio-economic change. Sustainable forest management must consider other land uses, including agroforestry, and changes in land use to or from forested land. Although this is an important aspect of sustainable forest management, the manipulation of land use is primarily achieved by political and administrative strategies and is not covered in this book.

When discussing silvicultural methods, it is always necessary to consider what is universal and what is specific to local areas. Modifications of silvicultural methods made to suit a local area's natural and social conditions may be able to be extended and applied elsewhere if there is continued information exchange both nationally and internationally. This will lead to the improvement and development of new silvicultural methods, and it is hoped that this book will contribute to this process.

As noted above, forests and forest management differ greatly around the world. The discussion on tropical forests is limited, although the strategies discussed may also be applied to these forests. This book focuses mainly on temperate and boreal zones, and is based largely on my experiences in Japan and information published in Japanese and English. Wherever possible, I have used information from around the world. Valuable information would be found in the literature of non-English speaking countries, and it is important to further explore this (Piussi and Farrell, 2000).

Despite its limitations, I believe that this book can contribute to improved ecological and silvicultural strategies for sustainable forest management around the world.

Part I

Forest Ecology as the Foundation of Sustainable Forest Management

As described in Chapter 1, sustainable forest management requires much greater understanding of forest ecology if multiple functions of forests are to be satisfied. Effective sustainable forest management requires that the various functions of forests are considered within each stand and across various stands at the landscape level. To establish the theory of sustainable forest management and develop suitable silvicultural systems, knowledge and understanding of forest ecology is essential. Part I summarizes the features of forest ecology needed to support sustainable forest management.

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Chapter 2

Characteristics and Ecological Adaptive Features of Trees and Forests

Silviculture is the management of forests for human benefit. Sustainable silviculture requires that ecosystem functions be manipulated. In order to discuss silviculture and alternative silvicultural methods, the way in which trees grow and develop, both as individuals and in forest communities, must be understood. It is essential to be able to predict how trees grow and how a stand develops, because then it is possible to predict how a stand will develop in relation to its environment, or how a stand will respond to silvicultural treatment. It is especially important to understand the influence of growth and architecture of trees on timber production, because the growth of individual trees usually needs to be managed to control their quality and quantity.

2.1 Characteristics of trees and forests

2.1.1 What are trees?

A tree is a lignified (woody) perennial plant that is typically large, with a single, well-defined stem or stems carrying a more or less definite crown (Ford-Robertson, 1971; Helms, 1998). Trees generally grow larger in both height and diameter over many years, and have life spans of between several decades and several hundred years, or sometimes more than a thousand years. Trees are distinguished from other woody perennial plants such as shrubs by their stature and well-defined stems, and from herbaceous plants by the presence of the cambium and resulting persistent woody stems.

Trees have a characteristic structure and growth pattern that develops as a result of primary and secondary growth (Figure 2-1). Trees have crowns comprising branches that spread the leaves widely and enable effective photosynthesis. They develop root systems that support the large above-ground parts and which absorb water and nutrients. The trunk, which acts as a pipe that connects the crown and roots, continues to grow as long as the tree is healthy. The development of a large woody trunk is a notable feature of trees, and is the component traditionally regarded by humans as the most valuable.

A seedling develops into a large tree by a complex combination of primary and secondary growth. Primary growth is the result of the activity

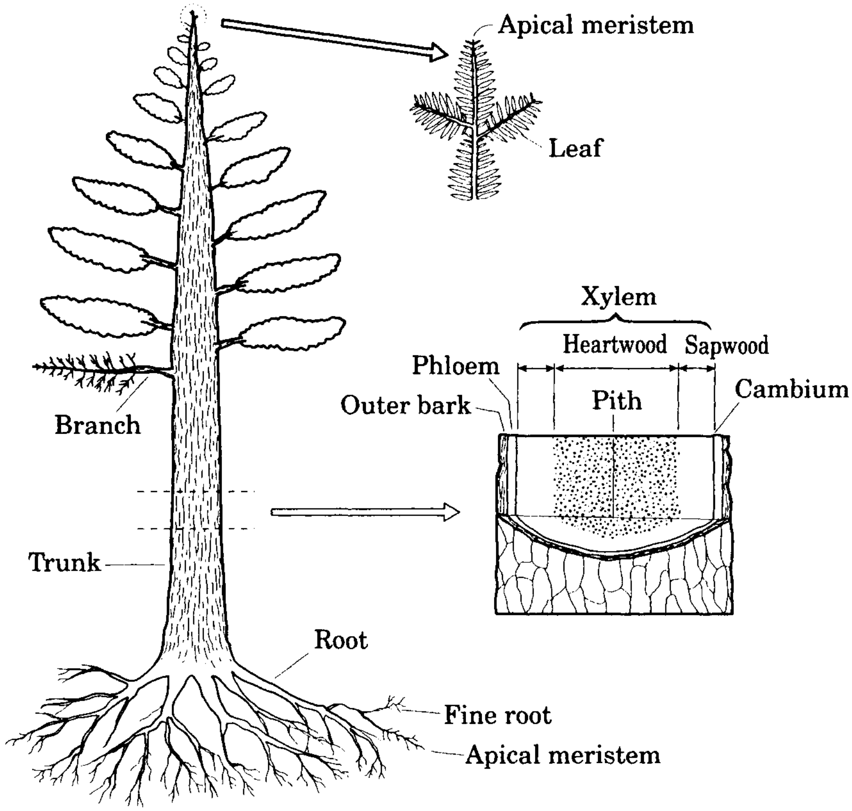


Figure 2-1 The organs and tissues of a tree.

of apical meristems at each growing point (shoot and root apices) and this process forms the leaves, branches and roots. Secondary growth is the growth of the cambium, enabling diameter growth of the stem, branches, and roots (Kozlowski, 1971a, 1971b; Zimmermann and Brown, 1971; Oliver and Larson, 1990; Barnes et al., 1998).

Apical meristems occur at the tips of shoots and roots, producing new cells which develop into various tissues. As shoots develop, the precambium develops into vascular bundles that link to form the cambium. The cambium surrounds stems and roots like a sheath and provides the capacity for secondary growth that enables trees to grow large (Kozlowski, 1971a, 1971b; Zimmermann and Brown, 1971; Shimaji and Kurata, 1978; Shimaji and Higuchi, 1978; Oliver and Larson, 1990; Barnes et al., 1998).

The cambium adds cells to both its inside and outside forming the xylem and phloem, respectively (Figure 2-1). Xylem cells function as a water-conducting system (generally tracheids in gymnosperms and vessels in angiosperms) until they become lignified and cease to function. The functional portion of the xylem is referred to as sapwood and the non-functional portion as heartwood. In sapwood, living parenchymous cells transport water, nutrients and physiologically active products from the roots to the shoots, and various physiological functions occur there. Heartwood is the accumulation of physiologically non-functional, dead cells that provide structural strength to the tree (Kozlowski, 1971a, 1971b; Zimmermann and Brown, 1971; Shimaji and Kurata, 1978; Shimaji and Higuchi, 1978; Oliver and Larson, 1990; Barnes et al., 1998).

The phloem transports photosynthetic products and other substances from the leaves to other parts of the tree. Phloem cells live for a few years and when they die, become part of the outer bark. The outer bark protects the phloem and cambium from the heat of direct sunlight, cold or mechanical injury. As the stem grows, the outer bark splits and peels off. Thus, phloem cells return to the ground as part of the litter fall and xylem cells accumulate, changing from sapwood to heartwood, as long as the tree is healthy (Figure 2-1). The large biomass of forested ecosystems is due to the accumulation of heartwood. The crown of a tree develops as the terminal shoot grows and branches (lateral shoots) develop. Branches increase the aerial distribution of leaves, enabling the leaves to photosynthesize effectively. A sequence of individual crowns is referred to as a canopy. As a canopy develops, the branches in the lower strata gradually stagnate and die because of reduced illumination (Section 6.1.2). Thus, leaves and branches fall continuously, forming an important component of the litter and enabling nutrient cycling in forested ecosystems.

The root system of a tree develops concurrently with the shoot system. Generally, the biomass of leaves and fine roots is in balance, matching physiological demand and supply. This relationship determines the cross-sectional area of sapwood, which is usually closely related to the amount of leaves and fine roots (Grier and Waring, 1974). Structural roots provide anchorage to the tree and fine roots provide nutrient and water uptake. There is less knowledge about the growth of roots compared with shoots, but the root apex differs structurally from the shoot apex. Lateral roots do not develop near the apical meristem of the root but arise endogenously in the pericycle some distance behind the root apex (Zimmermann and Brown, 1971). Therefore, most fine roots are a kind of adventitious bud (Kozlowski, 1971b; Zimmermann and Brown, 1971). Fine roots are often mycorrhizal, that is, they form a symbiotic relationship with a particular fungus that enhances uptake of water and nutrients by the roots (Spurr and Barnes, 1980; Perry, 1994; Okabe, 1997; Barnes et al., 1998). The life span of fine roots is short, like that of leaves, and the litter of dead roots also contributes to mineral cycling.

2.1.2 What are forests?

The definition of a forest is difficult, because it is closely related to the natural conditions or social conditions of a region. A range of attempts have been made to try to provide an universal definition of forests, particularly in the context of international surveys (e.g., FAO, 1992; Bolin et al., 2000), but these tend to define quantitative thresholds of crown cover, tree height or management conditions which can be locally inappropriate. If there is no such administrative requirement, a more general definition is useful, and a forest can be described as an ecosystem characterized by a more or less dense and extensive tree cover, and more particularly, a plant community of predominantly trees and other woody vegetation, growing more or less closely together (Ford-Robertson, 1971; Helms, 1998). An ecosystem-based definition includes all elements of the community, including other living plants and animals, and the inorganic components such as soil (Section 2.4).

2.2 Factors affecting the growth of trees and forests

2.2.1 Individual factors

Growth is the result of assimilation, which is the balance between production by photosynthesis and losses from respiration. Maximum growth requires that all environmental resources that affect these processes are available at the necessary level. If one factor required for growth is deficient, growth is reduced. Photosynthesis converts carbon dioxide (CO_2) from the atmosphere and water from the soil into carbohydrates and oxygen, using energy from sunlight (Figure 2-2). Photosynthesis is limited to a specific temperature range (different for each tree species) and requires mineral nutrients as catalysts and for

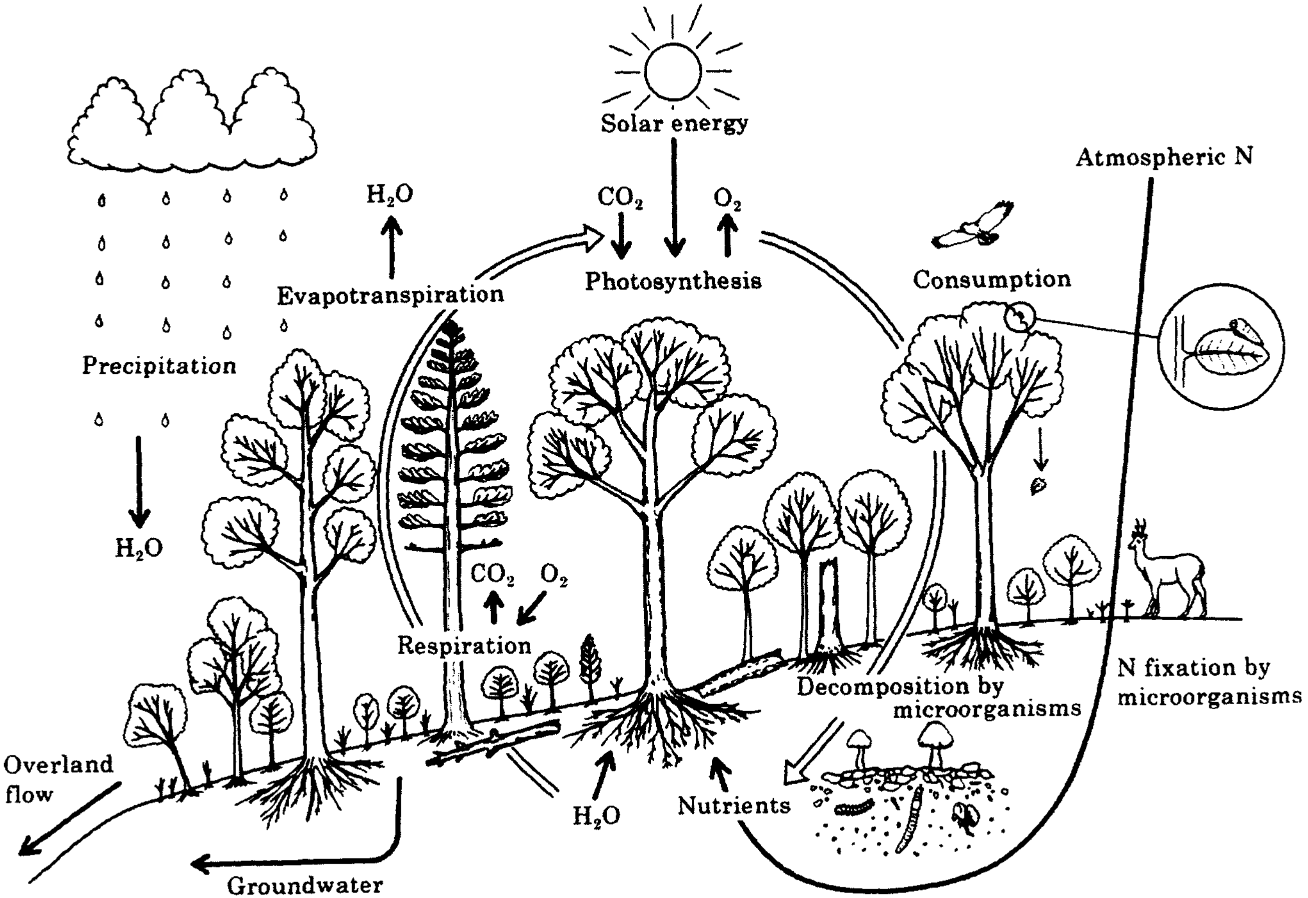


Figure 2-2 Forest ecosystem cycles.

incorporation into the carbohydrate products. Respiration releases energy for growth and carbon dioxide, and requires oxygen. Thus, water, nutrients, temperature, carbon dioxide, oxygen, and sunlight are necessary for the growth of trees. The supply of these factors can be limited by environmental conditions such as wind, snow, soils, topography or the presence of other trees (Barnes et al., 1998).

Water

Water is fundamental to tree life. It is a component of the photosynthetic reaction, provides transport for nutrients and photosynthetic products, maintains cell hydration, and allows cooling of leaves through transpiration. Most water is absorbed by the fine roots, so adequate soil moisture is vital; however, atmospheric moisture is also important because it affects transpiration, and thus the rate of water loss.

As trees transpire, water moves from the soil into fine roots, into the xylem and through the stomata to the atmosphere, following a gradient of decreasing water potential. The rate of transpiration is controlled by the stomata, which close as the difference between leaf and atmospheric water contents rises. When stomata close, the leaf temperature increases, photosynthesis rates decrease and respiration increases, leading to a decreased rate of cell enlargement, decreased leaf area expansion and reduced growth rates (Sparr and Barnes, 1980; Hatano and Sasaki, 1987; Barnes et al., 1998).

As growth rates are reduced during dry periods, productivity is lower in areas with a dry season. Water is supplied to the soil from the atmosphere via rain, snow, dew, or fog. Only a limited amount of water is absorbed directly from the atmosphere by the foliage. In some areas, if water is not supplied by rainfall, fog or dew can compensate. For example, along the coastal range from northern California to Washington State in the United States of America and British Columbia in Canada, fog usually occurs during the dry season and the forests in this narrow belt are highly productive. The cool air that accompanies fog during the summer also improves the conditions for photosynthesis for coniferous species (Waring and Franklin, 1979).

Nutrients

Carbon, hydrogen, and oxygen are the basic components of the carbohydrates formed during photosynthesis (Figure 2-2). These products and physiological processes within the plants also require a range of essential nutrients. The essential macronutrients, required in relatively large amounts, are nitrogen, phosphorus, potassium, magnesium, sulphur, and calcium. Essential micronutrients, required in small amounts, include iron, manganese, copper, and zinc.

Essential nutrients are absorbed from the soil by the roots. Most nutrients in the soil, such as phosphorus and potassium, are derived from rock materials through weathering — these are referred to as mineral nutrients. Nitrogen is fixed from the atmosphere by microorganisms in the soil and by symbiotic nitrogen-fixing bacteria which form root nodules on some tree species such as legumes and alders. Nitrogen and minerals also are supplied to the forest ecosystem from the atmosphere via precipitation or as dry particulate fallout. Mutualistic associations between fungi and tree roots (mycorrhizae, Figures 2-3, 2-4) increase the ability of the tree to absorb nutrients, and in some species are essential for their survival and growth (Spurr and Barnes, 1980; Perry, 1994; Okabe, 1997; Barnes et al., 1998). The mycorrhizal fungus receives food from the plants in the form of sugars and other organic molecules, and in return, enhances the uptake of water and nutrients, protects the plant against root pathogens, and provides many other benefits (Perry, 1994; Barnes et al., 1998).

The supply of nutrients to trees depends on the presence of non-photosynthesizing microorganisms in the ecosystem. These microorganisms obtain their energy from organic compounds in the deposited litter on the forest floor and in the mineral soil, decomposing organic material and releasing carbon dioxide, water, heat, and inorganic nutrients (Figure 2-2).

Temperature

Plant processes function in a broad range of tissue temperatures, generally between 0° and 50°C, as long as living cells and protein compounds are biologically stable and enzymes remain active.

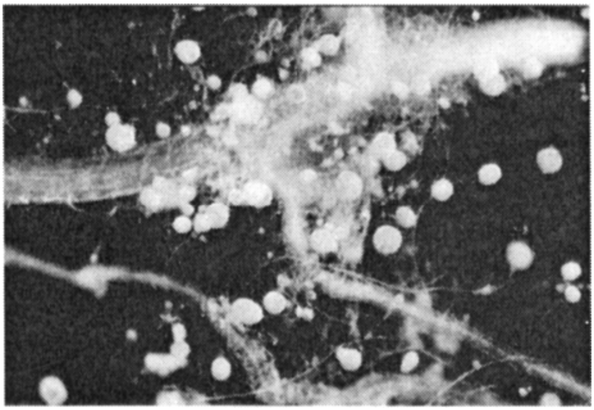


Figure 2-3 Arbuscular mycorrhizal fungi infected roots of *Miscanthus sinensis* (susuki). Arbuscular mycorrhizal fungi are distributed worldwide and are particularly common in tropical and warm-temperate zones. They are associated with a wide range of plants, from mosses to trees (Photograph by H. Okabe).

Figure 2-4 Well developed ectomycorrhizal fungi in the surface soil of a broad-leaved deciduous stand dominated by *Quercus*. Ectomycorrhizal fungi are common in high latitudes although they are also commonly associated with species of the *Dipterocarpaceae* in tropical zones (Photograph by H. Okabe).

Temperatures above about 55°C are lethal (Spurr and Barnes, 1980). Most physiological processes in plants have an optimal temperature range, above and below which the rates are reduced. Maximum gross production and net production are highest in a limited temperature range, which varies between species. Generally, optimum temperatures are higher for species in warmer regions than those in cooler regions.

Temperature extremes of either heat or cold can be damaging or lethal. Generally, tropical species are immediately killed if the temperature falls below 0°C, and they may lose viability and gradually die below 15°C (Sasaki, 1982; Hatano and Sasaki, 1987; Mori et al., 1990). In contrast, boreal species such as *Larix gmerinii* (dahurian larch) in Eastern Siberia can withstand temperatures as low as -60°C. In Hokkaido in Japan, mixed coniferous and broad-leaved deciduous forests can withstand temperatures around -40°C. These species achieve frost hardiness (frost resistance) to low temperatures (Sakai, 1982) as winter approaches, and lose their frost hardiness in spring. The extent of frost hardiness differs between species.

Cold injuries can be divided into two categories; frost damage (freezing damage, Figure 2-5) and winter desiccation damage (frost drought damage, Figure 2-6). Freezing damage injures the base of the main stem of seedlings (saplings) or shoots. It usually occurs in early winter when frost hardiness is not yet at its maximum or in late winter when frost hardiness has begun to lessen (Horiuchi, 1976; Sakai, 1982). It tends to occur in low hollows in the land where the temperature falls below that of the

Figure 2-5 Frost damage (freezing damage) of *Cryptomeria japonica* (sugi) in central Japan (Photograph by T. Yoshitake).

Figure 2-6 Winter desiccation damage (frost drought damage) of *Chamaecyparis obtusa* (hinoki) in central Japan. The upper part of the front tree was killed (Photograph by T. Yoshitake).

surrounding land when an inversion layer forms on still cold nights in fine weather. Such concave areas are known as frost pockets or frost hollows (Shidei, 1965; Barnes et al., 1998).

Winter desiccation damage causes a loss of turgor (pressure potential) in leaves because water uptake is prevented when the soil is frozen (Doi, 1984). Winter desiccation often occurs on sunny days in the spring when water uptake and translocation are prevented by frozen soil and stems (Larcher, 1985). This phenomenon is found worldwide, mainly in boreal forests and some parts of temperate forests.

Carbon dioxide

Photosynthesis requires large quantities of CO_2, which is present in only low concentrations in the atmosphere. On average, CO_2 concentration in the atmosphere is 0.037 percent by volume as of 1998. It has been shown that as CO_2 concentration increases to a certain level, photosynthesis increases (Spurr and Barnes, 1980; Liang, 1995), so CO_2 is considered a general limiting factor for plant growth. However, the fluctuation of CO_2 concentration in the atmosphere throughout the world is small and the concentration does not dramatically change from site to site as is the case for water or temperature. Carbon dioxide concentration cannot be manipulated significantly by silvicultural treatment and so in this context, CO_2 is not regarded as a limiting factor for plant growth.

The contributions of forest ecosystems to the global carbon cycle and the effects of increasing CO_2 concentration on forest ecosystems are discussed in Chapters 14 and 15.

Oxygen

Oxygen concentration in the atmosphere is 21 percent and does not limit the growth of plants. However, oxygen levels in the soil are often limiting. Soils with low permeability or with high water tables have limited oxygen available to roots, so plant growth is reduced and the number of species which can survive is limited. Most species grow best in soils with optimum structure and high permeability, if other factors are not limited.

Sunlight

The amount of energy from the sun dictates the general climate of a region and thus the growth of trees. On a global scale, the amount of solar radiation generally decreases with latitude from the equator to the poles. In mountainous areas, the direction and angle of mountain slopes affect the amount of solar radiation, especially in higher latitudes. In each forest stand, only a limited number of trees can grow in full sunlight. An important factor in regeneration and stand development is how trees adapt or survive under shaded conditions.

Solar radiation is divided into three categories: ultraviolet, visible, and infrared. Radiation of approximately 400 to 700 nanometers (nm) or 0.4 to 0.7 micrometers (μm) wavelength is visible to the human eye and is termed light. Radiation of this wavelength is required for photosynthesis. Within the visible spectrum, light can be further divided by increasing wavelength into violet, blue, green, yellow, orange, and red bands (Spurr and Barnes, 1980; Uchijima, 1982; Barnes et al., 1998). Blue and red light is effective for photosynthesis, but green and far-red light (700-760 nm) is not. Elongation of stems is promoted as the proportion of far-red radiation increases (Morikawa et al., 1983; Hatano and Sasaki, 1987).

When sunlight reaches the canopy, it is reflected, absorbed, or transmitted, and only a small percentage of the incident sunlight reaches the floor. Relative illumination (RI) within the forest is expressed as a percentage of incident sunlight (lux). Relative illumination is also called relative light intensity (RLI).

The growth of under trees is affected not only by the quantity of light but also by the quality of light. The canopy absorbs most of the blue and red wavelength and the diffuse light reaching the understorey is composed of mostly green and far-red wavelength. As illumination decreases, the ratio of far-red to red light increases. Therefore, understorey trees become more elongated and their overall growth is reduced (Hatano and Sasaki, 1987; Morikawa et al., 1983). If illumination is reduced greatly, the ratio of height growth to lateral growth decreases and the crown becomes flatter on top (Oliver and Larson, 1990). Under such shaded conditions, the ratio of leaves to branches also decreases and root systems develop less (Spurr and Barnes, 1980).

Wind

Wind plays an important role in the growth of forest trees. Wind enables the dissemination of pollen and seeds of many species, and it enhances photosynthesis by decreasing the thickness of the boundary layer at the leaf surface, thereby promoting gas exchange. The fluttering of twigs and leaves in wind also helps the leaves to maximize their illumination. However, continuous strong winds prevent the normal growth of trees. Swaying of a tree in the wind causes the tree to become tapered and form compression wood or tension wood (Kozlowski et al., 1991). Strong winds can break or uproot trees, or injure the roots, weakening the trees and providing an entry point for decay fungi (Kaneko et al., 1991). This is clearly disadvantageous for forestry, but contributes to regeneration in natural forests.

Snow

In areas of heavy snow, deep snow piles can delay the start of the growing season, limiting the growth of the trees in the snow pile areas

(Koizumi, 1993). Snow damages trees in two ways. When they are young, deeply piled snow damages seedlings and saplings, through snow pressure damage. Snow pressure damage arises from the creep and glide pressures of settled snow. Every year, seedlings or saplings are bent under these pressures, which usually tears the roots on the upper side of the tree. Older trees are damaged by crown snow damage which causes stem bending, stem breakage, uprooting, and branch breakage. Coniferous plantations are particularly vulnerable to snow damage (Saito et al., 1986).

Damage by avalanches can also be serious, but the extent of such damage is generally limited. When an avalanche occurs, forests are severely damaged and soil erosion, especially around the start zone, can follow. Generally, avalanches occur on slopes of 35-45°(Onodera, 1990). The avalanche generally starts on the part of the slope where there is a transition from convex to concave. In Japan, avalanches tend to occur on areas without tall trees, usually in areas covered by dwarf bamboos and grasses such as *Miscanthus sinensis* (susuki).

Soils and topography

Soil is important site factor determining the growth of trees, because it is closely related to the supply of other factors such as water and nutrients. The structure of the soil develops as a forest ecosystem matures. Soil conditions are also related to the parent rock geology and topography. Mountain slopes generally exhibit a gradient in soil moisture and depth along the slope. Generally, the upper parts of slopes, which are often convex and tend to be exposed to high winds and subject to erosion, have shallow soils and are relatively dry. The lower parts of slopes, which tend to be concave and sheltered from high winds have an accumulation of soil with better texture and a higher moisture content, as a result of the movement of water and soil from the upper to lower slopes. The mid-slopes are generally intermediate in character (Tsutsumi, 1972).

2.2.2 Growing space, habitat and niche

Growing space and site quality are both terms used to define the suitability of an area to support the growth of trees. The term "site" usually includes both the position in space and the associated environment of a specific area. The area where a species is distributed is known as its geographic range. Site quality is defined as the sum total of all factors affecting the capacity of an area to support forests or other vegetation (Spurr and Barnes, 1980). In its narrow sense, growing space means the space that the crown and roots of a tree can occupy. In its broad sense, it means the environmental capacity which allows trees to grow until a factor necessary for growth becomes limiting (Oliver and Larson, 1990). Compared with site, "growing space" has a more dynamic aspect, and includes the changes in available growing space which arise as plants grow and interact (autogenetic changes). Growing space is inclusive of changes in limiting factors from a daily to a long-term basis (Oliver and Larson, 1990). Therefore, the term "site" covers the stable and general aspects of the environment which influence the growth of trees or plants, and growing space is a more dynamic concept which includes changing limiting factors.

Growing space is determined by the immediate environmental conditions, as well as the presence of other trees and plants of the same or different species, and the results of competition between these trees. The limiting factors of a particular site and species regulate and define the growing space, although these limits cannot always be clearly identified. The ability to tolerate limiting factors differs between species, and their differences will give each species a different growing space, thus giving a competitive advantage to different species under particular circumstances.

The concept of growing space is generally associated with the concept of habitat. Habitat is the combination of physical and chemical site characteristics that is suitable for a species. Within that habitat, a species position, or niche, will depend on the space, time, and functional relationships of the community that occupies that habitat (Whittaker, 1970). This definition of niche is simple, but since the term was first used by Grinnell (1917), it has been used in different ways by many scientists. Whittaker et al. (1973) pointed out that "niche" has been used with the following three meanings:

a) The niche as the position or role of a species within a given community — the functional niche;
b) The niche as the distribution of a species within a range of environments and communities — the niche as habitat, or the place niche concept; and
c) The niche as a combination of both these ideas, and thus defined by both intracommunity and intercommunity factors. This is the "habitat + niche" concept.

It is often difficult to distinguish between niche and habitat, because the range of community for each species cannot always be clearly defined, and the habitat is sometimes one of the factors determining niche and sometimes not. Kimmins (1987) defines niche as the functional, adaptational, and distributional characteristics of a species. Obviously the definition of the niche of a species is complex, involving a large number of parameters. Also, the definition cannot be fixed, because species interactions, habitat adaptations, and area all vary over time. The niche of an individual when it is young may differ from its niche when it is old. Thus, the terms "niche" and "habitat" are often differently used. Whenever these terms are used, therefore, they must be defined. In this book, the concept of niche is based on the first definition given by Whittaker et al. (1973), but the usage of niche or habitat in cited literature is respected unless it causes confusion.

The range of site conditions on which a given species can grow without interspecific competition is called its fundamental niche (Hutchinson, 1957; Kimmins, 1987; Oliver and Larson, 1990). Within the fundamental niche, there is a habitat in which the species grows best; this is called its physiological optimum (Ellenberg, 1953; Miyawaki, 1985). The habitat where the species is found when interspecific competition is present is its realized niche or ecological optimum (Ellenberg, 1953; Miyawaki, 1985; Kimmins, 1987; Oliver and Larson, 1990). The realized niche of each species is determined by the requirements of other species with which it grows. One of the merits of establishing a plantation is that it can be located within the fundamental niche (physiological optimum) by controlling competing species which would otherwise dominate there (Gholz et al., 1986).

These concepts are illustrated in Figure 2-7, which shows an example of species distribution along a soil moisture gradient on a slope in Kyoto Prefecture in the cool-temperate zone in Japan. Soil moisture was regarded as the major factor determining species composition in this community.

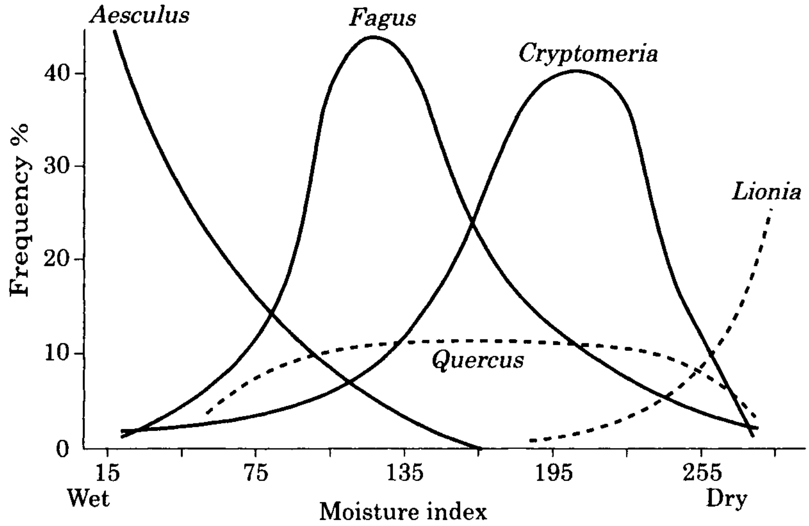


Figure 2-7 Distribution of major species along the soil moisture gradient of the cool temperate zone of the northern part of Kyoto Prefecture, Japan. Moisture index is after Curtis (1955) and Whittaker (1956). The species on the figure represent different types of the frequency distribution curves. (Modified from Tsutsumi et al., 1972)

Each species shown in this figure, except *Quercus crispula* (mizunara), has a competitive advantage in one segment of the soil moisture gradient. *Aesculus turbinata* (tochinoki) is dominant on wet soils, *Fagus crenata* (buna) on moderately wet soils, *Cryptomeria japonica* (sugi) on moderately dry soils, and *Lyonia neziki* (nejiki) on dry soils. *Quercus crispula* never dominates, but it is present over a wide range of soil moisture conditions, from wet to dry. Generally, most tree species are more productive on moist soils than dry soils, but as a result of competition, the soils on which a species dominates differs from the soils on which its growth is best. If *Cryptomeria japonica* is free from competition with *Aesculus turbinata*, *Fagus crenata*, and other broad-leaved trees, for example, it will occupy sites with moister soils and be more productive. Plantations of *Cryptomeria japonica* are most productive on moist to wet soils, supporting this observation.

2.3 Variations and adaptations of individual trees

Once an individual tree starts to grow, it cannot move to seek a better growing space or escape from competitors. Thus, trees growing together in a particular environment must compete with each other for the available resources of water, nutrient, and light. Trees have developed several adaptations to cope with their environment and to coexist with other trees in the forest. Adaptations of different species enable trees, shrubs, and herbaceous species to coexist within the vertical strata of a forest (Figure 2-8).

Figure 2-8 Vertical strata of an old-growth stand in Ise Shrine forest in Mie Prefecture, Japan.

2.3.1 Characteristic tree types

At a broad level, the easiest distinction between types of trees is the taxonomic split between gymnosperms and angiosperms. Gymnosperms do not have flowers in the commonly accepted sense; they produce naked seeds, usually on the scale of a cone. Many are evergreen, with needle-like linear, or scale-like foliage. Angiosperms have true flowers and bear their seeds within closed, often fleshy fruit (Brockman, 1968). The terms "conifers" and "softwoods" are associated with gymnosperms, and "broad-leaved trees" and "hardwoods" are associated with angiosperms. In an evolutionary sense, angiosperms are more recent, and better adapted to the present global environment. Generally, angiosperms tend to occur in tropical zones, wide areas of the temperate zones, and in disturbed parts in boreal zones, whereas gymnosperms tend to occur in boreal zones and some parts of temperate zones.

The anatomy of softwoods and hardwoods differ. The wood of softwoods is more or less uniformly composed of tracheids. Tracheids are the xylem cells that link vertically to enable water transport and give strength to the woody structure. Ray parenchyma and ray tracheids are distributed horizontally and provide lateral transport for water, photosynthetic products, and other substances. Annual growth rings can be distinguished by the differences in cell size and cell wall thickness between tracheids produced during the early and late part of the growing season. Larger diameter cells with thinner walls are produced early in the growing season and are referred to as earlywood (Figure 2-9). Smaller and thicker-walled cells are produced later in the season and are called latewood. Generally, the wood of softwoods is softer than that of hardwoods (Kozlowski, 1971a, 1971b; Zimmermann and Brown., 1971; Shimaji and Kurata, 1978; Shimaji and Higuchi, 1978; Oliver and Larson, 1990; Barnes et al., 1998).

In hardwoods, the xylem comprises vessels and fibers. The majority of the xylem cells are fibers, which provide strength to the woody structure. Vessels are the water-transporting cells, and are a sequence of tubular cells whose adjacent walls have disintegrated. Their effectiveness in transporting water and nutrients may be higher than that of tracheids in conifers. Annual rings are not always discernible in hardwoods. In some genera, vessels that form early in the growing season are far larger than those formed late in the season and such wood is referred to as ring-porous wood, and in these cases, annual rings are distinguishable (Figure 2-10). In other genera, the distribution of large and small vessels is uniform and has no relation to the growing season. Such wood is referred to as diffuse-porous (Figure 2-11).

Trees can also be distinguished by whether they are deciduous or evergreen. Deciduous trees drop their leaves before the cold winter or dry season to avoid consuming stored resources and water. They are therefore most common in temperate and boreal zones. Deciduous trees relocate

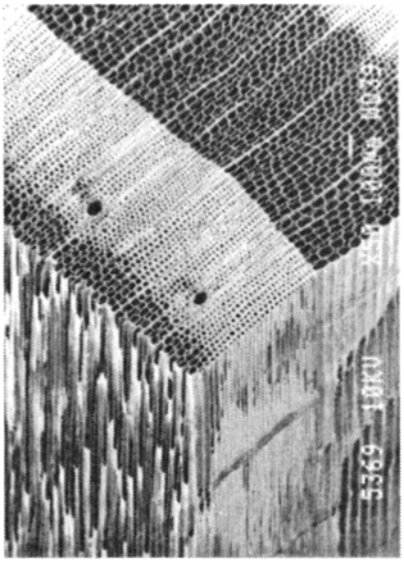


Figure 2-9 Wood structure of softwood (*Larix kaempferi*, karamatsu). Early wood and late wood are distinguishable. Vertical line figured at upper right hand is equivalent to 1 mm. (Photograph by T. Fujii).

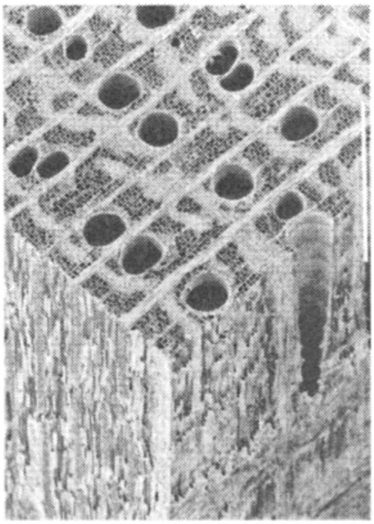


Figure 2-10 Structure of ring-porous wood of hardwood (*Zelkova serrata*, keyaki). Vertical line figured at right hand is equivalent to 1 mm. (Photograph by T. Fujii)

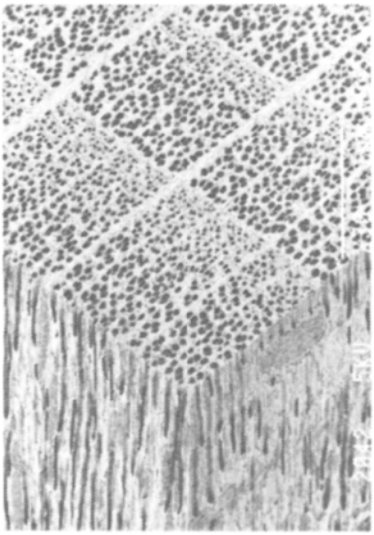


Figure 2-11 Structure of diffuse-porous hardwood (*Fagus japonica*, inubuna). Vertical line figured at right hand is equivalent to 1 mm. (Photograph by T. Fujii)

nutrients in the leaves to twigs and woody parts of the tree for storage before they drop their leaves (Tamm, 1951; Kozlowski, 1971a). Deciduous species are generally hardwoods, although there are some deciduous softwoods. Evergreen trees retain their leaves throughout the year. They are typically found in tropical rainforests, warm-temperate forests, and boreal forests. Evergreen species in tropical forests are usually hardwood species with normally large leaves, but in boreal forests, evergreen species are usually softwoods with needle-leaves. Evergreen species dominate in the tropics because there is no dry season or cold winter, so trees can grow throughout the year. By contrast, coniferous species are the dominant evergreens in boreal forests, because needle-leaves can resist cold temperatures and water deficits, but are adapted to the short growing seasons because they can react to increasing temperatures quickly (Larcher, 1985).

2.3.2 Variety of tree forms

Root systems

The form and structure of the root system is, to a large degree, genetically controlled. However, site conditions markedly influence the form and pattern of root development. Angiosperms trees, evolving later than conifers, have generally developed root systems that are more extensive and efficient (Kozlowski, 1971b; Barnes et al., 1998). The root system of these species is characterized by several orders of woody, perennial thick, long roots and one or more orders of small, fine non-woody roots (Barnes et al., 1998). Fine non-woody roots usually have mutualistic associations with mycorrhiizal fungus (Section 2.2.1, Figures 2-3, 2-4).

Roots can develop both horizontally and vertically. On sandy sites, lateral roots of species such as pines and birches can extend as far as tens of meters, thereby occupying large volumes of soil (Kozlowski, 1971b; Barnes et al., 1998). Where soil layers are deep and drought is frequent, roots can penetrate to great depths to obtain water. In general, as soil moisture decreases, the proportion of net production allocated belowground increases (Keyes and Grier, 1981). In the humid-savanna from Tanzania in the north to Zimbabwe in the south, *Baikiaea plurijuga* (Zambezi teak) has a canopy height of about 15 m and generally develops roots to about 10 m depth (Calvert, 1986). Other species, such as *Quercus*, *Eucalyptus*, and *Juglans* can adapt to drought by developing roots deeper in soil. However, if a water table is near the surface, root systems will be shallow and the trees become susceptible to windthrow (Barnes et al., 1998).

In temperate zones, the growth period of roots is generally longer than that of shoots. Roots start expansion growth earlier in the spring and end it later in the autumn in comparison with shoots (Barnes et al., 1998). This may be due to the less extreme changes of temperature in the soil.

Crown and stem forms

A tree's terminal bud controls the length and orientation of lateral branches. This physiological control is referred to as epinastic control (Zimmermann and Brown, 1971; Oliver and Larson, 1990) and it differs in extent. In cases of strong epinastic control, the terminal shoot grows faster than the lateral branches below, and the branches develop systematically in such a way as to form a single, straight main stem and narrow conical crown. This is termed the excurrent form (Figure 2-12). Conifers commonly have excurrent form, as do some hardwood species.

In cases of weak epinastic control, lateral branches grow nearly as fast or faster than the terminal shoot, which results in a rounded crown form and makes it difficult to distinguish between the main stem and branches in the crown. This is termed the decurrent form (Figure 2-13). Most hardwoods such as oaks, beeches, and maples have decurrent form.

Tree shape is thought to be an adaptation to the environment. Trees with thin excurrent form (columnar) are commonly found in high latitudes, while trees with wide conical or rounded crowns are frequently found in lower latitudes. It has been hypothesized that the gradation in crown form with latitude is an adaptation for efficient absorption of light (Shidei,

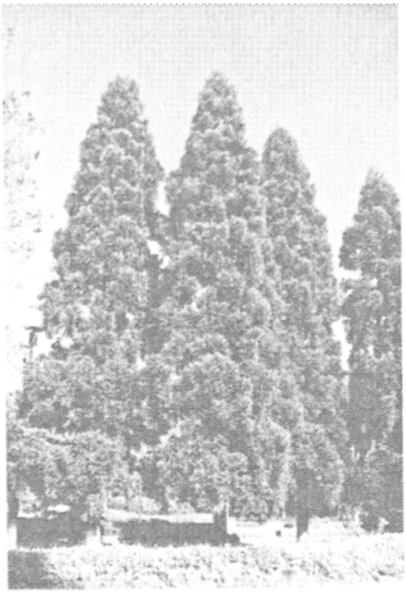


Figure 2-12 A tree of excurrent form (*Cryptomeria japonica*, sugi).

Figure 2-13 A tree of decurrent form (*Quercus crispula*, mizunara).

1985). In high latitudes, increasing the side area of a crown may improve the efficiency of light absorption because of the lower angle of sunlight, but in lower latitudes, a crown that is flat on top may be more efficient. The difference in the angle of sunlight may also cause a difference in the wavelength of radiation and thus tree form may reflect the light quality.

Crown shape can be modified by the presence of other trees through the effect of shade. Shade restricts the growth of branches, and this is particularly evident in the understorey. Sprugel et al. (1991) pointed out that most branches are functionally independent organs of photosynthesis, and shaded branches can never import carbohydrate. Thus, when shaded, the growth of branches decreases and lower branches die. Thus, the development of crowns varies according to the intensity and uniformity of side shade. If shade is intense, such as in the lower stratum of a stand, epinastic control weakens and crown shape is greatly modified. As the ratio of growth in the lateral shoots to that in the terminal shoots increases, the crown becomes flat on top, like an umbrella. When the light conditions improve, the terminal shoot may reassert epinastic control, if the tree has maintained a central leader (Oliver and Larson, 1990).

Epicormic branches

In many tree species, especially in broad-leaved trees, epicormic branches (sprouts) often arise along the trunk below the crown, and are conspicuous after trees are released from side shade or following damage to the crown (Wahlenberg, 1950). If the available growing space increases, branches and leaves whose growth was previously limited will increase their growth and epicormic shoots may begin to grow. Epicormic branches degrade the wood, so for production of timber it is important to understand the mechanisms by which epicormic branches arise and to control them. Most epicormic branches arise from suppressed (dormant) buds which develop from lateral buds (definite buds) and keep active during much of the growing season, laying down new leaf and scale primodia and keeping pace with cambial growth (Zimmermann and Brown, 1971). These buds are ready to develop as soon as conditions are suitable. Epicormic branches rarely arise from adventitious buds (Kozlowski, 1971a; Zimmermann and Brown, 1971; Yokoi and Yamaguchi, 1996). Adventitious buds arise from callus tissue around wounds in the cambium, or from mature tissues in the endodermis or pericyclic region (Kozlowski, 1971a).

Quercus crispula (mizunara) can produce epicormic branches, even in a closed stand, but most of them die within one or two years of emergence (Yokoi and Yamaguchi, 1996). However, if the growing space is expanded by thinning, many of the epicormic branches which emerged just before or after the thinning develop and persist (Wahlenberg, 1950; Tanaka et al., 1989; Ono et al., 1994; Yokoi and Yamaguchi, 1996). Persistent epicormic buds also develop after strong pruning (Fujimori, 1994).

Bark morphology

Bark plays an important role in protecting living tissues inside the bark. The outer bark is the accumulation of dead phloem cells, and protects the inner living tissues from extreme temperature, fire, pests, diseases, and physical impacts. Outer bark is mechanically resistant to temperature, fire, and physical impacts and physically and sometimes chemically resistant to pests and diseases. Species with thick bark such as *Quercus* and *Pinus* have strong resistance to fire and are often prevalent on sites where fire occurs frequently.

Quantitative relationships between organs

Monsi and Saeki (1953) developed a profile diagram which identified a relationship between the amount of photosynthetic organs (leaves) and the amount of non-photosynthetic organs in relation to relative illumination in each vertical stratum of a grass stand. They called this diagram the production structure diagram. A similar production structure pattern was found in forest stands (Tadaki and Shidei, 1960a, 1960b). This was then examined by Shinozaki et al. (1964a, 1964b) and a quantitative relationship was found between leaves and non-photosynthetic organs using a pipe model. In this model, a unit quantity of leaves is supported by a unit of xylem "pipe", and a quantitative relationship between leaves and stem could be defined. Grier and Waring (1974) further developed the pipe model theory by relating the amount of leaves to the cross-sectional area of sapwood. This model implies that the amount of water used in photosynthesis and by transpiration is regulated by the cross-sectional area of the sapwood. Further development of the pipe model (Oohata and Shinozaki, 1979; Chiba et al., 1988; Osawa et al., 1991) has shown that there are quantitative relationships between various parameters of tree growth, such as stem growth, leaf mass, leaf efficiency, and the length of clear trunk. Such relationships presumably extend to root structures as well, because the amount of fine roots will also be important in determining the potential for conducting water. However, these relationships have not been examined thoroughly, as analysis of fine roots is difficult, and there is limited information on fine roots as a part of the forest production structure.

2.4 Variations and adaptations of forest communities and ecosystems

2.4.1 Forest communities

A plant community is an aggregation of interacting species in one place. A forest community comprises trees, other plants, animals, insects, birds, fungi and microorganisms. Each component of the community acts as a producer, consumer, or decomposer. Plants which photosynthesize are called producers or primary producers, herbivorous animals and carnivorous animals are consumers; and fungi, which get energy by decomposing organic matter (litter of plants and animals) to inorganic matter, are decomposers. Trees are great producers, providing various kinds of food, such as leaves, xylem, fruits, honey, and sap to consumers.

Within a forest community there is a large quantity and variety of food and the forest structure provides many niches for various species. The range of niches available and the interaction between species will determine the level of species diversity, or overall biodiversity of the community (Perry, 1994; Watanabe, 1994). The species diversity of a forest community is generally very high (Roxburgh and Noble, 2001). The interdependence between species in a forest community extends beyond the different functions of species as producers, consumers and decomposers. For example, the reproduction of the plant species is usually dependent on insects, birds and animals as vectors of either pollen or fruit and seed, or to create suitable habitats for regeneration.

An important characteristic of forest communities is the development of vertical layers as the stand ages and becomes more stratified. The upper-layers modify the environment beneath, and the lower layers develop accordingly. The ability of an individual tree to reach the overstorey depends on its relationship with neighboring trees and plants; specifically, how fast the tree grows and occupies the growing space and how it tolerates being affected by the surrounding plants on the site. Once a tree with a long life-span occupies the overstorey, it exerts great influence on the understorey of the community by affecting the growing conditions in the understorey. Dominant trees affect the illumination, temperature and moisture conditions, and modify the environment through other mechanisms such as allelopathy. The vertical structure that develops eliminates some species, but provides a range of habitats and niches that other species, including plants, animals, and fungi, can occupy. A forest community is referred to as a coexistent society (Watanabe, 1994).

The habitats and niches that develop within a forest community continue to change over time. As a natural forest reaches the old-growth stage, declining trees, dead standing trees (snags), and dead fallen trees (logs) develop as the large trees that were dominant in the overstorey senesce and die. These components provide an essential food resource and habitat for various organisms (Franklin et al., 1981; Spies et al., 1988; Franklin, 1989; Franklin and Spies, 1991; Swanson and Franklin, 1992; Franklin et al., 1997; Schnitzeler and Borlea, 1998). Large declining trees and snags are particularly important for primary cavity excavators, such as woodpeckers and owls. Large logs provide habitat for microbial and fungal species and for vascular plants, but are also an important habitat for many vertebrate and invertebrate species. Logs also play an important role, providing niches for mosses and ferns, and also sites for some regenerating tree species.

The large woody debris that occurs in streams is also important for the aquatic ecosystem within old-growth forests. Such debris provides a variety of aquatic habitats, stabilize stream beds and stream banks, and control the movement of sediment and water through the stream system (Franklin et al., 1981; Swanson and Franklin, 1992). In forested areas, the stream ecosystems are closely related to the forest ecosystem, and in riparian zones, the stream and forest may be regarded as one ecosystem. The shading of streams by trees and the supply of fine and coarse organic debris to streams are essential for maintaining water quality and aquatic habitats. Thus, snags and logs fulfil a number of functions, including providing habitat, contributing to nutrient cycling, preventing soil erosion and acting as "bridges" between old-growth forests and young regrowth forests, particularly after a major disturbance (Franklin et al., 1997).

Communities whose physiognomies, structures, and compositions are similar are generally found on similar sites (Numata, 1974). Based on this, communities can be systematically classified; for example, by the Zurich-Montpellier method. *Fagus crenata* (buna)-*Sasa kurilensis* (chishimazasa) and *Abies firma* (momi)-*Illicium religiosum* (shikimi) associations are examples of forest communities in Japan which have been classified by their physiognomy and composition. Such a classification is helpful for the comparative discussion of communities and is commonly used.

Autoecological theories have been developed to understand the structure and composition of a community (e.g., Whittaker, 1970). A community is composed of individuals of the same and/or different species and within the community, there can be relationships of cooperation, mutualism, commensalism, amensalism, or disoperation and competition (Watanabe, 1994). These relationships can be analyzed in terms of individual species attributes which determine their relationship to the environment. Such attributes include reproductive or breeding systems, growth rate, shade tolerance, and life span.

2.4.2 Flow of energy and materials

There is a flow of water, carbon, nutrients, and energy within a forest community and between the community and the environment surrounding it (Figure 2-2). The flow of energy and minerals occurs through the food chain, the carbon cycle, the nutrient cycle and the water cycle.

The food chain commences with photosynthesis by plants, which converts carbon dioxide and inorganinc matter into biomass (primary production). Consumers eat the plants and are in turn eaten by other consumers. This production of biomass based on the consumption of organic matter produced by photosynthesis is called secondary production. Thus, organic matter and the energy accumulated in it are transferred between organisms. When plants and animals die, decomposers such as microorganisms and fungi convert the organic matter back into inorganic substances (Whittaker, 1970; Kimmins, 1987; Perry, 1994; Barnes et al., 1998).

The water cycle is the exchange of water and energy between the atmosphere and the forest community. A large proportion of precipitation which falls on forests is returned to the atmosphere by evapotranspiration and in this process a large proportion of solar energy entering forests is returned to the atmosphere as latent heat in the water molecules. In a young *Chamaecyparis obtusa* (hinoki) stand in Japan, for example, the ratio of evapotranspiration to precipitation was 50-80% during the growing season and the ratio of latent heat of evapotranspiration to solar energy was slightly higher than 50% (Chikarashi et al., 1987). When water vapor is condensed into droplets in the atmosphere, latent heat is discharged and the atmosphere is warmed. This cycling of water and energy by forests moderates temperatures by protecting the ground from excessive heating.

Carbon and nutrient cycling within forest communities enables the recycling and reuse of the components of biomass. Leaves and fine roots generally wither and die within a period of several days to several years. The dead leaves and roots are shed, providing a constant supply of organic matter to the forest floor. Larger trunks, boughs and thick roots are also occasionally shed. Some of this dead biomass is eaten by soil animals, but most is decomposed by fungi and returned to soil as inorganic matter. Decomposition provides a source of nutrients, such as nitrogen, phosphorus, and magnesium, which is then re-absorbed by the trees through their roots. Uptake by trees is often enhanced by mycorrhizae. Once a forest has developed, it can supply a high proportion of its nutrient requirements itself and this self-fertilizing ability is an important characteristic of forests. Additional nutrients are supplied by the fixation of nitrogen from the air by bacteria, weathering soil parent material, and rain. Snags (dead standing trees) and logs (dead fallen trees) also contribute to nutrient and carbon cycling and are important for soil and water conservation (Franklin et al., 1981; Spies, et al., 1988; Franklin, 1989; Harmon et al., 1990; Franklin and Spies, 1991; Swanson and Franklin, 1992; Perry, 1994; Franklin et al., 1997). Large snags and logs are significant reservoir of organic matter in forests, playing an important role in the long-term cycling of energy, nutrients and carbon.

The flow of energy and materials in forest ecosystems is directly related to the functions of forests that are important to humans, such as conservation of soil and water resources, production of wood, mitigation of the microclimate or climate, and the carbon budget of the globe.

2.4.3 Disturbance and regeneration mechanisms

Forest stands seem stable after they have become established, but they are dynamic. Each individual has a limited life span or can be killed prematurely by natural agents. Regeneration occurs either following the death or damage of trees or while overstorey trees are still alive. Disturbances are events which create new environments in forests and these events are essential for the regeneration of forests (Franklin and Hemstorm, 1981; Neilson and Wullstein, 1983; White and Pickett, 1985; Nakashizuka and Yamamoto, 1987; Oliver and Larson, 1990). Disturbances may be caused by natural or human impacts such as fire, strong winds, logging, and include death by natural mortality. Disturbances are usually considered allogenic phenomena, but in many cases they are partly autogenetic, because the impact of a disturbance is the result of both the magnitude of the disturbance and the predisposition of the stand to a particular type of disturbance (Odum, 1971; White, 1979; Nakashizuka and Yamamoto, 1987; Barnes et al., 1998).

Tree species have various regeneration mechanisms including both sexual reproduction from seed and asexual reproduction by vegetative sprouting. When a disturbance occurs, species with regeneration mechanisms adapted to the environmental conditions will regenerate successfully. During the herb/brush stage or stand initiation stage (Section 2.4.4 in this Chapter), severe interspecific competition occurs and the competitive advantage of an individual tree or species is largely determined by the timing of disturbances and regeneration mechanisms. Manipulation of disturbances and regeneration allows different stand structures of a forest to be achieved. Such manipulation can be done using silvicultural techniques. A basic knowledge of the mechanisms of natural regeneration is necessary not only for natural regeneration techniques but also for artificial regeneration techniques. The age when seed production commences and the type of sprouts produced at different ages are important factors that dictate the species composition of a regenerating forest. Rotation length is also an important determinant of species composition in secondary forests (Kamitani, 1986a). Information about the species' ability to produce seed or sprout in relation to tree age is important for determining appropriate silvicultural methods as discussed in Parts II and III. Secondary forests are those forests that are at a seral stage in secondary succession following major natural or artificial disturbance.

2.4.3.1 Regeneration mechanisms

There is a fundamental difference between sexual reproduction from seeds (Figure 2-14) and asexual vegetative regeneration (Figure 2-15). Most species can regenerate from seed but some are dependent on

Figure 2-14 Regeneration of *Betula maximowicziana* (udaikanba) from seed.

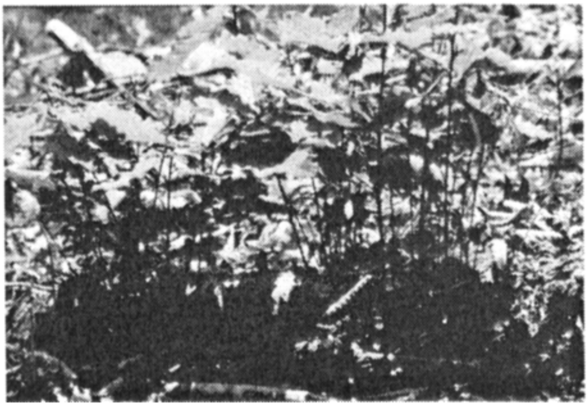


Figure 2-15 Regeneration of *Quercus crispula* (mizunara) by coppice. (Photograph by T. Kamitani)

vegetative regeneration. Regeneration from seed enables genetic recombination. New individuals may survive on new sites or may be exposed to unfavorable conditions and killed. Vegetative regeneration maintains genetic composition and limits the ability of plants to extend their habitat, but enables a dominating species to regenerate rapidly *in situ* and maintain its dominance.

Sexual regeneration

Following germination, trees develop asexual organs such as stems, leaves, and roots and then after a certain period, begin to produce flowers, fruit and seeds. The stage in which trees do not produce flowers, fruit, or seeds is called the juvenile stage and the stage in which they are produced is the adult stage (Barnes et al., 1998). Generally, fast-growing, shade-intolerant species, such as poplars and birches, produce seeds sooner than slow-growing, shade-tolerant species, such as beeches and firs. In Japan, poplars produce seeds at about 10 years of age, while beeches and firs from 40 to 60 years (Kamitani, 1986b; Hashizume, 1991). The age of flowering and seed production can vary considerably depending on site conditions or stand structure. Seeds tend to be produced earlier and in greater abundance if the trees are growing in a more favourable environment (Matthews, 1963; Wilson, 1983; Kamitani, 1986b). Also, trees regenerated by sprouting produce seeds faster than those grown from seed (Kamitani, 1986b). The difference between species in age of seed production and life span, and the frequency of disturbance are important conditions determining species composition in a stand. Differences in sprouting ability also affect stand composition.

The cyclic nature of seed production is one of the most important traits of regeneration in a tree species. In general, fast-growing, light-demanding (shade-intolerant) species such as birches and pines tend to produce similar sized seed crops each year, and do not exhibit extremes of good and poor seed years. For example, observations of *Pinus densiflora* (akamatsu) in the Tohoku region in Japan over a 30-year period showed that seed years occurred 70% of the time and mast years (good seed years) occurred 27% of the time, but poor seed years only happened 3% of the time (Kato, 1971). Average seed years for *Pinus densiflor* occur at least every other year (Yanagisawa, 1965). The seed production of *Pinus densiflora* in average seed years is sufficient for successful regeneration. Similarly, average seed production satisfies the seed requirement for regeneration of most light-demanding, pioneer species.

Slow-growing, shade-tolerant species such as beeches and firs tend to have distinct differences between good and poor seed years and the interval between good seed years can be quite long. For example, observations of *Fagus crenata* (buna) in Tohoku in Japan over a 70-year period found that the average interval between mast years was 5.3 years, with a range of 3-8 years (Maeda, 1988). A mast year is usually followed by a poor seed crop, and good and poor seed years tend to be synchronized in different areas on both national and regional scales, although this is not always so (Hashizume, 1991; Hiroki and Matsubara, 1995). The same tendency is reported in *Chamaecyparis obtusa* (hinoki) (Sakaguchi, 1952).

The dispersal of seed can occur by animal vectors, gravity or the wind.

Windblown seeds are usually light and have aerodynamic structures which allow them to be disseminated long distances. Such seeds are generally small but are produced in such great numbers that the differences between good and poor seed years are inconsequential. Seeds of most pioneer species are windblown and can be rapidly disseminated, even to distant places. The seeds of some species with windblown seed may be dispersed into closed stands, where they will remain dormant if it is too shady to regenerate. Often, these seeds will be gradually buried under organic matter or mineral soil. This enables the seed to withstand extreme conditions such as drought for several years, decades, or even longer. As buried seeds are usually small and not palatable to animals they can accumulate over a long period of time, although some may die from various causes. When the light conditions are improved by a disturbance such as fire or logging and land preparation, they soon germinate. Buried seeds are often those of pioneer species and the seedlings grow rapidly, dominating the site at least during the herb/brush stage (stand initiation stage) (Smith, 1986; Barnes et al., 1998).

For some species, such as oaks, the seeds are large and contain a large amount of food reserves, but the actual number of seeds is low. Acorns of oaks are disseminated below and just beside their parent tree by gravity. The germinated seedlings survive on the food reserves stored in the seed until they reach a stage where they can survive by photosynthesis alone. Such seeds and seedlings cannot survive dry or hot conditions, but can persist in shady conditions. Therefore, they can survive under a canopy until a disturbance creating a small gap occurs (Smith, 1986; Barnes et al., 1998).

The large quantity of food reserves in such seeds make them a good food source for mammals such as rodents. These seeds are therefore prone to scavenging. However, species with large seeds generally have comparatively long intervals between mast years, with poor seed years in between. This helps control the population of seed predators. Under normal seed production levels, the predator population is kept low because of the limited supply of seed. However, sporadic good seed production provides sufficient seed to feed the predators and to regenerate the species (Miguchi and Maruyama, 1984; Barnes et al., 1998).

Seeds can be dispersed by animals either prior to or following a disturbance. Palatable seeds are eaten by animals, such as rodents and birds. This has both advantages and disadvantages for the regeneration of the species. Some animals (e.g., rodents and some insects) and birds [e.g., the jay (*Garrulus glandarius*)] transport and hoard seeds by burying them in the soil within or beyond the stand. Although most seeds are eaten, this habit seems favorable to the regeneration of the tree species if any seeds are left uneaten by chance (Nakamura and Kobayashi, 1984). Birds eat the fruit of many species, such as cherry, *Rubus*, and *Vaccinium*, and disperse the seeds when they excrete them. In many species, the sarcocarp of the fruit contains retardants which hinder germination until the seeds are eaten. The dispersal of seed by animals and birds into new environments contributes to succession.

Asexual regeneration

Many hardwood species (e.g., oaks, ashes, and hornbeams) and some conifers [e.g., *Sequoia sempervirens* (redwood)] are capable of sprouting from their stumps if they are cut or damaged. Other species can regenerate from root suckers, by air layering or following fragmentation. Asexual regeneration is an important mode of reproduction for some species.

In most species which sprout from their stumps, the sprouts develop from the side of the stump, but in some species, sprouts grow from the cambium on the face of the stump (Kawakami, 1958; Kamitani, 1986a). This type of sprout probably arises from adventitious buds, and are generally not viable, as the connection between the sprout and the sapwood of the stump is not firm and the sprouts are vulnerable to breakage by snow or wind (Fujishima, 1932). Those species that produce sprouts from near the roots and or side of the stump tend to produce viable shoots. As sprouts age, the number of shoots generally decreases, although the extent of self-thinning of the sprouts is species-dependent. It is particularly noticeable in *Quercus acutissima* (kunugi), for instance, but not in *Quercus serrata* (konara) in Japan (Forestry Agency of Japan, 1991). Sprouts from vigorous stumps generally grow faster than seedlings of the same species germinated at the same time as cutting the stump. This is because the sprouts can grow immediately after the stump is cut and use the food reserves in the stump and roots.

Layering can occur if the lower branches of a tree touch the ground or the lowermost parts of bending branches are buried in litter or soil. The buried branches take root and new individuals are produced. This type of regeneration is important for *Cryptomeria japonica* (sugi) in snowy regions in Japan. Lower branches of *Cryptomeria japonica* are often bent by the weight of snow and if the branch reaches the upper soil layer, it may take root (Figure 2-16).

In regeneration by fragmentation, branches that are broken off by wind or falling tephra during volcanic activity can take root after being buried in soil or ash. Fragmentation is common amongst willows (*Salicaceae*).

2.4.3.2 Disturbance agents

Ecologically, disturbance is necessary for regeneration but it is usually regarded as disastrous from a forestry perspective. Therefore, it is necessary to understand the relationship between disturbance and

Figure 2-16 A selection forest of *Cryptomeria japonica* (sugi) regenerated by layer in Akita Prefecture, Japan.

regeneration and how to mimic the effects of natural disturbances through "artificial disturbances" such as felling and harvesting. This is discussed further in Parts II and III, and here only the relationship between disturbance and regeneration is considered. Each disturbance agent is characteristic in its behavior and the conditions it creates for regeneration.

Fire

On a global scale, the most influential natural disturbance affecting regeneration and forest stand development is fire. Each year, there are an estimated 50,000 forest fires caused by lightning worldwide, about a fifth of which occur in the United States of America (Taylor, 1974). Natural fire is liable to occur and spread widely in the regions where the dry season and warm season are concurrent (Figure 2-17). In general, such conditions are found in boreal forests, forests in western and inland regions of continents in temperate and sub-tropical zones, and summer green forests in the tropical zone. Natural fire is usually rare in tropical rain forests or forests in eastern regions of continents in temperate or sub-tropical zones in the northern hemisphere. In most of these regions, warmth and drought do not combine, and because decomposition rates of litter (fuel) are high, the accumulation of fuel is limited and it is hard to ignite because of its moisture content (Borman and Likens, 1979; Uhl et al., 1998). In the southern hemisphere, however, south-eastern Australia is one of the most fire-prone regions in the world. Summer is the dry season in this region, and catastrophic fires are characteristic under conditions of extreme drought, when fuel loads are high and the fuel moisture content and soil

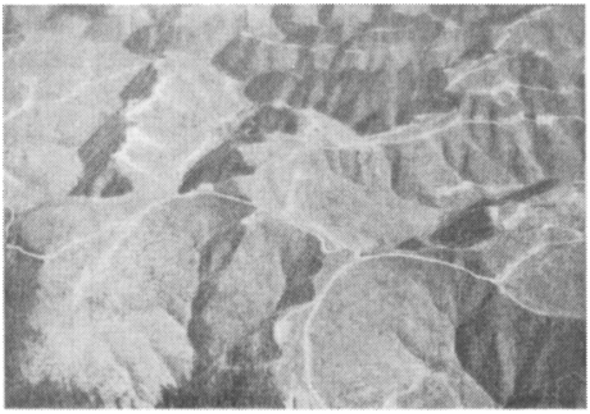


Figure 2-17 A forest land affected by a large scale fire in Coast Range of Oregon State, the United States of America.

moisture contents are very low (Walker and Singh, 1981).

Although fire is often perceived as a disaster that must be prevented, fire is an essential driving factor for ecosystems where it occurs naturally. Some pine species such as *Pinus contorta* (logepole pine) and *Pinus banksiana* (jack pine) in North America cannot survive without fire, because the cones remain closed until the cones are heated by fire. When the cones accumulated over years are heated by fire, they open easily and the seeds are disseminated onto the burned ground which provides favourable conditions for these light demanding pines to regenerate (Barnes et al., 1998). The species composition of many eucalypt ecosystems in Australia is a consequence of the intensity and frequency of fire (Walker and Singh, 1981). Fire is also essential for some ecosystems to maintain their character. In the *Pinus ponderosa* (ponderosa pine) forests in interior western North America, the reduction of fire frequency because of increased control measures unexpectedly led to the increased duration and intensity of spruce budworm outbreaks. This happened because fir trees, which are hosts to the budworm, were able to invade *Pinus ponderosa* forests in the absence of fire (Perry, 1994).

Human induced fires are much more widespread than natural fires, and they affect forests that would not normally experience fire, such as tropical wet forests (Kaufman et al., 1990; Barnes et al., 1998; Toma, 1999; Mori, 2000). These fires are often associated with developmental activities, and tend to be larger in extent than natural fires, varying from a few hectares to thousands of hectares (Lähde et al., 1999). In the boreal zone forests of Europe, genuine natural forest fires are relatively rare. However, at the height of the slash-and-burn cultivation period, plantation fires occurred frequently, sometimes only decades apart. In Japan, the total area of forest land affected by fire each year has decreased greatly during 20th century, i.e., the affected area in the later period of the century is less than 25% of that in early period of the century (Nakamura, 1954; Fire Defense Agency of Japan, 1990). This may be because burning is no longer used to prepare land for artificial regeneration of forests, shifting cultivation has ceased and maintenance of grazing areas by repeated burning no longer occurs. The accidental fires that must have started as a result of these practices probably affected the species composition of the forests in Japan, although precise information is not available. However, species such as *Quercus serrata* (konara) and *Quercus crispula* (mizunara) and the pioneer species *Pinus densiflora* (akamatsu) are prevalent in and around areas where frequent burning was common. These species have thick insulative bark, which is common trait of fire resistant tree species. In addition, oaks (*Quercus*) and many other hardwood species; have the ability to sprout, which enables individuals to survive fire.

Forest fires are generally classified into three types (i.e., surface, crown, or ground fire) depending on their intensity and thus the strata of the forest that they burn. Surface fires generally burn the forest floor and low vegetation. Pole-size and mature trees of fire resistant species survive light surface fires in varying proportions. However, intense surface fires may damage even the cambium of fire resistant species and leave a scar (Barnes et al., 1998). Crown fires may develop from surface fires if winds are strong. These fires travel from one crown to another, killing most trees in their path. However, even in intense crown fires, unburned strips may be left due to powerful, downward air currents. Conifers are most susceptible to crown fires because of the high flammability of their foliage (Barnes et al., 1998). In surface and crown fires, the roots of plants are usually not killed and species which can propagate by sprouting soon regenerate. Ground fires are lingering fires that continue to burn or smolder in the soil. They are most prevalent in peaty soils. Trees with surface roots are commonly killed by ground fires because their roots are burned (Oliver and Larson, 1990).

The extent of tree mortality depends on the intensity of fire, the species, the age of tree, and rooting habit. Young pines may succumb to a surface fire, whereas older individuals of the same species survive due to thicker bark protecting the cambium from heat damage and the higher elevation of the crown above the flames (Barnes et al., 1998).

Different fire regimes are distinguished by the type, frequency, and intensity of the fires. Frequent or infrequent surface fires are generally non-lethal and only affect the understorey. Depending on the extent of the damage, species composition of the understorey may change. Crown fires of any frequency tend to be stand-replacing fires because of the extensive death of trees. Variable mixed fires are combinations of understorey and stand-replacing fires (Barnes et al., 1998).

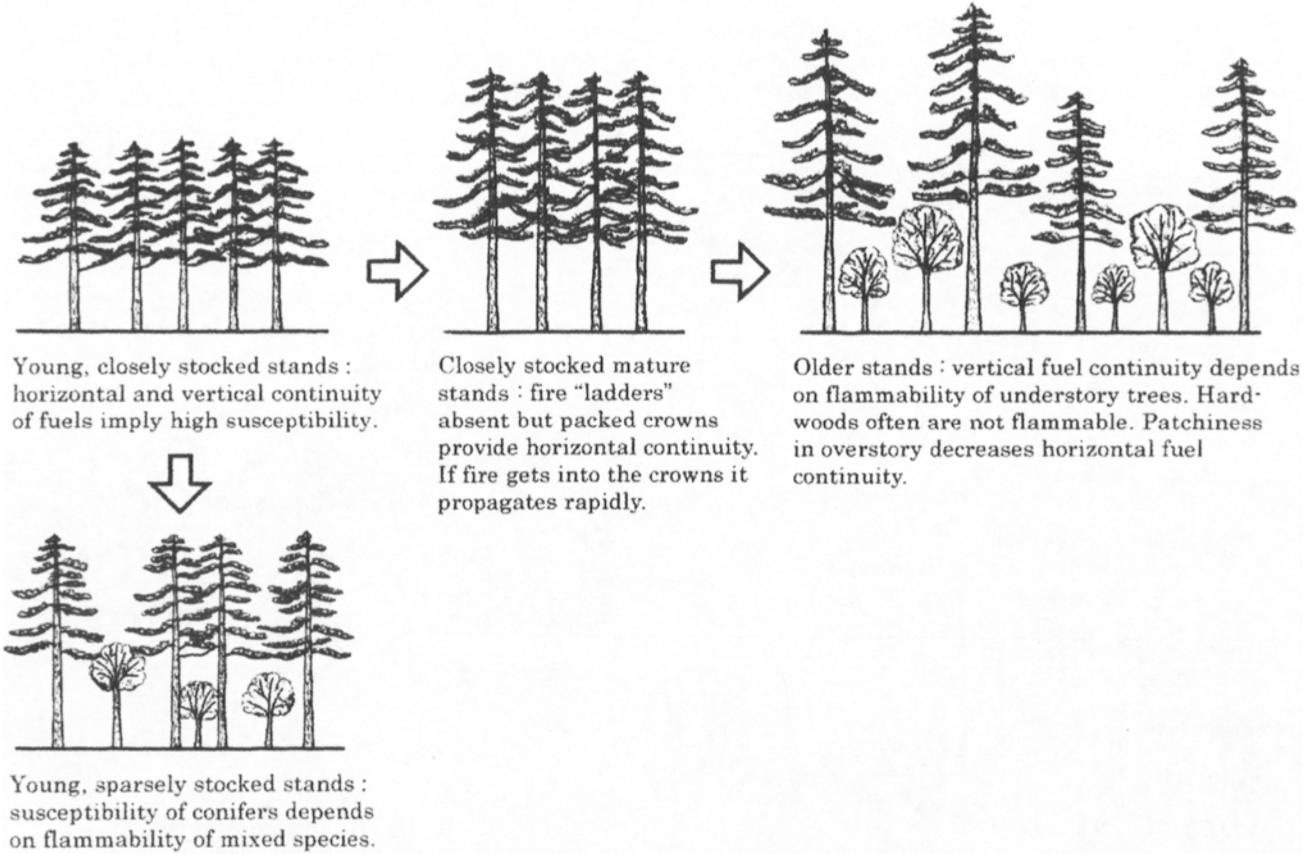
The relationship between stand development stage (or stand age) and susceptibility to fire is complex and likely to vary depending on regional climatic conditions and forest type. Age is an indirect determinant of fire susceptibility, being important only as far as it determines forest structure, which influences the distribution and flammability of fuels (Figure 2-18). Generally, conifer forests tend to be most vulnerable to crown fires when young, again when very old, and least vulnerable during their middle years (mature stage) (Perry, 1994). However, there are exceptions, as shown in Figure 2-19. Old-growth *Picea abies* (Norway spruce)-dominated stands in the boreal forests of Europe seem to be less vulnerable to fire if the extent of the disturbance is limited. After a fire, some trees survive and partially cover the area (Lähde et al., 1999). Regional climatic conditions are therefore likely to be greater determinants of fire susceptibility than forest type.

Wind

Throughout the world, wind is probably the second most important natural disturbance after fire. Strong winds may result from tropical depressions (typhoons, hurricanes, and cyclones), temperate depressions, frontal passages, tornadoes, or thunderstorms. Disturbances by temperate depressions and frontal passage are common in many regions of the world, but are not as severe as disturbances caused by tropical depressions or tornadoes.

In eastern Asia, including eastern China, the Philippines, Japan, and Korea, the most common and influential disturbance is typhoons, which are defined as tropical depressions whose maximum wind speed is greater than 17 meters per second. Typhoons generally occur over summer and fall, beginning in and around Micronesia then usually moving northwest then northeast. Many typhoons are accompanied by heavy rainfall. Precipitation of several hundred millimeters from a single typhoon is not rare. This can cause landslides and floods. On average, about 60 tropical depressions (typhoons, hurricanes, and cyclones) occur throughout the world each year, 45 percent of which are typhoons. Typhoons are stronger than other tropical depressions; the mean annual minimum pressure of typhoons is 915 hectopascal, compared to 951 hectopascal for other tropical depressions (Kurashima, 1973). Between 1941 and 1960, an average of 27 typhoons occurred annually. About 4 typhoons struck Japan each year between 1931 and 1960 (Takahashi, K., 1971).

The damage caused by wind can be extensive, but is often patchy. Typhoon No. 15 of 1954 disturbed large tracts of old-growth natural forests in Hokkaido when it struck Japan. In the hardest-hit areas, many *Picea jezoensis* (ezomatsu) — *Abies sachalinensis* (todomatsu) old-growth forests were uprooted. The average area of single patches of forest completely destroyed by this typhoon was 15 ha (Tamate et al., 1977). In 1991,



Young, closely stocked stands : horizontal and vertical continuity of fuels imply high susceptibility.

Closely stocked mature stands : fire "ladders" absent but packed crowns provide horizontal continuity. If fire gets into the crowns it propagates rapidly.

Older stands : vertical fuel continuity depends on flammability of understory trees. Hardwoods often are not flammable. Patchiness in overstory decreases horizontal fuel continuity.

Young, sparsely stocked stands : susceptibility of conifers depends on flammability of mixed species.

Figure 2-18 Some aspects of stand structure that influence susceptibility of conifer forests to crown fires. (Perry, 1994)

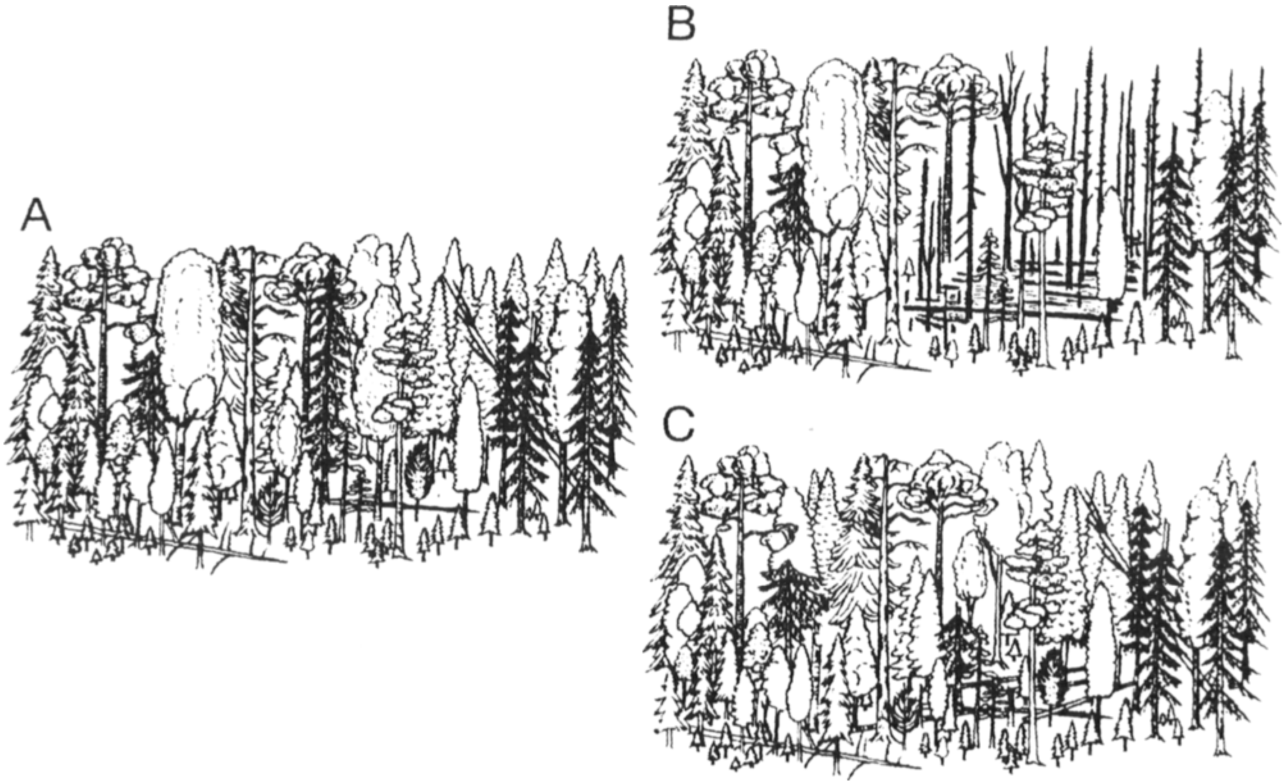


Figure 2-19 Example schemata of forest stand dynamics after annual disturbances in the Finish Boreal Zone. A = Typical naturally developed old-growth *Picea abies* (Norway spruce)-dominated stand. B = Same stand after wild forest fire. Trees still partly alive maintaining the area covered. C = Initial stand after wind-blow. Some trees or groups of trees broken or fallen. (Lähde et al., 1999)

typhoon No. 19 struck northern Kyushu, southern Japan, severely damaging mostly *Cryptomeria japonica* (sugi) plantations (Figure 2-20). The disturbed patches ranged in size from less than 1 ha to 60 ha, with most comprising several hectares (Fujimori, 1992a). The limited size of damaged patches from this typhoon might be attributed to the complex topography and ownership patterns, where each owner has only a small area of forest.

Two powerful hurricanes (John and Gilbert) swept through tropical forests in the Caribbean and Central America during 1988. John destroyed much of the canopy over 500,000 ha of primary forests Nicaragua. Gilbert defoliated dry tropical forests in the Yucatan peninsula of Mexico and blew down approximately 25% of the trees in Jamaica's montane forests. Another powerful hurricane (Hugo) passed directly over the largest rainforest in Puerto Rico in the fall of 1989, heavily damaging about 9000 ha of the 11,000-Caribian National Forest. Hugo then moved north along the east coast of the United States of America, coming ashore in South Carolina to heavily damage roughly half the sawlog stands in the Francis Marion National Forest (Perry, 1994).

The type of damage caused by wind is not determined solely by the force of wind; it also depends on the structure of forests, i.e., species, age, and stand density. Coniferous trees are more susceptible to wind than broad-leaved trees (Isamoto & Takamiya, 1992; Fujimori, 1995). There may also be a relationship between stand age and wind resistance of a stand, although there is little data to support this. Figure 2-21 shows the relationships between stand age and the proportion of stands damaged in

Figure 2-20 A heavily damaged *Cryptomeria japonica* (sugi) stand by Typhoon 19 in 1991 in northern Kyushu, Japan.

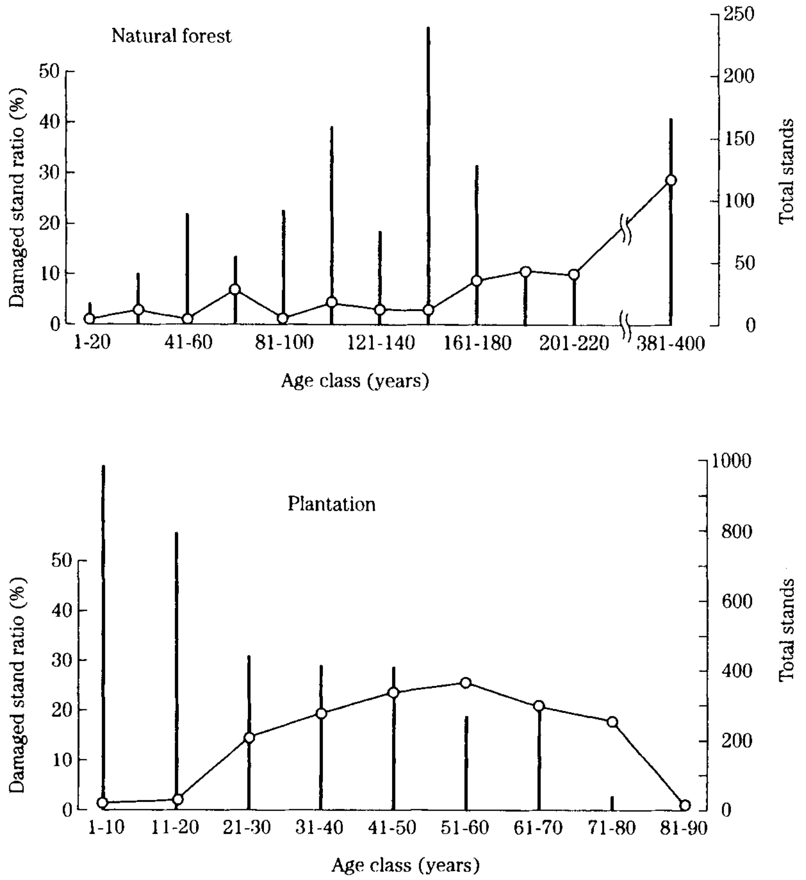


Figure 2-21 Proportion of stands damaged and total number of stands by age class in the Tokyo Regional Forestry Office area after Typhoon 7 in 1959. Open circles and vertical bars represent the proportion of stands damaged and the number of stands, respectively. (Fujimori, 1995)

coniferous plantations and natural forests of mainly broad-leaved trees in the same region in Japan and affected by the same typhoon. In the plantations, damage was limited in stands up to 20 years of age, then increased and peaked in stands about 50 years old, then decreased again. As there were few older stands, more data are needed to establish the effects of typhoons on older stands and therefore consider appropriate rotation lengths and stand density control measures (Part III). In the natural forests, the proportion of damaged stand was low in forests less than about 160 years old. It then increased, although the relationship was not linear. Figure 2-21 implies that the wind resistance of coniferous plantations is lower than that of natural broad-leaved forests. However, age class or stand development stage must be considered when discussing the wind resistance of a forest. Sudden exposure of trees to wind following silvicultural activities such as intense thinning can increase windthrow (Fujimori, 1992a; Perry, 1994).

Uprooting creates humps and hollows of mineral soil and breaks up the dense cover of understorey species such as dwarf bamboos, thus providing suitable conditions for regeneration of trees (Oliver and Larson, 1990; Yamamoto, 1995). Light-seeded species such as birch may invade, or advanced growth be released and develop rapidly. Although the development of advanced growth is generally favoured by windthrow, it may be killed by the sudden change in the microclimate if the gap is large and the climate severe (Tanimoto et al., 1987). In many cases, the secondary succession that occurs following windthrow will therefore consist of a mixture of shade tolerant species released from the understorey together with pioneers that have invaded the site (Spurr and Barnes, 1980). Each species will have an optimum gap size for regeneration at each site. Generally, comparatively smaller gaps are preferable for advanced growth and larger gaps offer more opportunities to pioneers. This is discussed further in Chapter 8.

Most investigations of wind damage concentrate on the most severely damaged areas. Information on both major and minor disturbances is necessary for a full understanding of regeneration in relation to the disturbance by wind.

Landslide

The frequency of landslides depends on various factors, particularly the angle of the mountain slope, properties of the parent materials, and the climate. Landslides remove all buried seeds, advanced growth, organic matter, and soil. However, exposed mineral soil or rock provides suitable regeneration sites for windblown seeds of some pioneer species such as pines and birches. The areas where the dislodged soil accumulate are also favorable for the germination of windblown seeds, but the opportunity for buried seeds to germinate is low because the soil profile is disturbed. Areas affected by landslides are usually restored by artificial revegetation, with the expectation that natural regeneration by windblown seeds will follow.

Volcanic activity

The consequences of volcanic activity with respect to the disturbance and regeneration of forests depend on various factors including the type of ejecta, depth of deposited tephra (ash), and the time of year of the eruption. Forest trees are killed, injured, or their growth restricted by the heat of falling tephra, battering by coarse pumice, or the coating of leaves with fine tephra. The forest floor may be covered by tephra, which can kill advanced growth and buried seeds. Flowing lava kills all living things and it takes many years for trees to regenerate and establish cover (Tagawa, 1964).

The source and type of regenerate differs depending on the extent of damage. In areas where the deposited volcanic ash is thin and/or surface erosion occurs, seedlings from buried seeds and sprouts from plants buried under the ash survive and dominate, whereas seedlings from windblown seeds dominate in areas where the ash is thick and erosion is minimal (Riviere, 1982; Toyooka et al., 1983; Ito and Haruki, 1984). The effects of volcanic activity on forests differ according to the species composition. *Populus maximowiczii* (doronoki) and *Quercus crispula* (mizunara) can both regenerate following damage by volcanic activity. *Populus maximowiczii* regenerates by fragmentation (Ito and Haruki, 1984), and *Quercus crispula* survives the volcanic impact with its thick, corky bark which resists the heat and impact of volcanic ejecta, and it recovers by growing epicormic buds and sprouts. *Fagus crenata* (buna) is not resistant to volcanic damage (Tsumura, 1929, 1935), because it does not have any protection or recovery mechanisms.

Avalanches

In Japan, species common to avalanche-prone areas include *Quercus, Alnus, Weigela*, and *Sorbus*. These species are flexible to bending and capable of regeneration by sprouting (Iizumi and Kikuchi, 1980; Yuasa et al., 1981; Onodera, 1990). The path of an avalanche offers a gradient of disturbances from very severe in the upper start zone to mild in the lower runout zone, with varying regeneration mechanisms being favored along the gradient. The start zone of an avalanche is generally scoured as the slipping snow removes the vegetation. Species with light, windblown seed commonly regenerate in the upper zone, sprouting species are common in the central zone, and advanced growth species favor the runout zone (Oliver and Larson, 1990).

Flood

Floods, erosion, and landslides are generally associated with heavy rainfall. Floods are important for the regeneration of forests near rivers, especially for certain species such as willows (Kaneko, 1995; Sakio, 1995; Sakio et al., 1995). Willows can rapidly regenerate on the silt deposited by floods. However, a high percentage of rivers in the world have now been blocked by artificial banks and most riparian forests have been replaced by farmlands or residential areas. As a consequence, riparian forests and flood storage basins have largely disappeared, along with their characteristic species such as willows, alders, and elms, and the conservation of riparian forests is therefore urgently required.

Insects and disease

Trees weakened by overcrowding, strong winds, age, or other agents are susceptible to damage from insects and disease, which in turn may make them vulnerable to weather damage. Therefore, insects and disease can play both a direct and indirect role in accelerating succession. Introduced insects and disease can inflict severe damage even in healthy trees, and it is not rare for most of the dominant trees of a stand to be killed within a few years of the introduction of a new pest. This is discussed more in detail in Section 15.3.2.2.

Mammals and birds

As previously mentioned, animals play an important role in the dissemination of seeds, and they also induce disturbance by killing trees. Browsing by rabbits, deer, antelopes, and other animals can kill seedlings and saplings. Rodents, rabbits, deer and bears eat the phloem (inner bark) of trees, either partially or completely girdling the trees. Girdled trees are either killed or their growth is reduced and the wounds become entry-points for pathogens. Large mammals such as *Sus scrofa* (inoshishi) and deer graze dwarf bamboo or other undergrowth and they often scarify the soil when seeking food. Acorns hoarded in exposed soil by rodents may regenerate. A decrease in the numbers of such mammals may have negative effect on the regeneration of trees (Watanabe, 1994).

Logging

The greatest difference between natural disturbances and logging is that logging times and operations are planned. The scale of logging ranges from clearcutting of large areas to cutting of individual trees in thinning or selective cutting operations. Regeneration and the successive stand structure varies depending on the condition of the logged stand, the surrounding stands, and the method of logging. This is discussed in Parts II, III, and IV. Although the processes of logging and timber removal disturb the undergrowth and soil, normally land must be treated after logging to create conditions conducive to natural or artificial regeneration.

2.4.3.3 Regeneration in response to disturbance

Disturbance of the forest floor is vital for many types of regeneration. Removal of vegetation provides favorable light conditions, and exposure of the mineral soil provides a better environment for seeds to germinate and survive. On unshaded sites, the forest floor litter can become very hot (as high as 75°C) and rapidly lose moisture (Smith, 1986). In these conditions, most seedlings which germinate in the litter layer are killed by drought during the first summer, because their roots have not yet reached the mineral soil layer or their roots are exposed to lethally high temperatures.

The type of regeneration that follows disturbance is determined by the severity of the disturbance. Severity can be classified according to the frequency, extent and impact of the disturbance, as measured by the impacts to the forest soil and the forest floor vegetation. Disturbance which completely destroys or covers the soil layer and vegetation, such as may be caused by a landslide or lava eruption, is more severe than that caused by other agents such as logging or windstorms. Succession which starts on a site on which there is no soil or vegetation is called primary succession, and that which occurs on a site where there is soil and/or vegetation is called secondary succession. The extent of the disturbance is another factor determining which species can regenerate. However, the affected area varies greatly even among sites disturbed by the same agent, and therefore trying to categorize the type of disturbance by the area affected is difficult. Even so, some types of disturbance, such as death of individual trees from old age, logging, snow damage, and windstorms are often smaller in area than other types of disturbance. Categorizing the type of disturbance by frequency is also difficult because frequency differs considerably from site to site.

Table 2-1 shows some general patterns of regeneration mechanisms according to disturbance severity. Severe disturbances, such as floods, eruptions, landslides, and fire, eliminate both overstorey and understorey vegetation and can alter the soil profile or expose mineral soil. Regeneration following severe disturbance is restricted almost completely to windblown seeds that can cope with the large differences between minimum and maximum temperatures and high levels of water loss by direct evaporation. Some less extensive disturbances, such as uprooting by windstorms, create mounds of mineral soil which are favorable for the regeneration of newly disseminated seeds. Less severe disturbances such as crown snow damage, minor windstorm damage or logging, do not remove the understorey completely, or severely disturb the soil. In these circumstances, regeneration is usually enhanced by removing the understorey, and to ensure successful regeneration by newly disseminated seeds, soil scarification is required. Slight disturbances, such as individual trees falling as they die followed by the rotting of the fallen logs, provide conditions suitable for the regeneration of conifers such as *Picea, Abies,* and *Tsuga*. Fallen logs provide sites free of dwarf bamboo cover, and improved substrate pH (Watanabe, 1994). For *Picea jezoensis* (ezomatsu), logs are preferable sites for isolation from soil-borne fungal blight such as *Phacidium* or *Racodium* snow blight (Takahashi, 1991). Fallen logs are favoured sites for regeneration of *Tsuga heterophylla* (western hemlock) in the Pacific Northwest of the United States of America (Franklin et al., 1981).

The desired species composition, their different regeneration mechanisms and requirements must be considered when developing

Table 2-1 Relationship between types of disturbance and regeneration mechanisms.

Type of disturbance	Regeneration mechanism		Windblown seeds	Buried seeds	Rhizomes	Root sprouts	Stump sprouts	Layering	Advance growth
Primary succession (Elimination of soil and all vegetation)	Lava eruption		○						
	Landslide		○						
	Flood		○						
Secondary succession	Hot fire		○	○	○	○			
	Cool fire		○	○	○	○	○		
	Avalanche	Upper zone	○	○					
		Center zone	○	○	○	○	○	○	○
		Runout zone					○	○	○
	Windthrow	Large area	○	○	○	○	○		
		Small area					○	○	○
	Logging	Large area	○	○	○	○	○		
		Small area					○	○	○

logging and regeneration treatments within a silvicultural method. Shade-intolerant pioneer species generally can tolerate the extreme temperatures that characterize sites subject to severe disturbance by quickly developing roots that penetrate below the upper soil layers. In contrast, shade-tolerant species can survive the shade of less disturbed sites, but cannot endure the harsh conditions of severely disturbed sites. Silvicultural methods are closely related to regeneration methods, which in turn determine harvesting methods. Therefore, the size and geometric features of the disturbed area that follows harvesting must maximize the chance of successful regeneration of each species within the area.

2.4.4 Stand development patterns

Succession

The word "succession" is widely used. The concept of succession has been discussed since the term was introduced by Clements (1916). However, modern concepts of succession differ from those proposed by Clements and other pioneers. Traditionally, it was believed that species change continually during succession and each species is replaced by ecologically similar species until the end of succession, when the species composition is stable. This stage was referred to as the climax. However, Watt (1947) proposed a patch dynamics theory, which has become widely accepted and greatly changed the old concepts of climax and regeneration mechanisms (White and Pickett, 1985).

Species composition within a stand may be determined by the species that enter the stand just after a disturbance or may be determined by species invading one after another as the environment is altered by the previous species. The first pattern is known as initial floristic composition (Egler, 1954) and has been identified in many case studies (Kimmins, 1987; Oliver and Larson, 1990; Osawa, 1992). The alternative pattern is known as relay floristics, and is observed where environmental modification is the major driving force of succession (Kimmins, 1987), such as on sites covered by volcanic ejecta where primary succession is occurring (Tagawa, 1964). Relay floristics is generally observed in the herb/brush stage (stand initiation stage).

Stand age and cohort

As a natural stand or plantation grows, it usually becomes vertically stratified, as different groups of trees develop canopy layers. Single-storied stands are often described as even-aged stands and multi-storied stands as uneven-aged stands. Strictly speaking, this is not always correct, because a stand can develop into a single storey as the stand ages, even if the age of individual trees differ. Conversely, if the species comprising the forest have different levels of shade tolerances and differing growth rates, trees that have established simultaneously can develop into a multi-storied stand (Harper, 1977; Oliver, 1981). In this context, the more recent terms of even-sized and uneven-sized stands have become common (e.g., Lähde et al., 1999).

A group of trees which develops after a single disturbance is referred to as a cohort (Bazzaz, 1983). A cohort can be regarded as synonymous to an age-class, a term which is commonly used in forestry, although the age range within a cohort can be as wide as several decades. Therefore, even if there is a wide range of ages in a stand which developed after a single disturbance, it should be called a "single-cohort" stand. In the same way, "uneven-aged" stands, i.e., stands with groups of trees which developed after several disturbances, should be called "multi-cohort" stands.

In multi-cohort stands, trees of a stratum or cohort are often aggregated rather than randomly distributed in the stand. Aggregations, or patches, within stands can be classified in two ways. One way applies to discrete shorter stratum surrounded by taller stratum, and is referred to as a gap. The other applies to a tall stratum surrounded by shorter stratum and is called a clump (Oliver and Larson, 1990).

Stages of stand development following major disturbance

Although stand development patterns vary according to the species which invade after the disturbance and the frequency and intensity of disturbances, they can divided into several stages. Four stages of stand structure development following a major disturbance were identified by Bormann and Likens (1979), Oliver (1981), and Franklin and Spies (1991). Each used different terms for the four stages, but the stages had the many characteristics in common. Emborg et al. (2000) described stand development as having five phases; innovation, aggradation, early biostatic, late biostatic, and degradation. The four stages of stand structure and their equivalent terms are defined below:

(a) First stage:

Bormann and Likens (1979) referred to this stage as the reorganization phase and defined it as the period immediately following the disturbance, when pioneering plants are establishing. Oliver (1981) referred to this stage as the stand initiation stage and defined it as the period when new individuals and species continue to appear which can last for ten years or more after the disturbance. Franklin and Spies (1991) referred to this stage as the herb/brush stage and defined it as the period before tree-canopy closure. This period may last for a considerable period if there is a lack of seeds because, for example, there was a large-scale disturbance and multiple subsequent disturbances (Franklin et al., 1981). This stage equates to the innovation phase defined by Emborg et al. (2000).

(b) Second stage:

Bormann and Likens (1979) referred to this stage as the aggradation phase and defined it as the period of rapidly accumulating leaf area and biomass. It is during this stage that the economic rotation of an even-aged forest crop usually occurs. Oliver (1981) referred to this stage as the stem exclusion stage and defined it as the period when new individuals do not appear and some of the existing ones die because of the intense competition during canopy closure. Franklin and Spies (1991) referred to this stage as the young stage and defined it as the heavily shaded period. The aggradation stage defined by Emborg et al. (2000) is equivalent to this stage.

(c) Third stage:

Bormann and Likens (1979) referred to this stage as the transition phase and defined it as the period when total biomass (living and dead) declines from the peak reached during the aggradation phase. Oliver (1981) referred to this stage as the understorey reinitiation stage and defined it as the period when forest floor herbs, shrubs, and advanced growth re-appear and survive in the understorey, although they grow very little. Franklin and Spies (1991) referred to this stage as the mature stage and defined it as the period when heavy shade reverts to intermediate shade. This is equivalent to the early biostatic phase defined by Emborg et al. (2000).

(d) Fourth stage:

Bormann and Likens (1979) referred to this stage as the steady state phase and defined it as the period when the biomass remains approximately constant, fluctuating only slightly around the mean. Oliver (1981) referred to this stage as the old-growth stage and defined it as the period when overstorey trees die in an irregular fashion, and some of the understorey trees begin growing into the overstorey. Franklin and Spies (1991) also referred to this stage as the old-growth stage and defined it as the period when the stand comprises living trees of various sizes, including old-growth trees, and has large snags, and large fallen logs. In unmanaged natural forests, large fallen logs usually persist even in other stages. The late biostatic and degradation phases defined by Emborg et al. (2000) are equivalent to this stage.

The phases defined by each of the above authors may overlap. The aggradation phase as defined by Bormann and Likens (1979) might correspond to the phases from the stem exclusion stage (young stage) to the beginning of the understorey reinitiation stage (mature stage) classified by Oliver (1981) and Franklin and Spies (1991). The transition stage as defined by Bormann and Likens (1979) might include the phases from the later part of the understorey reinitiation stage (mature stage) to the beginning of the old-growth stage as classified by Oliver (1981) and

Franklin and Spies (1991).

The versions of Oliver's (1981) and Franklin and Spies' (1991) definitions of each stage are used in this book, because the stages are well defined by structural traits. The stages classified by structural traits can be useful for the discussion on function of forests. The terms used are herb/brush, young, mature, and old-growth stages, because the terms are easy to understand. However, as the terms stand initiation stage, stem exclusion stage, understorey reinitiation stage describe the traits of the stages, these terms are used as well. Figure 2-22 shows models of the stand development stages for natural forests and plantations. A general description of each stage follows:

(a) Herb/brush stage (Stand initiation stage)

After a major disturbance, in unmanaged natural forests, new cohorts develop from advanced growth, buried seeds, newly disseminated seeds, and sprouts. As favorable conditions for regeneration and growth develop, various species invade and compete with one another. During this stage, herbaceous plants and fast-growing shade-intolerant species generally dominate initially, but their life span is short or their growth slows earlier so they are excluded during the herb/brush stage. Fast-growing shade-intolerant species such as pines and birches, which live longer and have continuing high growth rates, dominate during this stage. This dominance may continue into the young stage, the mature stage, or even until the old-growth stage. If shade-tolerant species invade during this stage, they do not generally develop much, but coexist with the growing shade-intolerant species and they may dominate in later stages.

Many species are present during the herb/brush stage. However, during this stage, most species and individuals are eliminated due to the unsuitability of their microsites, competition from other vegetation, or predation by animals. The herb/brush stage is also a period when many animals are found, since there is a variety of palatable plants and seeds available, and dense vegetation cover close to the ground which provides good cover. New species can continue to invade as short-lived herbaceous plants die and relinquish their growing space, or when other species begin to provide protection or improved the growing space (Oliver and Larson, 1990).

The most noticeable difference between natural forests and plantations during the herb/brush stage is that fallen logs and/or snags exist in natural forests but not generally in plantations. Logs provide suitable regeneration sites for seedlings, especially shade-tolerant species. Logs and snags also play an important role in preserving a part of the previous ecosystem and contribute to higher biodiversity (Franklin et al., 1981).

In plantations, logs are not generally found because the larger trunks are harvested and smaller ones are removed during land preparation. The

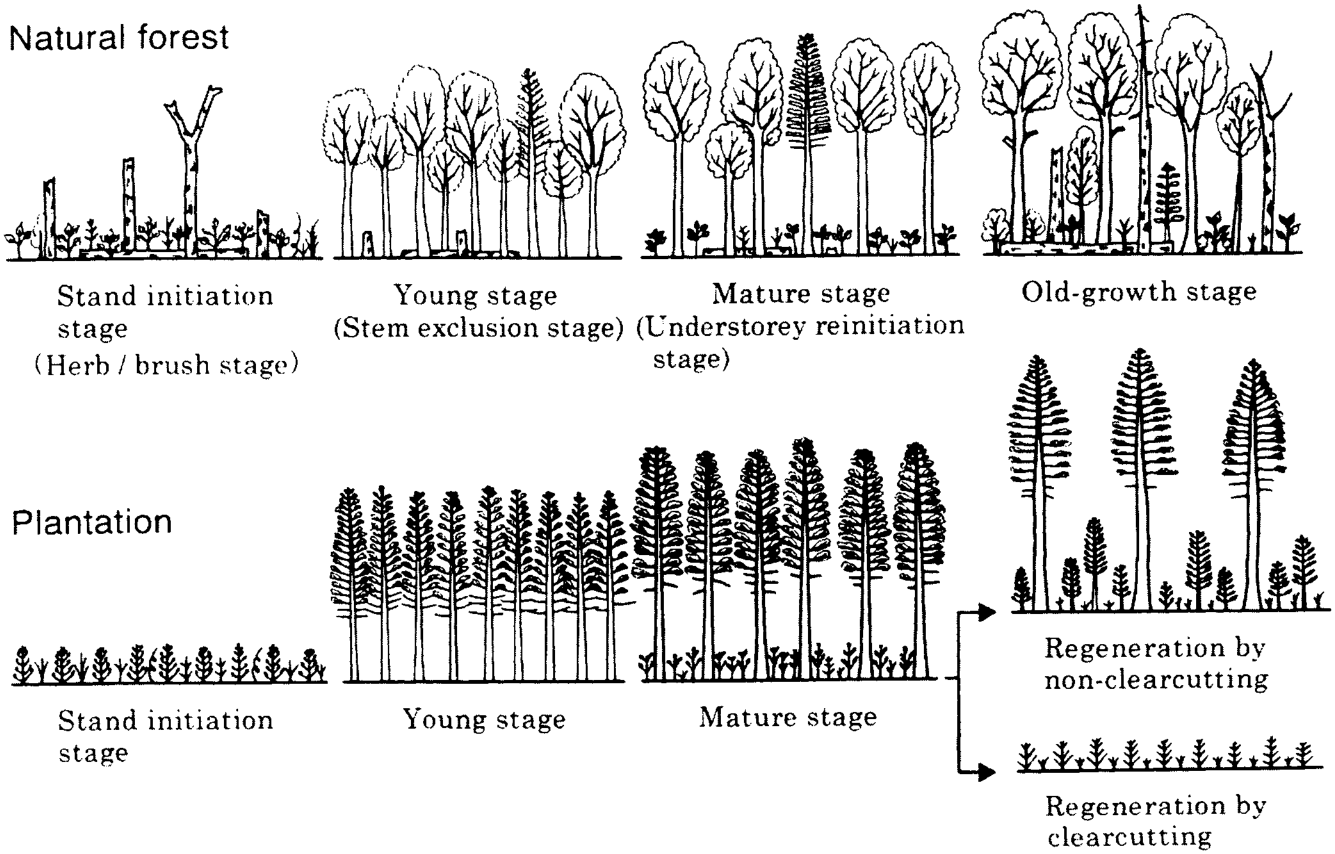


Figure 2-22 Models of general stand development for natural forests and plantations. This was drawn with reference to Bormann and Likens (1979), Franklin and Hemstorm (1981), Oliver (1981), Oliver and Larson (1990), and Franklin and Spies (1991).

microclimate of the regeneration site is therefore harsher, and light-demanding species tend to be more frequent. Therefore, the biodiversity of the herb/brush stage of plantations might be less than that of natural forests. The herb/brush stage of plantations, generally, is shorter than in natural forests, because weeding (Section 5.2) is practised when necessary and comparatively tall seedlings are often planted at uniform spacing.

(b) Young stage (Stem exclusion stage)

By the beginning of the young stage, the various species which developed in the herb/brush stage continue to compete and the growing space becomes completely occupied by a limited number of tree species during most of the young stage. Competition is intense and it is difficult for new individuals to invade the stand. During this stage, undergrowth is scarce because illumination on the forest floor is very low. This is one of the most notable physiognomical features of this stage. Biodiversity is lowest of all stages during this stage (Franklin et al., 1981, Oliver et al., 1985, Franklin and Spies, 1991).

In stands where a single species regenerates, a single canopy layer will develop. Plantations are the extreme case of this, because seedlings of identical size are planted at regular intervals, allowing the individual seedlings even growing space to develop crowns. After stand closure, the structure of a single-species plantation is the most simple. At this stage, branches of adjacent trees invade adjacent crowns and the stand is completely closed by a single canopy layer.

(c) Mature stage (Understorey reinitiation stage)

As the overstorey grows older, small vacant spaces between the crowns develop, allowing new herbs, shrubs, and trees to invade in the improved illumination of the forest floor. These spaces in the canopy develop because as the trees of the overstorey grow tall, the amplitude of the trunk sway increases, and the crowns collide, breaking twigs and abrading the outer branches of the crowns. At the same time, the elongation of the branches slows, and the crowns cannot close the canopy again. Light from the stand edge also increases as the trees of the overstorey grow taller.

In *Chamaecyparis obtusa* (hinoki) plantations, if a suppressed tree dies or a light or moderate thinning is conducted during the young stage, the gap in the canopy is refilled within a few years and undergrowth cannot develop. However, after 40 years, undergrowth starts invading even if thinning is not practiced (Kiyono, 1990). This is regarded as the transition to the mature stage.

During the mature stage, individuals of many tree species germinate but their growth is limited and they die within a period of a year to several decades. Regeneration is continual, although the regenerating individuals rarely survive for long period (Kiyono, 1990). Even if individuals live longer, their growth rate is very low, and the ratio of height growth of the main shoot to that of branches is smaller than that of trees growing in full sunlight, keeping the understorey clearly distinct from the overstorey. The mature stage generally contains more plant and animal species than the young stage (Oliver and Larson, 1990; Franklin and Spies, 1991).

(d) Old-growth stage

As stands grow older, the overstorey trees become weakened by aging and/or the accumulated effects of pathogens, pests, and climatic stresses. They may be destroyed by catastrophic disturbances like typhoons or hurricanes, but if such disturbances do not occur, the overstorey trees autogenically die. As the overstorey trees gradually die off, understorey trees whose growth was inhibited during the mature stage begin to grow more strongly, and stand becomes stratified. The autogenic condition achieved when the trees regenerate and grow without the influence of external disturbances is referred to as the old-growth condition (Oliver, 1981; Runkel, 1981). However, the term "old-growth" has also been used in terms of structure, i.e., a stand which is composed of various size of trees, large snags, and large fallen logs (Figure 2-23) and in this case the term

Figure 2-23 An old-growth stand dominated by *Pseudotsuga mensiezii* (Douglas-fir) and *Tsuga heterophylla* (western hemlock) in Cascade Range in Oregon State, the United States of America.

does not reflect whether autogenic or allogenic processes were involved in creating the structure (Franklin et al., 1981; Franklin and Spies, 1991; Spies and Franklin, 1991).

Gaps are created by individuals or groups of large old trees dying and falling, which leads to a multi-cohort, mosaic structure. Development of a forest following such minor disturbances has been referred to as gap phase development (Watt, 1947; Pickett and White, 1985). Old-growth forests do not always mean climax forests. Pioneer species like *Pseudotsuga menziesii* (Douglas-fir) continue to grow for over 500 years and up to 1000 years old if allogenic disturbances do not occur. After about 200 years, *Pseudotsuga menziesii* forests generally reach the old-growth stage, but the succeeding shade-tolerant *Tsuga heterophylla* (western hemlock), which is regarded as the theoretical climax forming species, does not generally dominate the overstorey. Within a period as long as 500 years, an allogenic disturbance will occur; hence theoretical climax forests are seldom found (Franklin and Hemstorm, 1981; Franklin et al., 1981).

The most distinctive feature of old-growth forests is the presence of large, live old-growth trees, large snags, and large fallen logs (Franklin et al., 1981). These components are essential to the functioning of the ecosystem because they play important roles such as providing habitat, contributing to the maintenance of the nutrient cycle (Franklin et al., 1981; Swanson and Franklin, 1992), and accumulating carbon (Spies et al., 1988; Harmon et al., 1990). Large fallen logs may protect the site from surface erosion by dissipating the energy of overland flow and they provide habitats for various organisms in riparian ecosystems (Franklin et al., 1981; Swanson and Franklin, 1992). The logs produced in the old-growth stage continue to fulfil these roles in the succeeding herb/brush, young, and mature stages (Spies et al., 1988; Spies and Franklin, 1991; Franklin, 1997).

The number of plant and animal species in old-growth stands is greater than in the young and mature stages, because the structure becomes more complex and the habitat available for various species increases. However, the species diversity is generally lower than in the herb/brush stage in natural forests (Franklin et al., 1981; Manuwal and Huff, 1987; Oliver and Larson, 1990).

Developmental patterns following minor disturbances

Minor disturbances may occur more frequently than major disturbances and may reduce the frequency of major disturbances. When overstorey trees are destroyed by a minor disturbance, gaps are created and new trees regenerate *in situ*. If the gap is large and/or residual trees are not vigorous enough to re-occupy the growing space, multi-storied (multi-cohort) stands develop. If the gap is small and/or the residual trees are vigorous, new trees are excluded and single-storied (single-cohort) stands are maintained.

Disturbance type and frequency

The structure of a forest is closely related to the frequency and type of disturbances which have affected it. If minor disturbances frequently affect the stand, it will develop into a complex multi-cohort stand. However, if a major disturbance occurs, a single-cohort stand usually forms and lasts until it reaches the old-growth stage. The development of the stand varies according to the combination of forest type (dominant tree species), type of disturbance (wind, fire, etc.), magnitude of disturbance, and frequency of disturbance. Various types of forests are found as a consequence of different combinations of the above factors.

White and Pickett (1985) defined a number of terms to characterize the properties of a disturbance regime. According to their definitions, the "return interval" is the inverse of frequency, which is the mean number of events per unit period. The "rotation period" is the mean time needed to disturb an area equivalent to the study area (the study area is arbitrarily defined; some sites may be disturbed several times in this period and others not at all, thus, the study area must be explicitly defined). The "return interval" can be regarded as the interval between minor or major disturbances. The "rotation period" refers to the interval between major disturbances and is a result of both allogenic and autogenic factors. In this context, a major disturbance is defined as a disturbance which results in the complete replacement of a stand, and a minor disturbance is one in which the stand is only partially destroyed (Oliver and Larson, 1990). Nakashizuka and Yamamoto (1987) defined the relationship between the return period, rotation period, and stand structure by adding a "time to old-growth" factor (Table 2-2). Type D in Table 2-2 is not common in many parts of the world, but it is commonly found in the Pacific Northwest of North America, because the life span of forests of pioneer species, *Pseudotsuga menzisii* (Douglas-fir) is long and a major disturbance (fire) usually occurs before they lose dominance (Franklin and Hemstrom, 1981).

Patch dynamics

Old well-developed stands are usually characterized by multi-storied canopy structure and a mosaic-like distribution of gaps or patches. Usually it is difficult to determine how a stand has developed into its present structure, that is, to what extent it has developed autogenically or allogenically as a result of minor catastrophic disturbances. In Japan, most well-developed stands have probably been affected by relatively frequent minor disturbances. The dynamics of a well-developed mixed old-growth stand are described below with reference to reports by Ishizuka (1980, 1981, 1984, 1989) and Ishizuka and Sugawara (1986).

Old-growth mixed stands in the conifer-broadleaf transition zone in

Table 2-2 Return interval, rotation period, and stand structure. (Nakashizuka and Yamamoto, 1987)

Relationship between time periods	Stand condition
A. Rotation period >Return interval≧Time old-growth Stage	Mosaic of various stand development stages including old-growth stasge
Rotation period >Time to old-growth stage >Return interval	
B. Time to old-growth stage >Rotation interval >Return interval	Mosaic of various stand development stages before old-growth stage
C. Rotation period =Return interval≧Time to old growth stage	Stand is affected by major (complete) disturbances. Between major disturbances, the stand becomes mosaic-like including the old-growth stage owing to minor allogenic or autogenic disturbances.
D. Time to old-growth stage >Rotation period=Return interval	Stand is affected by major disturbances. Stand development stage before old-growth stage is repeated.

Note : In the original table, the term, "matuture stage" was used instead of "old-growth stage" , but "old-growth stage" is used here on the basis of the definition given in this chapter.

central Hokkaido were studied. Figures 2-24 to 2-27 show the results of an example 50 m × 50 m plot. Figure 2-25 shows the height growth of all trees above 12 m height. The oldest tree was a 285 year-old *Picea jezoensis* (ezomatsu) followed by a 280 year-old *Tilia japonica* (shinanoki). In trees between 50-200 years old, cohorts at 10-30 year intervals were found, suggesting that gaps were created at such intervals. Figure 2-25 shows the spatial distribution and species composition of cohorts in the same plot. In each cohort, most individuals are aggregated in patches. Figure 2-26 shows the crown projection of the same plot and a grouping of the patches based on species composition. Figure 2-27 shows the height growth of the individuals in each patch in the plot. Patch 1 consisted of an overstorey of several cohorts of *Picea jezoensis* with several younger cohorts of *Abies sachalinensis* (todomatsu) under and around them. The distribution of heights of the different cohorts within this patch is complex, because the difference in height growth rate is large even within the same cohort. Patch 2 consisted of multi-cohorts (140-240 years) of *Acer mono* (itayakaede) which developed around the 280-year-old *Tilia japonica* (shinanoki) and 50-90 year-old mixed species such as *Tilia japonica* and *Picea jezoensis*. In this patch, crowns did not overlap so much. Patch 3 consisted of *Acer mono* and *Abies sachalinensis* under *Tilia japonica*. Two

Figure 2-24 Height growth of individual trees in a research plot (50 m × 50 m) in a natural forest in Hokkaido, Japan. Trees taller than 1 m were measured. (Ishizuka, 1989)

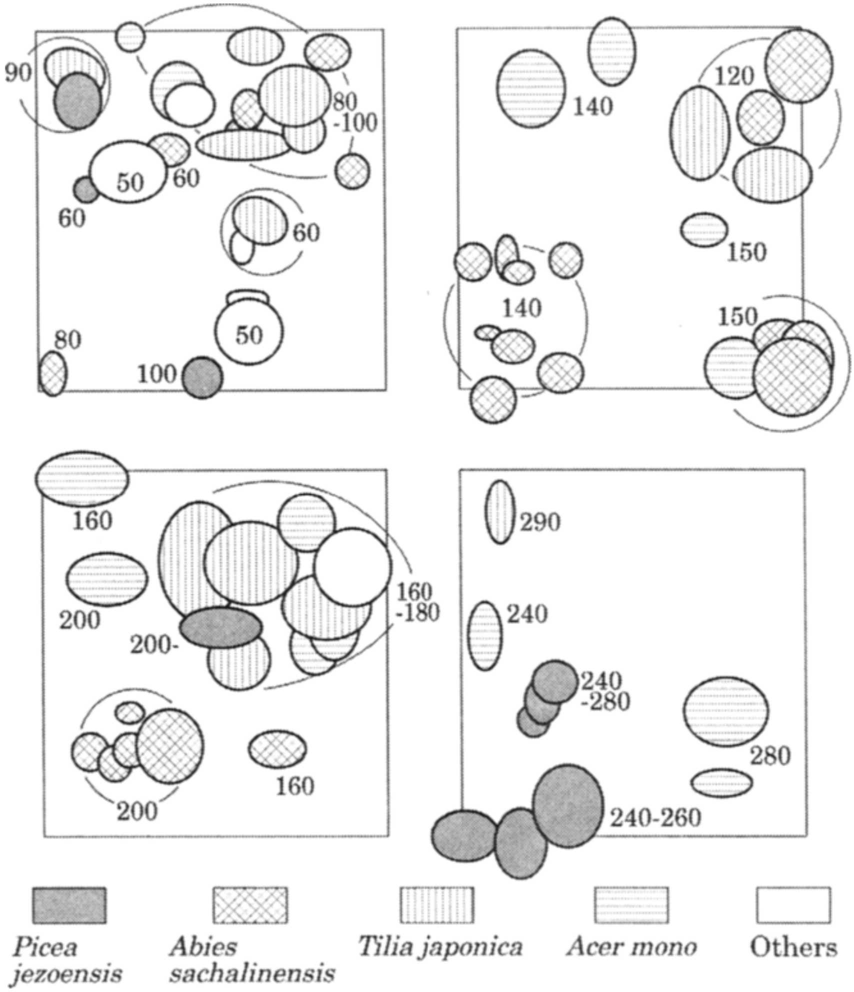


Figure 2-25 Distribution of trees which were regarded as belonging the same cohort in the same plot as shown in Figure 2-24. Figures are tree age expressed as 10-year-units.
Upper left: ages 50 - 100
Upper right: ages 120 - 150
Lower left: ages 60 - 200
Lower right: ages 0 - 290
(Ishizuka, 1989)

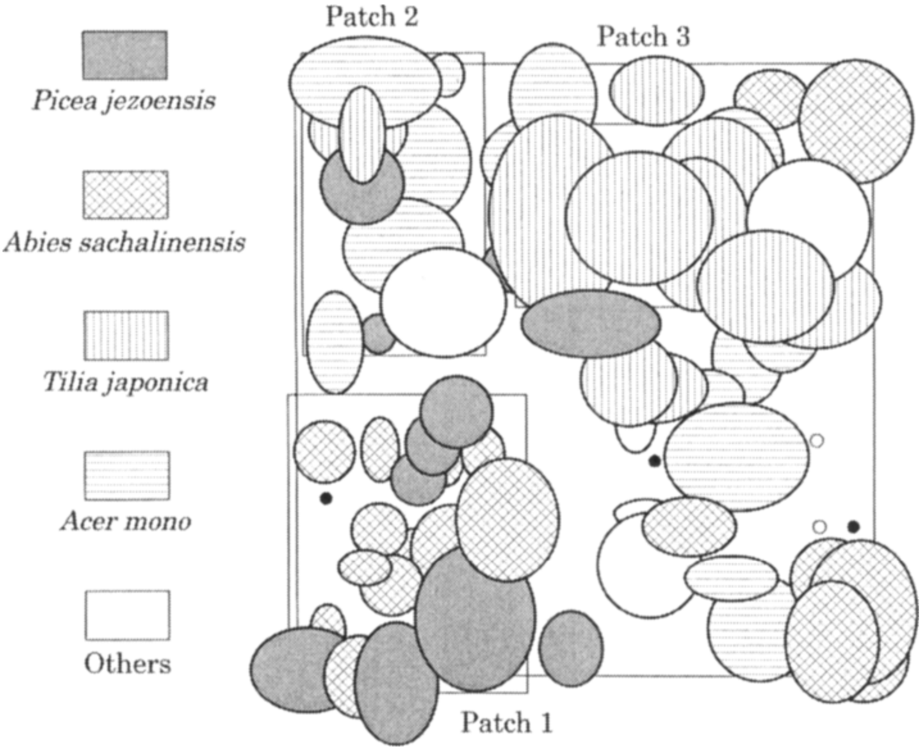


Figure 2-26 Distribution of three patches with different species composition in the same research plot as shown in Figure 2-24.
Patch 1: *Picea jezoensis* and *Abies sachalinensis* patch
Patch 2: *Acer mono* patch
Patch 3: *Tilia japonica* patch
○ and ● represent the stem base of unmeasured conifer and broad-leaved crown trees, respectively. (Ishizuka, 1989)

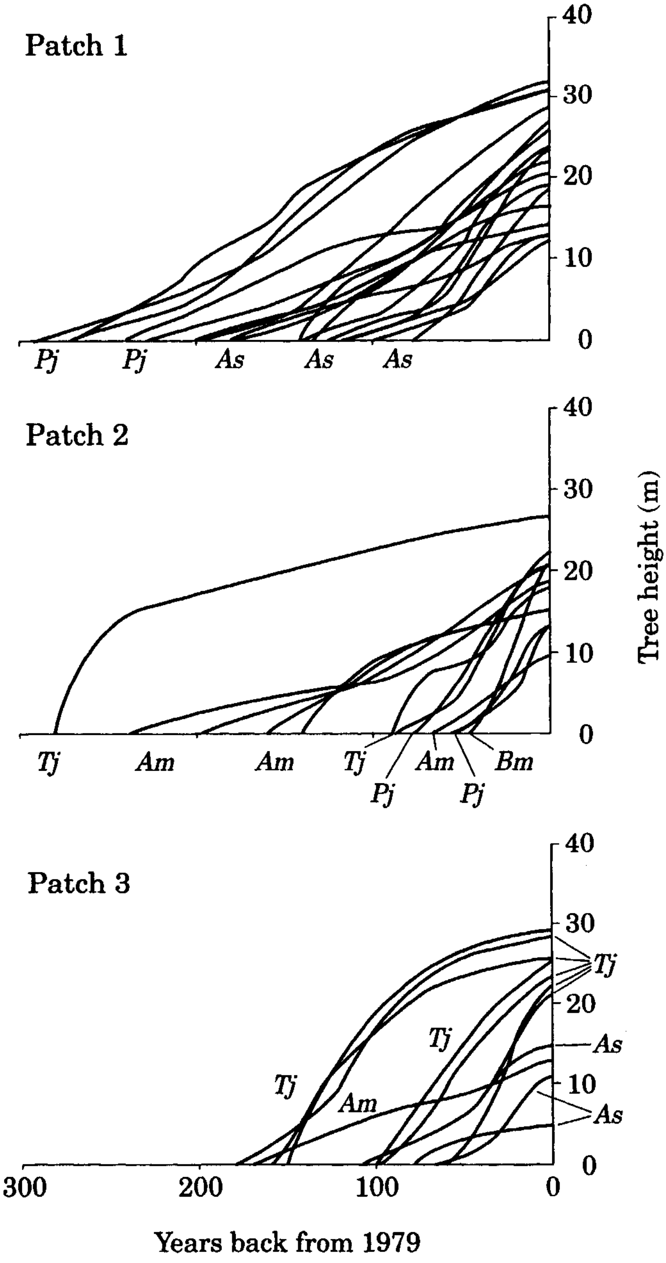


Figure 2-27 Height growth of individuals in each patch shown in Figure 2-24. Am: *Acer mono*, As: *Abies sachalinensis*, Bm: *Betula maximowicziana*. (Ishizuka, 1989)

or three cohorts of *Tilia japonica* formed a single overstorey. *Acer mono* was in the same cohort as the oldest *Tilia japonica*, but its growth rate was apparently lower, as it formed the understorey. *Picea jezoensis* was in the same cohort as the second and third cohorts of *Tilia japonica* but formed the understorey due to its slow growth rate. As seen in Figures. 2-26 and 2-27, the development patterns of patches differ according to the species and their growth characteristics.

Similar patterns have been found in other research plots. In old-growth forests, there is usually evidence of patch dynamics occurring, and this may be one reason why biodiversity is high in old-growth forests. Patch dynamics are related to the microsite requirement and propagation strategy of tree species. The patch development shown in Fig. 2-27 generally seemed to depend on initial floristic composition, although this was not always clear, especially in patch 1.

Chapter 3

Factors Influencing Forest Productivity

Maintaining and enhancing productivity of forests is a fundamental component of sustainable forest management. This is true of not only for timber production but also other forest functions such as carbon sequestration and pool to mitigate atomospheric carbon concentration and conservation of biodiversity. Obtaining information of factors influencing forests productivity is essentially necessary for the implementation of sustainable forest management.

3.1 Growth of individual trees and forest productivity

A proportion of the photosynthate synthesized by a tree provides energy for the physiological activities of daily life and the remaining part is converted to cells of new tissues. The proportion of photosynthate consumed as energy is respiration, and the proportion used to develop new cells is net primary production (hereafter called "net production"). Net production results in growth or increment, and is the source of energy flow in forest ecosystems. Mechanisms of growth of individual trees and the role of nutrient and energy cycling within a forest ecosystem were described in Chapter 2.

The total production of a forest ecosystem comprises primary production by plants and secondary production by animals, which rely on the primary producers. In this section, primary production and net production are of most interest. The methods of estimating net production discussed below are based on those developed through IBP (International Biological Program) from the late of 1960s to early 1970s (Kira and Shidei, 1967; Tadaki and Hatiya, 1968; Ogawa, 1977; Ogawa and Kira, 1977). The components of primary production are gross production (P_G), net production (P_N) and respiration (R). These are related in the following way:

$$P_G = P_N + R$$

Net production can be estimated by measuring changes in total biomass over one year. It can be estimated by measuring the increase in biomass (Δy), calculated by subtracting the value at the start of the period from the value at the end; the amount of new litter produced over the period (L); and the amount of grazing of the newly produced biomass (G). The relationship between these quantities is expressed by the following equation:

$$P_N = \Delta y + L + G$$

As L and G are difficult to measure and their amounts are generally small, they are usually neglected.

The net production above ground can be estimated comparatively accurately by analyzing annual rings and measuring new leaves, but the net underground production is very difficult to estimate. Many reports on the net primary production of various forest types are published, but many of these estimates were calculated as a proportion of the growth rate of stem. It has since been shown that this is not adequate. Keyes and Grier (1981) reported that the net production of fine roots when measured directly was about twice that estimated from the growth rate of thick roots or the production of leaves. The production of fine roots and their amount of litter can be measured by sampling cores of soils at regular intervals during the growing season.

Gross production is estimated by adding net production and respiration. However, respiration is hard to measure, because it must be measured in each organ throughout the day and season. Plant surfaces are occupied by other respiring organisms, including crown and stem epiphytes as well as symbiotic root bacteria and fungi which further complicates these measurements (Waring and Schlesinger, 1985). Therefore, the amount of data available on gross production of forests is far less than that on net production.

Net production may be estimated by the harvesting method. A sample plot is established in a standard place in a stand, with the length of one side of the plot at least as long as the height of the tallest tree in the stand. The diameter of all trees is measured and at least 10 trees covering all diameter classes are chosen as sample trees for analysis. These trees are felled and the mass of each organ in each tree is measured. The relationship between any two organs (X and Y) can be expressed by the equation for relative growth:

$$Y = AX^b$$

Stem (D^2 or D^2H) is usually used for X, because D (diameter) or H (height) of all trees can be measured directly. Equations estimating the quantity of leaves, branches, roots, and stem are obtained using the values of sample trees, and by putting the measured value of D^2 or D^2H of each tree into X, the value of each organ in each tree is calculated. D^2H is an indicator of stem volume or stem weight.

3.2 Main factors regulating productivity

The productivity of a forest is determined by the genetic capacity of the species for growth and by the environment in which it is growing. Even if the genetic capacity for productivity of the species is high, productivity will be low if it is growing on a poor site. If the environmental conditions are optimal for growth, it usually cannot reach its full genetic potential because of interspecific competition. These characteristics of growth within ecosystems were explained in Section 2.2.2 as the differences between the fundamental niche, realized niche, physiological optimum, and ecological optimum. As a stand develops through the four stages identified in Section 2.4.4, its productivity varies (Kimmins et al., 1986).

The most basic environmental factors that determine productivity are temperature and water availability. Low temperature limits photosynthesis, and extreme cold in winter can induce physiological stress in the tree, such as water stress, and productivity is reduced. If the temperature is higher than the optimum for the species, productivity also decreases. If overnight temperatures are high, respiration losses are high and the net production also falls.

Above-ground productivity also decreases with decreasing precipitation, when other factors are similar. Generally speaking, the growth of trees on lower parts of a mountain slope is greater than that on upper parts. This may be due to the moisture levels in the soil. In the same species, the above-ground net production of a stand on a dry site is lower than on a wet site, but if below-ground net production is included in the measurement, the difference in total net production becomes smaller. It is known that with decreasing soil moisture, a greater proportion of total net production is allocated below-ground (Keyes and Grier, 1981). Therefore, when net production is discussed in relation to site condition, the value of below-ground net production must be included.

High productivity of a forest is achieved if the temperature is optimal with only small fluctuations and moisture availability is moderate and approximately constant. If such conditions prevail throughout the year, the physiological stress of the trees is minimized and the growth period is lengthy.

Other environmental factors determining productivity include nutrients, topography (altitude, place in a slope, aspect of slope, etc.), winds, snow, etc. Altitude has a strong effect on temperature and the place in a slope has a strong effect on moisture and nutrient conditions. The aspect of the slope determines wind and temperature conditions, which affect soil moisture. In this way, various factors which influence productivity are directly or indirectly related to temperature and water conditions. Leaf area index (LAI, leaf area over a defined area) is regarded as an indicator of the environmental conditions for gross production. The product of LAI and the period when photosynthesis is possible is closely related to gross production (Kira and Shidei, 1967).

3.3 Changes in productivity with time or stand age

Although the productivity of forests is basically regulated by the genetic traits of the species and the site conditions, it also varies according to the stand development stage or stand age. Figure 3-1 is an example of the relationship between stand age and net production in *Abies veitchii* (shirabe) natural stands. Net production increases with age until about 40 years of age and then gradually decreases. Figure 3-2 shows the relationship between stand age and above-ground net production of *Chamaecyparis obtusa* (hinoki) plantations. In this case, net production over time may have been affected by thinning. However, in both Figures 3-1 and 3-2, it is clear that net production peaks in the young stage (stem

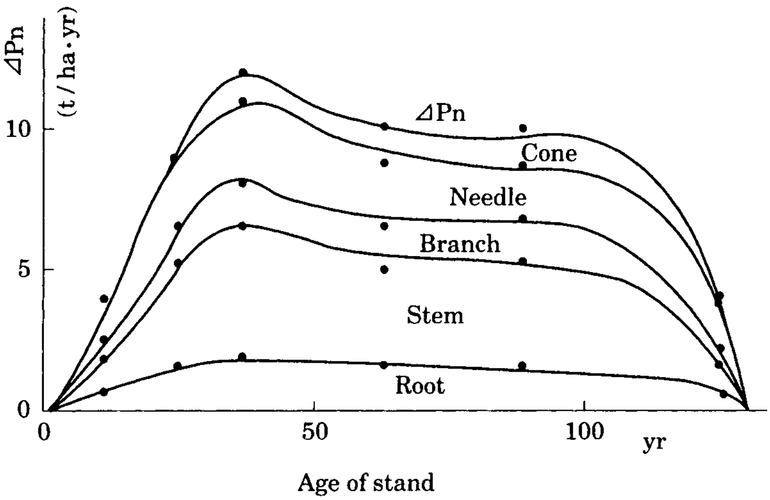


Figure 3-1 Net production of different aged *Abies veitchii* stands. ΔPn stands for net production. (Tadaki, 1977)

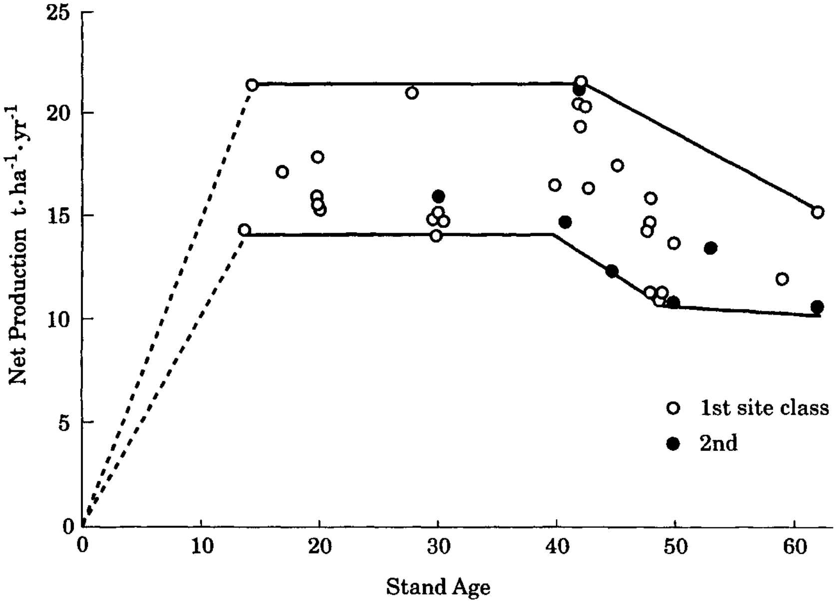


Figure 3-2 Relationship between stand age, site quality, and above-ground net production for *Chamaecyparis obtusa* (hinoki). (Fujimori, 1987a)

exclusion stage), then gradually decreases. Borman and Likens (1979) demonstrated a similar relationship, and it has also been shown that plantations and young forests have higher productivity than mature natural forests (Gholz, 1986).

The tendency for net production to increase rapidly to a certain age in the young stage and then gradually decrease is a general pattern. The stand can increase its leaf area until the canopy is closed. At this stage, the proportion of non-photosynthetic organs is small and the respiration rate low. The subsequent decrease in net production may occur because spaces created by branch damage from intersecting crowns, self-thinning or artificial thinning cannot be fully reoccupied by the remaining crowns. Spaces therefore develop between individual crowns and the leaf area index decreases.

Net production continues to decline after the young stage. Initially, it was thought that this decline was due to an increase in respiration as the proportion of non-photosynthetic organs increased as stand age increased (Kira and Shidei, 1967). However, Hatiya et al. (1989) found that respiration changes in a similar way to gross production with stand age, although the change in respiration is smaller than the change in gross production, as shown in Figure 3-3. As a result of the slight differences

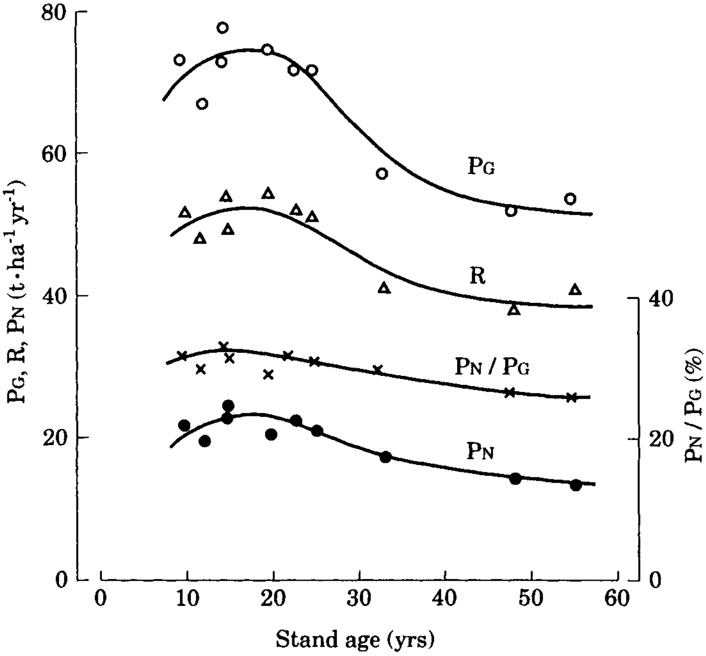


Figure 3-3 Changes in gross production (P_G). respiration (R), and net production (P_N), with stand age in *Pinus densiflora* (akamatsu) stands. (Hatiya et al., 1989)

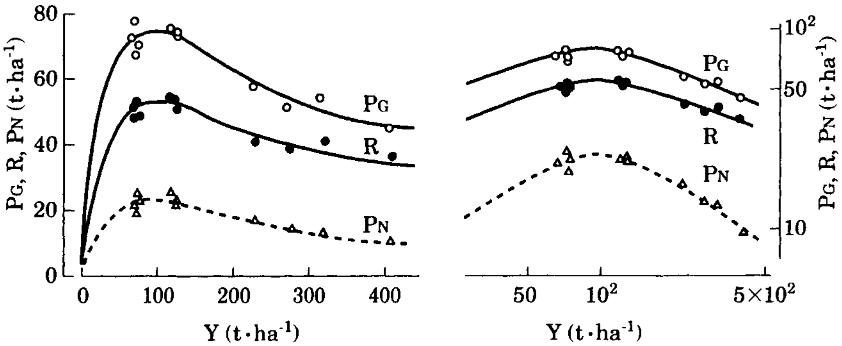


Figure 3-4 Changes in gross production (P_G), respiration (R), and net production (P_N), with biomass (Y) in *Pinus densiflora* (akamatsu) stands. (Hatiya et al., 1989)

between the patterns of gross production and respiration, net production changes in a way that is intermediate between the two (Figure 3-3). Similar changes in gross production, respiration and net production can be found with biomass as with stand age, as shown for *Pinus densiflora* (akamatsu) in Figure 3-4 (Hatiya et al., 1989).

Figure 3-5 shows an example of the seasonal change in above-ground net production in a 9-year-old *Zelkova serrata* (keyaki) stand. *Zelkova serrata* is deciduous, and above-ground net production is highest in April and May (spring), then generally decreases until November (late fall). Net production is negative after the middle of September. This can be ascribed to the seasonal loss of leaves (Figure 3-6) and the transfer of resources from above-ground to below-ground (Tamm, 1951; Kozlowski et al., 1971a). Thus, the time of measurement of LAI is important, particularly in deciduous stands.

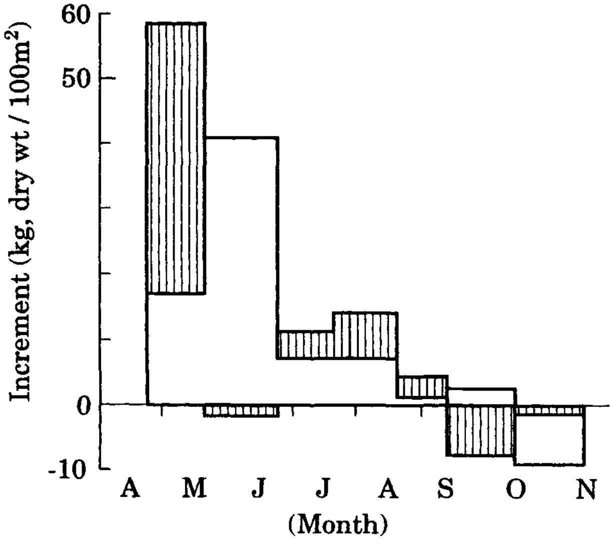


Figure 3-5 Seasonal change in above-ground of a *Zelkova serrata* (keyaki) stand. Black and white parts represent photosynthetic and non-photosynthetic organs, respectively. (Kanazawa et al., 1984)

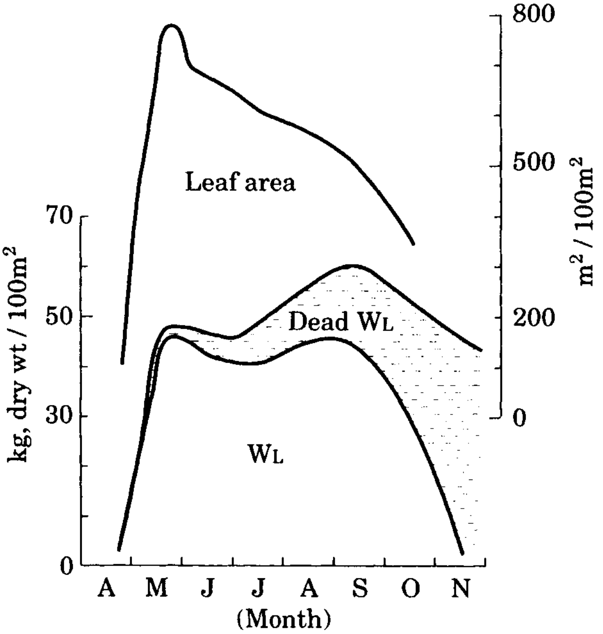


Figure 3-6 Seasonal changes in leaf biomass of *Zelkova serrata* (keyaki) stand. W_L is dry weight (Kanazawa et al., 1984)

3.4 Range of productivity within different forest types around the world

The mean above-ground net production of forest types from various areas of the world were collated in 1988 (Table 3-1). The data were selected from reports which used comparable methods of calculation. The net production of tropical rain forests is about 18 t/ha/yr. This is the highest value of net production of all natural forests in the world, and is only exceeded by intensively managed plantations [i.e., *Pinus radiata* (radiata pine) in New Zealand]. The net production of broad-leaved evergreen forests in Japan is close to that of tropical rain forests. The reason that the net production of tropical rain forest is not as high as might be expected can be attributed to the high respiration rates that occur in the high temperatures of the tropical regions. Also, although the volume production of fast-growing species in tropical rain forest is high, dry matter production is not as great, because the specific gravity of most tropical fast-growing species is low (Kawahara et al., 1981).

The net production of tropical deciduous forests is about 7 t/ha/yr,

Table 3-1 Above-ground net production and standard deviation of different forest types in the world. (Fujimori, 1989b)

Area	Forest type	Number of stands	Net roduction ($\text{t ha}^{-1}\text{yr}^{-1}$)
Tropics (Southest Asia, Central Africa, Neotropical)	Broad-leaved evergreen forest (Tropical rain forest)	27	17.8±7.5
	Broad-leaved deciduous forest (Rain green forest)	6	7.2±4.4
	Savanna	6	1.5±1.3
West Europe (Including East Europe but not former Soviet Union. Excluding the Mediterranean	Coniferous forest (Cool-temperate forest)	8	13.8±6.0
	Broad-leaved deciduous forest (Cool-temperate forest)	49	9.7±3.0
	Pine forest (Cool-temperate forest)	11	11.3±4.9
Scandinavia	Coniferous forest (Cool-temperate, boreal forest)	2	8.1±6.5
	Coniferous deciduous forest (Cool-temperate, boreal forest)	9	8.6±5.1
	Pine forest (Cool-temperate, boreal forest)	3	4.1±1.2
West Europe (Former Soviet Union)	Coniferous forest (Cool-temperate, boreal forest)	26	6.4±2.2
	Broad-leaved deciduous forest (Cool-temperate, boreal forest)	15	9.2±3.4
	Pine forest (Cool-temperate, boreal forest)	3	4.6±2.0
West of North America (Canada, U. S. A.)	Coniferous forest (Cool-temperate forest)	39	10.5±5.4
	Broad-leaved deciduous forest (Cool-temperate forest)	7	15.2±6.7
	Pine forest (Cool-temperate forest)	9	12.8±3.1
	Coniferous forest (Boreal, subalpine forest)	10	4.0±2.5
	Broad-leaved deciduous forest (Boreal, subalpine forest)	3	4.4±0.4
East of North America (Canada, U. S. A.)	Coniferous forest (Cool-temperate forest)	19	9.8±2.5
	Broad-leaved deciduous forest (Cool-temperate forest)	54	8.9±4.9
	Pine forest (Cool-temperate forest)	27	4.8±2.5
	Coniferous forest (Warm-temperate forest)	9	14.5±2.8
	Broad-leaved evergreen forest (Warm-temperate forest)	1	13.7
Semi-arid area of North America (U. S. A.)	Coniferous forest (Temperate forest)	12	6.4±4.4
	Broad-leaved deciduous forest (Temperate forest)	6	1.1±0
Australia	Broad-leaved evergreen forest (Warm-temperate forest)	5	11.3±4.5
New Zealand	Radiata pine plantation (Temperate forest)	2	24.2±0.1
Japan	Coniferous forest (Subarctid forest)	88	11.2±3.8
	Broad-leaved deciduous forest (Cool-temperate forest)	55	8.7±3.5
	Coniferous forest (Temperate forest)	96	14.3±5.8
	Pine forest (Weam-temperate forest)	44	13.6±5.0
	Broad-leaved evergreen forest (Weam-temperate forest)	33	20.7±7.2

Note : The values, except Japan, are based on Fujimori (1989b). Most data were obtained from Cannell (1982).
The values for Japan were from Kira (1977a).

which is less than half that of tropical rain forests. This can be attributed to the shorter growing season and the different allocation of photosynthate between above and below-ground parts. The net production in savanna regions is about one-fifth that of the tropical deciduous forest, because of restricted water availability in these regions.

The net production of coniferous forest in the cool-temperate zone in the east of North America (Canada and the United States of America) is about 10 t/ha/yr and this is almost the same as coniferous forests in Japan, excluding *Cryptomeria japonica* (sugi) plantations. The net production of broad-leaved deciduous forests of eastern North America and the pine forests of southeastern North America are also similar to that in Japan. The similarities in net production of the forests in Japan and those in mid-eastern North America are probably due to both regions being in the east of continents and in the middle latitudes of the northern hemisphere.

The net production of coniferous forest in the cool-temperate zone in western North America is about 11 t/ha/yr, which is similar to coniferous forests of Japan other than *Cryptomeria japonica*. However, most of the data for Japan came from young plantations, whereas the data for western North America are from natural mature forests. Plantations usually have greater productivity than natural forests of the same species if they are on an appropriate site (Gholz et al., 1986), and the productivity of young forests is usually higher than mature forests (Figures 3-1, 3-2). The net production of young natural forest of *Tsuga heterophylla* (western hemlock) on the Oregon coast of the United States of America is over 30 t/ha/yr (Fujimori, 1971). Therefore, the productivity of coniferous forests of western North America is higher than in Japan if they were compared at the same age class or stand development stage.

The net production of broad-leaved deciduous forests (*Alnus rubura*, red alder) in western North America is about 15 t/ha/yr, which is high. Most of western North America is occupied by coniferous forests and *Alnus rubura* is the main pioneer species, occurring on disturbed sites in the coastal area (Franklin and Dyrness, 1973). The net production of pine forests in western North America is similar to those in southeastern North America and Japan.

In western Europe, excluding Scandinavia, the Mediterranean, and the former Soviet Union, the net production of plantations of exotic species such as *Pseudotsuga menziesii* (Douglas-fir) and *Picea sitchensis* (sitka spruce) from western North America is high. Excluding the exotic species, the net production of coniferous forest in western Europe is similar to coniferous forests of many other cool-temperate zones in the world. The net production of broad-leaved deciduous forests in western Europe is slightly higher than in eastern North America and Japan, and the net production of pine forests in western Europe is a slightly lower than in North America and Japan.

The net production of cool-temperate and boreal forests in Scandinavia and the former Soviet Union is low, but the productivity of broad-leaved deciduous forests in former Soviet Union is comparatively high.

Although the data is limited, the net production of exotic *Pinus radiata* plantations in New Zealand is very high.

3.5 Factors limiting high productivity and large biomass

The biomass allocated to the trunks, boughs, and thick roots of trees accumulates annually, and continues to increase within a forest stand until it reaches the old-growth stage. However, the biomass of forest cannot increase without limit because the potential for growth is generally limited by the environment. The largest forest biomass in the world is found in natural *Sequoia sempervirens* (redwood) forests on the coast of North California, the United States of America; the average height of dominant trees in one stand was 90 m and the total stem biomass was 3500 t/ha in dry weight (Fujimori, 1977; Figure 3-7).

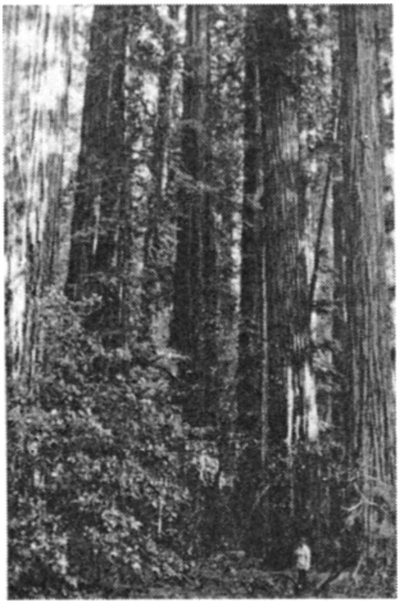


Figure 3-7 *Sequoia sempervirens* (redwood) old-growth forest (Humbolt State Park in California, the United States of America). The average tree height of the overstorey is about 90 m and stem volume per ha is 10,800 m^3 (Fujimori, 1977).

Forests with a high productivity and large biomass are found in the Pacific Northwest of the United States of America (Fujimori, 1971; Fujimori et al., 1976; Fujimori, 1977; Waring and Franklin, 1979; Franklin and Waring, 1980) and tropical rain forest zones (Ogawa et al., 1961; Kato et al., 1978). The following factors are necessary for such forests to develop:

1) low water stress;
2) low temperature stress (i.e., the difference between maximum and minimum temperatures is small, and mean annual temperature is close to optimum for photosynthesis for the species);
3) few destructive winds;
4) few large scale fires;
5) the species present inherently grow large and are long-lived;
6) the species are occupying their fundamental niche or physiologically optimum habitat (i.e., it naturally occurs on sites best suited to it); and
7) tall trees can grow at high densities.

In New Zealand, Chile, and other temperate regions of the southern hemisphere, there are areas where conditions 1) to 4) are satisfied but condition 5) and its related conditions 6) and 7), are lacking. However, species which have the capacity to grow fast and/or accumulate large biomass, such as *Pinus and Eucalyptus* species, have been grown outside their natural range and in these circumstances exhibit very high growth rates. In New Zealand, *Pseudotsuga menziesii* and *Sequoia sempervirens*, introduced from the western North America, have accumulated large biomass although their ages are less than 100 years as of 1990s.

In Japan, moisture conditions are good and fast-growing, long-lived species exist, but strong winds are common and temperature differences throughout the year can be large (over 20°C). Species such as *Cryptomeria japomica* (sugi) do not naturally dominate sites which are optimal for their growth because there is intense interspecific competition. The productivity and biomass of species such as *Cryptomeria japonica* is improved if they are grown as monospecific plantations on good sites. Introduction of exotic tree species for forestry has not been particularly successful in Japan, because indigenous species such as *Cryptomeria japonica* can grow very well when interspecific competition is removed.

3.6 Linkages between manipulating productivity and forest management

Maintaining or enhancing the productivity of a forest is fundamentally important for any forest management purpose. For wood production, matching species to sites, and selecting an appropriate rotation age that suits the species and site is important, and the stand would usually be maintained in a phase of high biomass production. For the conservation of biodiversity, soil or water resources, mature and old-growth forests are suitable, although the growth rate of the forests decreases and may approach zero. Carbon sequestration to mitigate increasing atmospheric CO_2 can be achieved by either harvesting wood at a stage when the growth rate is still high followed by regeneration, or by managing a stand such that it has the largest possible carbon pool (old-growth stage). Conservation of soil is fundamental to maintaining the productivity that underpins sustainable forest management. Ways of harmonizing these diverse objectives are discussed in Parts III and IV.

Part II

Specific Silvicultural Techniques

Recently, the development of new silvicultural practices that better simulate ecological processes has been of interest all over the world. In this Part, established silvicultural techniques are reviewed as a basis for further discussion of new silvicultural systems that can be used for sustainable forest management. Most current silvicultural techniques were developed for the production of wood, primarily from plantations or intensively managed forests. Therefore, the discussion about specific silvicultural techniques in this Part is biased towards such forests. Improved or new silvicultural techniques or strategies for sustainable forest management including conservation of biodiversity, soil and water resources are discussed in Parts III and IV.

Chapter 4

Regeneration

The regeneration techniques discussed in this chapter are related to the regeneration mechanisms discussed in Chapter 1. Many of the techniques discussed in this Chapter were reported in Smith (1986), Forestry Agency of Japan (1990), and Kawana et al. (1992).

4.1 Production of planting stock

Stands managed for wood production should be established using genetically superior trees. If natural regeneration by seeds is used, the selection of seed trees is important, and for plantations, a supply of genetically improved, healthy seedlings is important. This section discusses the production of planting stock.

4.1.1 Selection of species and provenances

The selection of species to be planted must satisfy two conditions:

- the characteristics of the species must fulfil the required objectives (e.g., timber production); and
- the species must be suited to the site.

The second condition requires that the selected species must be adapted to the environmental conditions of the site, as discussed in Section 2.2. The important environmental factors include temperature, water, wind, nutrients, diseases, pests, and animals.

As shown in Figure 2-4, in natural forests different species dominate different sites along the soil moisture gradient on a slope. This does not necessarily mean that the dominant species at each site is the best for that site. The species that exist naturally on a site do so as a result of competing with other species for light, moisture and nutrients, and the site occupied naturally by a species is called its realized niche (Section 2.2.2). As discussed in Section 2.2.2, *Cryptomeria japonica* (sugi) occurs on comparatively dry or poor sites under natural conditions, but has greater productivity if established as a plantation on wetter sites usually occupied by broad-leaved species. One of the main objectives of establishing a plantation, therefore, is to artificially recreate the fundamental niche (Kimmins, 1987) for the desired species.

4.1.2 Genetic improvement

When seedlings are planted, it is important to select appropriate genetic material. Genetic improvement allows genetically superior material to be used for the establishment or regeneration of plantations. Even when natural regeneration is used, if supplementary planting is required, superior material should be used. The traits desired in trees depend on the objectives of planting. In timber production, genetic improvement is generally used to boost yield, wood quality, adaptability to the site and resistance to harmful agents.

Breeding relies on sexual reproduction, as this maintains variability and if traits of interest are heritable, provides opportunities for selection and further breeding of elite individuals. The first step in most tree improvement programs is the selection of superior phenotypes from the wild population. This is called mass selection, and selected trees are termed plus-trees. Most breeding programs work on the assumption that superior parents have a high probability of producing superior offspring, but this needs to be tested, as plus-trees may be superior as a result of non-genetic causes such as a particularly favorable microenvironment. Seedlings from the plus-trees must therefore be tested to see if the desired characteristics are heritable. This is called progeny testing. If the heritability of the desired traits is high, improvement by breeding is possible. Progeny testing of a single generation of trees takes a reasonably long time and the field environment of the tests is not usually uniform. Progeny tests should therefore be conducted over a number of different sites, and selection should combine a number of desirable traits in each generation. The selected traits should reflect the environmental conditions where the improved plants will be deployed. Generally the traits of interest are resistance to climatic, disease, pest and mammal damage; superior wood quality (straightness, roundness, tapering grade of stem, size of branches, color of wood); and rapid and sustained growth. The results of progeny tests can be used to identify female parents whose progeny performed consistently well, and these females can then be used for ongoing seed production.

Elite trees identified in breeding programs can be deployed into forests by either sexual (seed) or asexual (vegetative) reproduction. Seed orchards and scion gardens of plus-trees are used for the mass production of superior progeny. Seed orchards are generally established by planting a mixture of grafted plus-trees. They should be isolated from sources of contaminating pollen, so trees of the same species should not exist within a distance that could be traversed by pollen vectors. The distance required for effective isolation depends on the pollen vector (wind, insect, bird, or mammal), but in the case of *Cryptomeria japonica* (sugi) it may be about 500 meters from other trees of the same species (Ohba, 1992). The number of clones included within an orchard should be sufficient to maintain genetic diversity, but few enough to maximize the genetic gain of the seed produced in the orchard. Clonal seed orchards commonly contain about 25 clones. Clones should be distributed across the orchard to ensure cross-pollination. If 25 clones are planted, the orchard could comprise units of 5 × 5 clones, with the clones randomly distributed within each unit. Such a design, and a similar design for an orchard with 49 clones, is shown in Figure 4-1.

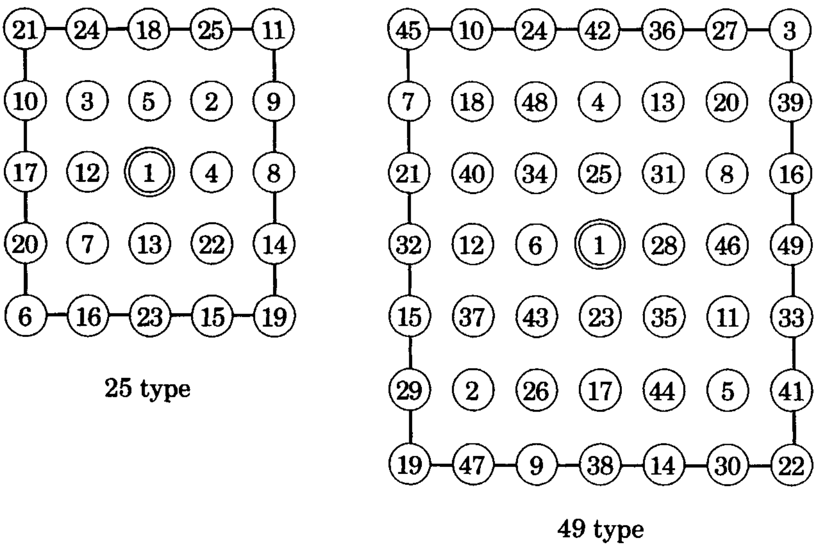


Figure 4-1 Example of clone distribution patterns in a seed orchard. (Furukoshi, 1983)

Vegetative propagation (asexual reproduction) preserves genetic gains that have been made by selection or breeding. Vegetatively propagated offspring from one tree are called clones, as they share their genotype. The capture of genetic gain in forests can be speeded up by vegetative propagation.

Cryptomeria japonica plantation establishment has occurred for over 300 years in Japan (Yamauchi and Yanagisawa, 1973). Throughout this time, many local varieties have been selected and vegetatively propagated in the Kyushu, Sanin, and Hokuriku districts. It is estimated that about 200-300 local varieties exist as a result. In the Yoshino forestry area, which has a long history of advanced forestry techniques, families of *Cryptomeria japonica* with desirable traits have been selected by collecting seed from female parents with superior progeny. In the Kitayama forestry area where traditional techniques developed over several hundred years, local varieties of *Cryptomeria japonica* have been selected, both as families and as clones propagated by cuttings. Most genetic improvement of *Cryptomeria japonica* has been done by private forest managers, and the gains have been substantial.

An early finding of the tree improvement programs in many countries in the world was that seed from distant provenances often performed poorly compared to trees native to an area. When large-scale plantation establishment began the 1900s, seed was often transported to distant areas, with unsuccessful results. This is known as the provenance problem (Ohba, 1992). In many countries, areas and stands for collecting seed and areas for distributing collected seeds have been designated. Distribution areas are divided into several areas for each species, according to natural conditions (climate, vegetation, and growth) and the level of technical inputs. Transportation of seeds and seedlings between areas is controlled.

4.1.3 Seed collection and treatment

As well as genetic superiority, the vigour and quality of the seed is important. Seed quality is higher if it is produced from areas where there are a number of fertile trees and collected following a mast year (a good seed year) when the opportunity for cross-pollination and out-crossing has been high. Seed quality is also affected by the age of the seed tree, the place in the crown where the seed are borne, harvesting time, and the treatment of the seed after collection.

Cones and fruit should be gathered from tall and straight trees, and in the case of softwoods, from the upper crown (Hashizume, 1991). In the field, cones and fruit cannot readily be collected from tall and straight standing trees, and in the past, workers often collected from short, poor quality trees and lower shaded parts of the crown. Such practices must be avoided, because although poor form in the parent is not necessarily inherited, it is possible.

The best time to collect cones and fruit is after seeds have matured but before they disperse. Fruit should be collected after the seed has ripened but before the fruit has matured. Most cones and some fruit are mature when desiccation starts (Smith, 1986; Hashizume, 1991). With experience, the maturity of cones, or required extent of desiccation can be judged externally from the color and luster of the fruit of each species.

Seed orchards make seed collection easier as well as contributing to genetic improvement. Seed orchards are treated like fruit orchards. Trees are widely spaced to ensure good light for the production of seed and to facilitate work in the orchard, and tree form is usually controlled so cones or fruits can be easily gathered. Fertilization and weed control enhance the production of seeds. Insecticides and fungicides are used as required. To enhance flower and seed bearing, hormonal treatments such as gibberellin are sometimes applied, or stems or branches of the trees may be girdled.

Cones and fruit contain a considerable quantity of water, so are dried as soon as possible to avoid fermentation or decomposition. Cones which need after-ripening are opened and spread in open sheds. Seeds which contain a lot of starch, such as *Quercus* and *Castanea*, are soaked in running water for several days or steam-treated with carbon disulfide to exterminate insects. The sarcocarp of fruit of species such as *Juglans* or *Prunus* is removed by decomposition and washing. Cones of softwoods and fruits of members of the *Leguminosae* do not dehisce easily naturally, and are desiccated until the seed can be extracted. This is done in direct sunlight, in the shade of open sheds or in kilns, depending on the species and the condition of the cones or fruit. After extraction, the seed of softwoods is de-winged by hand rubbing or with special equipment and waste material is removed. Seed is sorted according to size using sieves or separation by specific gravity in winds or liquid.

The period for which a seed remains capable of germination is called its longevity. The longevity of tree seed is generally short, for example, for species of *Salicaceae*, it is 10-50 days, for *Fagus* and *Quercus* it is 1 year, and for *Pinus densiflora* (akamatsu) and *Pinus thunberigii* (kuromatsu) about 4-5 years in Japan if they are stored indoors (Hashizume, 1991). Since many tree species have long intervals between mast years, seed must be collected during mast years and stored for later use. Storage conditions (temperature, moisture and oxygen) affect the longevity of seed, and temperature and moisture are particularly important. Seed should be stored between 5° and -20°C, depending species. The moisture content in storage should be 3-8% for softwoods and 40-50% for *Quercus* (Hashizume, 1991). Seeds of species such as *Fagus* quickly lose their capacity to germinate if they dehydrate, so must be stored wet. The most common form of moist storage is to mix seeds with moist material such as peat moss in a polyethylene bags and store the bags in a refrigerator or room kept at a low temperature.

The phenomenon whereby healthy seeds do not germinate even if the environmental conditions for germination are satisfactory is called dormancy. There are two causes of dormancy; seed-coat dormancy or embryo (internal) dormancy. Seed-coat dormancy is caused by impervious protective coverings which exclude oxygen and water from the embryo and by inhibitors in the pericarp. Seeds of the *Leguminosae*, for example, are generally hard-coated. Seed-coat dormancy can usually be broken by mechanical abrasion, called scarification, or chemical softening, such as dipping in sulfuric acid. Embryo dormancy is caused by immaturity of the embryo, and can be remedied by storing seeds in moist and/or cool conditions, called stratification.

Before sowing seed over a given area, the quality of the seed should be tested. Testing of a sample is usually done to determine germinative energy, i.e., the percentage of seeds in a well-mixed sample that germinate under optimum conditions over a period in which most seed germinates (Figure 4-2). This period extends through the first 7 to 35 days following the start of germination (Smith, 1986). The percentage of seeds capable of germinating at all (i.e., not restricted by a definite time period) is termed germinative capacity (Figure 4-2).

4.1.4 Nursery operations

Location, establishment and maintenance of nurseries

Forest-tree nurseries should be located in a place similar to the areas where seedlings will ultimately be planted. For example, if there is large difference in elevation between the nursery and the planting site, adaptation of seedlings to the planting site may be poor. Ideally, nurseries should be located in as many different sites as possible, but small nurseries often have higher labour and facilities costs. The suitability of the soil and topography and the availability of water and manual labor should be considered before establishing a nursery. Nurseries should be located on level or gently sloping ground (under 5°). The best soils are moderately well-drained loamy sands or sandy loams, which are fertile, slightly acidic and free of stones. Areas with micro-topography vulnerable to cold or wind damage must be avoided.

Grading of planting stock

Good development of fine roots is one of the most important characteristics determining the viability of bare-rooted stock. The ratio of

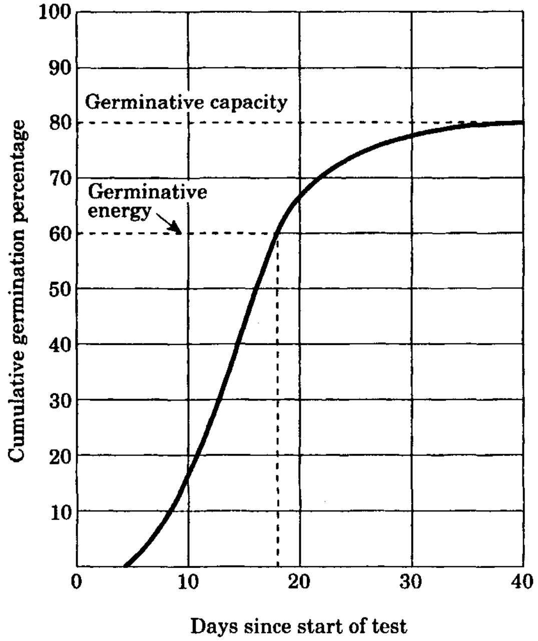


Figure 4-2 Cumulative germination curve showing the relationship between germinative capacity. In this example, only those seeds which had sprouted within 18 days of the start of the test, when the rate of germination started to decline, are regarded as capable of germination in the nursery. (Smith, 1986)

above-ground weight to below-ground weight of planting stock (T/R ratio) is a good indicator for grading of planting stock; the smaller the T/R ratio, the more viable the stock. The ratio of height to diameter of planting stock (H/D ratio) is also used as an indicator for grading; a smaller H/D ratio is desirable. The age and treatment of seedlings is expressed using a series of figures representing the number of years the plants grew as seedlings and transplants, and the sum of these indicates plant age. For example, a plant designated as 1-1-1 is a 3-year-old transplant which grew for 1 year as a seedling, 1 year as a transplant after the first transplanting, and 1 year as a transplant after the second transplanting. This designation is widely used (Baker, 1934; Sakaguchi, 1953; Harada, 1983; Smith, 1986).

Containerized stock

The production and planting of bare-rooted stock (Figure 4-3) is cheap. However, the period suitable for planting bare-rooted stock is limited. Digging up seedlings inevitably injures the roots and reduces the contact

Figure 4-3 A nursery producing bare-rooted stock in Japan.

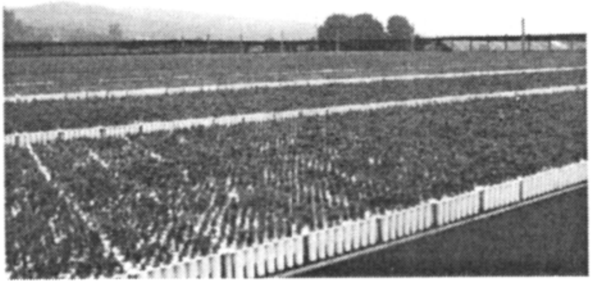


Figure 4-4 A nursery producing containerized stock in Chile.

between roots and the soil, so timing of dispatch and planting must account for root activity. As a result, the period available for planting is limited to a short time during the mild seasons of spring or autumn. Containerized stock (Figure 4-4) can be planted over a longer period, as transplanting shock is less for containerized plants. Where site conditions are severe, especially on dry or nutrient-deficient sites, containerized stock can significantly boost the survival of planted seedlings by protecting the roots and providing extra nutrients in the plug of the plant.

The use of containers allows planting stock to be produced from small quantities of seed, and enables fast-growing species to be easily propagated. Containerized stock can be planted at a very young stage, often one year or less, since their roots are protected and fed by the rich media in which they are grown. On sites where competition with other vegetation is not severe, small containerized stock can be planted. Containers can also be used to produce large seedlings. Recently, in some areas such as Quebec in Canada (Perreault et al., 1993) and Japan (Takeuchi, 1987), taller containerized planting stock has been produced to reduce weeding operations following planting. Larger seedlings tend to show a slightly more negative xylem water potential, but their greater size give them an advantage when exposed to competition (Lamhamedi and Jobidon., 1998). Containerized stock can be produced in greenhouses over a shorter period. Production costs are high but planting costs are reduced. Containerized stock can be considered as an alternative to bare-rooted stock if environmental and social conditions are appropriate.

4.2 Regulation of regenerative canopy openings

The success of regeneration of targeted species is determined by the light conditions on the regenerating site. Light conditions are in turn governed by the stand development stage and dynamics of the existing canopy. Although conditions suitable for regeneration will develop naturally over time (Section 2.4.4), the process can be accelerated by a series of scheduled thinnings. The extent of cutting required to promote regeneration is related to the shade tolerance of the species. In the case of very shade-intolerant species such as pine and birch, clearcutting or methods similar to clearcutting leaving only scattered mother trees is required for regeneration. Various non-clearcutting methods such as shelterwood methods with varying retained canopy densities or selection cutting can be used for species with moderate to high shade tolerance. The regeneration method is one of the most important factors used to classify silvicultural methods. The regulation of the canopy by thinning is an important component of regeneration. This is discussed in Chapters 6 and 8.

4.3 Site preparation

Successful regeneration of target species requires not only manipulation of the canopy by harvesting, but also treatment of debris, competing vegetation and soil to prepare the site for new trees.

4.3.1 Slash disposal

The residue left on the ground after felling is called slash. If slash remains dispersed, a high proportion of advanced regeneration is buried and the establishment of new shade-intolerant seedlings is inhibited. The efficiency of planting and tending operations is also reduced. Therefore, slash needs to be removed using a method suited to the management intensity and volume of slash.

Slash and litter, however, are important sources of minerals. They also prevent rain-splash erosion and frost heaving, and reduce the direct evaporation of water from the soil. Thin, loose layers of slash produce favorable conditions for exposure-intolerant species by protecting them from extremes of temperature, desiccation, grazing animals, and competition from shade-intolerant vegetation (Smith, 1986).

Slash is a fire hazard in boreal or temperate forests where unincorporated organic matter accumulates on the forest floor during the summer dry season. In such areas, slash disposal by burning is necessary to reduce the risk of forest fire (Brown and Davis, 1973; Smith, 1986). Slash is also burned if there is a risk that regeneration will be damaged by pests or diseases or if there is a dense cover of ferns. In summer moisture areas, slash is not regarded as a fire hazard, because moisture itself prevents fire and the decomposition of organic matter is comparatively quick. In such areas, fire is not a major threat to forests, and burning for fuel reduction is not necessary.

Slash disposal is usually carried out at the same time as competing vegetation is removed. Ideally, the slash is cut to a few meters length and is evenly distributed over the stand. This limits direct evaporation of water from the soil, prevents rain-splash erosion and frost heave, and provides a source of nutrients and organic matter to improve the physical and chemical condition of the soil.

In clearcut stands, large quantities of slash and competing vegetation can be disposed of in windrows constructed at intervals of 4-8 meters. On slopes, windrows are usually aligned with the contours (Figure 4-5). Windrow disposal is convenient for planting and weeding and prevents snow from sliding, but leads to an uneven distribution of planted trees and unwanted tree species often grow in the windrows. This is not desirable in a commercial context but does have some advantages because partial mixing of other species with planted species enriches the soil and enhances biodiversity.

Figure 4-5 Windrows in a clearcut stand in southen Kyushu, Japan. The picture was taken in early spring one year after the windrows were formed.

4.3.2 Treatment of the forest floor

Unincorporated organic matter on the forest floor provides a poor seedbed for most small-seeded species. Natural regeneration of such species requires scarification to expose the mineral soil. In small stands or on steep slopes this is carried out manually by raking small patches every meter or two, while on flat or gentle slopes and larger areas bulldozers equipped with root rakes or similar equipment are often used. In any cases, excessive scarification should be avoided to minimize soil erosion and carbon emission into the atmosphere.

4.3.3 Treatment of competing vegetation

Control of competing vegetation is an important part of site preparation. The type of treatment differs according to the structure of the previous stand. More work is required if the previous stand was a natural and/or older forest, with a developed understorey. Even if the previous stand was young, if the stumps can resprout and compete, treating them will require intensive operations.

Treatment prior to harvesting

In the shelterwood method, competing vegetation in the understorey should be removed prior to the final harvesting, i.e., just prior to preparatory cutting, seeding cutting, or the last thinning. In addition to promoting successful regeneration of the desired species, this has the advantage of improving working conditions, as removal of vegetation in the understorey and measurement of harvest trees can be done in the shade, and the logging operation can be conducted without the difficulties presented by an understorey.

Regeneration of planted *Pinus strobus* (eastern white pine) by shelterwood method in a mixed forest with a canopy of hardwoods and softwoods in Minnesota, the United States of America, requires removal of undergrowth if there is a partial removal of the canopy. When there is only partial canopy removal and the undergrowth is dense, the undergrowth suppresses the planted *Pinus strobus* (Smidt and Puettmann, 1998). For natural regeneration of *Fagus crenata* (buna) and *Quercus crispula* (mizunara) by the shelterwood method in Japan, competing vegetation should be removed 10-20 years before the final harvest to allow seedlings to establish on the forest floor (Kataoka, 1982; Sakurai and Saito, 1989). However, on drier sites where competing understorey vegetation is not prevalent, removal of undergrowth is less critical.

Weeding of the whole area

Weeding is the elimination of undesirable competing vegetation in the same layer or a layer close to the desirable tree species, so that the seedlings of the desirable tree species can survive and grow well until they dominate the undesirable vegetation. Weeding is discussed in more detail in Section 5.2. Weeding of an entire area is the most common and effective way of restricting competing vegetation, although it requires a great deal of labor if done manually. For individual workers, this method is simple and easy.

Strip weeding

Strip weeding is used to clear vegetation in rows where seedlings are to be planted or advance growth is to be fostered, especially when:

- the number of planted trees is few and the distance between the planted lines is large;
- the seedlings require protection from cold winds during winter; and
- erosion must be prevented.

The most common reason for strip weeding is to limit costs. However it may not necessarily be economical because successive weeding is required. The vegetation that remains re-invades the weeded area quickly and seedlings may be suppressed. This forces successive, more intensive weeding. Strip vegetation also provides conditions suitable for animals such as rodents and rabbits which may damage planted trees.

The use of contour strips on slopes helps restrict erosion and reduces the labor costs associated with moving through the stand. However, the vegetation remaining in upper rows may cover seedlings in lower rows. Strips going up and down the slope make it easier to weed up the slope to carefully remove vegetation around advance growth.

Spot weeding

The removal of vegetation from just around the planted or naturally regenerated seedling is called spot weeding. The spots are generally two to three meters in diameter. This method requires less labor and is less expensive than strip weeding but has similar drawbacks.

4.4 Tree planting

Planting is one of the most important operations in silviculture; the success of establishing a stand is greatly dependent on planting and if planting is inadequate, more tending work is needed. The quality and quantity of harvested timber are also greatly affected by planting. Planting procedures include the selection of planting stock, site preparation, stand density, spatial arrangement, method of planting, choice of planting season and treatments following planting. Site preparation was discussed in the previous section and the treatments following planting are discussed in Chapter 5.

4.4.1 Selection of planting stock

Planting stock production was discussed in Section 4.1. Bare-rooted or containerized stock can be used. Containerized stock is more expensive than bare-rooted stock, but survives well on dry sites, is appropriate for species which grow rapidly after germination, extends the planting season and enables large stock to be planted. Bare-rooted stock is commonly used because it is cheaper, and is suitable for most species and most sites.

In general, as the size of the planting stock increases, the top:root (T/R) ratio increases and the chances of survival decreases due to water stress both in bare-rooted stock (Hasse and Rose, 1993) and containerized stock (van den Driessche, 1991). However, small planting stock is vulnerable to suppression by competing plants, and if too small or young, cannot resist cold or frost heaving.

As mentioned in Section 4.1.4, the use of large containerized planting stock to minimize weed control operation in moist conditions has recently been evaluated in many parts of the world. For example, in the Province of Quebec in Canada, large containerized stock have been developed for conifers (Perreault et al., 1993; Lamhamedi and Jobidon., 1998). In Japan, large containerized planting stock have been evaluated combined with non-clearcutting method in an attempt to reduce weeding costs (Yamamoto, 1986; Takeuchi, 1987). Although the cost of producing the planting stock is a little higher than that of bare-rooted planting stock, the benefits are obtained if such stock are planted in the shade of old trees, where growth rate of light demanding grasses is relatively low. Planting stock of *Cryptomeria japonica* (sugi) raised in special wood pots for two years (three years old from germination) reach 80-100 cm tall and are thin. Three-year-old stock are planted by pulling them out from the pot, keeping the soil bundled with the roots. Although the planting stock is spindly, the survival ratio is nearly 100% and the stock can coexist with grasses. However, this method is not effective in snowy regions.

4.4.2 Planting season

The choice of planting season is usually based on the physiology of the planting stock and labor management considerations. Physiologically, the best time for planting is when the roots have commenced elongation but before the buds have started to flush. This is usually about one month before bud flush in the spring. An alternative time for planting is when shoot elongation and leaf spread have ceased, but root elongation is still active. This is usually between the beginning of autumn and when the leaves change color in the autumn in many parts of temperate forest zones. During these periods, roots can grow quickly to re-establish contact with soil and serious water stress is avoided.

The advantage of planting in spring is that following the rapid elongation of roots, the tree can grow throughout the growing season and develop cold resistance before the following winter. The advantage of planting in autumn is that the dry weather can be avoided if it is common in spring. However, the risks of planting in autumn include the potential for newly planted stock to be damaged by cold or frost heave. In snowy regions, transplanted seedlings are protected from the cold by the snow, and planting in these areas in autumn is effective. In regions with deep snow, the length of the planting season in spring is limited by the late snow melt, so planting is usually done in the autumn.

The planting season for broad-leaved evergreen species is later than that of broad-leaved deciduous species or coniferous species, because the physiological activity of broad-leaved evergreen species is slower in the spring than other species.

4.4.3 Planting methods

Planting methods vary according to a range of factors, including site, the characteristics of the tree species, and the size of planting stock. An important factor is the expected growth of the planted trees in the years immediately following planting. On sites where interspecific competition is not expected, the aim of planting is survival, and a more extensive planting method can be adopted. On sites where interspecific competition is expected to be severe, more intensive planting is required to enable the planting stock to immediately grow fast and compete with the surrounding vegetation. Intensive planting involves digging the soil widely and deeply so that relatively large plants can be used and the roots spread carefully over a large space. This is common in areas where precipitation is high during the warm growing season, and there are vigorous herbaceous plants, climbers and fast-growing tree species that dominate regeneration areas. Such areas occur in monsoon areas in the eastern or southeastern parts of the continents of the northern hemisphere and in tropical rainforest areas.

There are various planting methods used in different countries and areas within countries, depending on the natural and social conditions of the area. For example, Smith (1986) described 7 methods used for planting bare-rooted stock in North America, and Sakurai (1990) described 6 methods that are used in Japan, and that differ considerably. Generally, the methods used in Japan are more intensive than those used in North America, which might be attributed to the higher levels of interspecific competition and steeper topography found in Japan. Very intensive planting methods are often adopted for planting forests on steep slopes to prevent or mitigate avalanches as seen in Switzerland.

Care must be taken during transport and planting not to damage the root systems of the planting stock. Many root hairs are broken during lifting and transportation, yet the planting stock needs to be able to take up as much water as possible after planting. Fortunately, suberized roots can absorb water directly (Kramer and Kozlowski, 1979), thus providing planted trees with an immediate, but very limited, supply of water. This is one reason that it is essential for the soil to be firmly packed around the roots of planted trees (Smith, 1986). Similarly, litter must be excluded from the soil which is pushed back against the roots to avoid making it difficult for the roots to absorb water.

Mycorrhizal mycelia are also important for the uptake of water and nutrients, and the presence of mycorrhizae is closely related to the survival and growth of planted trees (Section 2.2.1). There are many example of the planting of exotic species becoming spectacularly successful, after earlier frustrations, as soon as nurseries were inoculated with the proper fungi (Smith, 1986). During transportation to a planting site, care must be taken to ensure that the roots remain moist. It is essential to avoid exposing the roots to sunlight or wind.

4.4.4. Density of planted trees

One of the advantages of planting trees compared to relying on natural regeneration is that it is possible to accurately control the initial density to suit the environment and the objectives of establishing the stand. The initial density should be determined according to the stand density control measures planned throughout the rotation. Initial stand density is an important factor affecting wood quality. Although genetic factors control characteristics such as the color and luster of wood, and environmental factors, such as injury to wood by climatic or biological agents, contribute to wood quality, there are stand management factors that affect wood quality. The distribution and size of knots and the pattern of annual growth are important determinants of wood quality and these are determined by the pattern of an individual's growth throughout its life in a stand (Fujimori, 1991a), which in turn is affected by stand density and other management factors. If a stand is being grown to produce wood for pulp or biomass, the initial density should ensure the greatest yield of logs of the requisite size per unit area as fast as possible without thinning.

In the areas where water availability is a limiting factor for tree growth, initial stand density is generally reduced to postpone the competition for water. On the other hand, in the areas where water availability is sufficient, it is important to minimize the number of years between planting and the last weeding and climber cutting by increasing initial density. As the initial density increases, the period of weeding and climber cutting decreases. The optimum initial density is a function of the costs of planting, weeding, climber cutting, precommercial thinning, and the price of harvested timber.

In areas where cold damage is frequent, a higher initial density is desirable until the sapling stage. In areas with deep snow, the initial density should be lower, because to acquire snow resistance, trees must be tapered during the young stage. In these areas, planting must be done carefully to provide suitable conditions for developing snow resistance, and if the trees are pushed over by snow pressure, they will require propping up. An appropriate number of trees must be planted to avoid such time-consuming work.

Stands younger than 20-25 years old are generally wind resistant, regardless of the stand density (Fujimori, 1995). Therefore, even in areas where strong winds strike frequently, it is possible to use a higher initial density if frequent thinnings can be done as the stand ages.

If broad-leaved tree species are given a lot of growing space, large branches develop on the lower trunk. In plantations of broad-leaved species where the objective is timber production, the initial density is increased to minimise the size of branches and raise the height of the base of the live crown. This is particularly important for species with decurrent form (Chapter 2.3.2). One of the advantages of natural regeneration is that if germination is prolific, the regrowth is dense and there is ongoing competition which controls tree form. This is one of the reasons why natural regeneration is usually used for broad-leaved tree species.

As shown above, various factors affect the selection of initial density, and initial density will vary according to the objectives of establishing the stand, environmental conditions and the species characteristics. In the case of *Cryptomeria japonica* (sugi), for example, a wide range of initial densities is found throughout Japan; from 1500 stems/ha in Obi in Kyushu where typhoons frequently affect the forests and the objective used to be to produce large logs for structural timbers of ships; to 10,000 stems/ha in Yoshino where the objective used to be to produce timber with narrow, uniform growth rings to use for sake (a kind of alcohol) casks. The objectives of production in both areas have now changed but the initial planting densities remain in both areas. In Obi, the initial density is still low enough to produce large logs in a short period, while in Yoshino, the density remains between 5000 and 10,000 stems/ha, and frequent thinning is conducted to produce high quality timber with uniform annual rings. Currently, the standard initial density of *Cryptomeria japonica* in Japan is around 3000 stems/ha. However, in snowy areas it is lower and in areas where high quality timber is produced, it is higher, i.e., 4000-5000 stems/ha for *Cryptomeria japonica* and 5000-6000 stems/ha for *Chamaecyparis obtusa* (hinoki).

4.4.5 Spatial arrangement of planted trees

The principle factors affecting spatial arrangement are the arrangement of the growing space for each crown and the efficiency with which planting, weeding and thinning operations can be conducted. Straight round stems are produced if the growing space of the crowns allows even development in all directions, while planting in rows facilitates operations, especially mechanized operations.

The most common and simplest spatial arrangement is square spacing (Figure 4-6, part 1). On flat land, this arrangement provides an even space for each individual and enables relatively easy operations. However, on a slope, this arrangement does not result in even spacing, because the crown develops faster on the valley side of the tree, and the upper part of each crown is overshadowed by the crown of adjacent trees on the mountain side when the canopy is closed.

Rectangular spacing (Figure 4-6; 2) solves this problem by providing a greater distance between trees in the direction of the slope. Equilateral, or triangular, spacing allows individual crowns to occupy the space most evenly and effectively (Figure 4-6; 3). On a slope, equilateral spacing is the best arrangement for crowns to develop as evenly as possible. It also helps reduce crown snow damage and protects the stand from a domino-style collapse, because of the even crown development. However, tending in stands arranged equilaterally is more time consuming. Equilateral spacing is used in areas of very intensive forest management, such as Kitayama in Kyoto Prefecture, Japan.

A staggered arrangement (Figure 4-6; 4) has similar advantages to equilateral spacing on a slope in snowy regions. Planting in rows of two or three trees (Figure 4-6; 5) is used to facilitate mechanized operations. Row

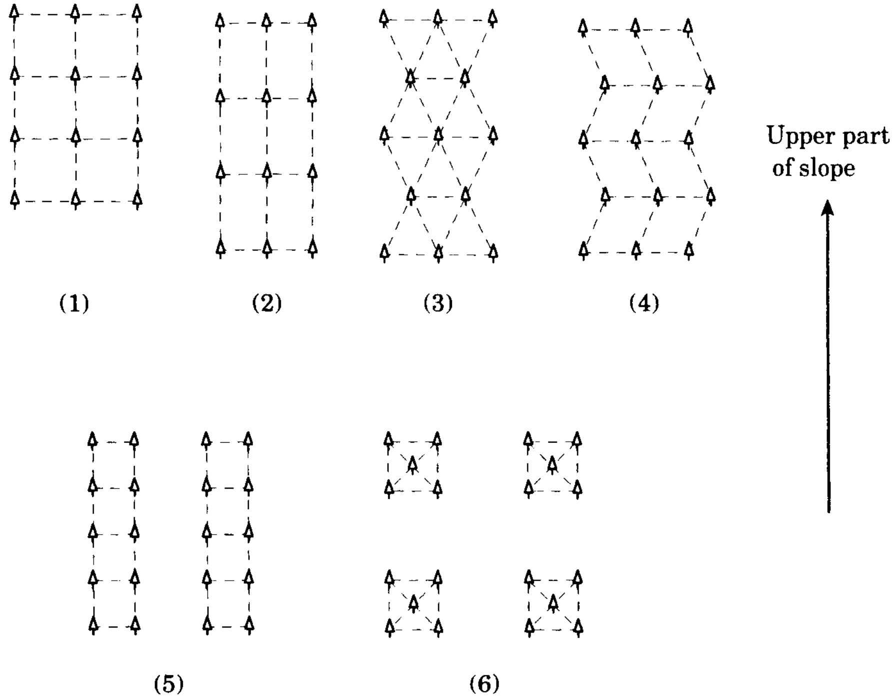


Figure 4-6 Alternative spatial arrangement for planted trees. (Modified from Fujimori, 1991a)

planting is an extension of rectangular spacing. Cluster arrangements (Figure 4-6; 6) are used to produce crop trees which are evenly distributed following thinning of the surrounding trees. The surrounding trees have a training effect on the crop trees. The distance between clusters is determined by the desired size of harvested trees, and the timing of thinning surrounding trees is also important. If thinning is delayed, the crop trees are suppressed and die, leaving the crooked surround trees with uneven shaped crowns. Cluster arrangements are sometimes tried to reduce weeding operations. However, their effectiveness has not been determined and it has been pointed out that the period for climber cutting is extended, because it takes longer for canopy closure to be reached in the area between clusters, and this provides an environment suitable for climbers to grow.

4.4.6 Mixed plantations

To establish a stand of mixed species, knowledge of the ecology of all species must be applied. Relationships between the traits of each species, such as light requirements, growth patterns and crown development must be analyzed. Species with similar traits should not be planted in an even mixture, because the species which is slightly superior will gradually surpass and finally eradicate the other. For example, in a plantation where *Zelkova serrata* (keyaki) and *Castanea crenata* (kuri) were planted with alternate lines in Japan, *Zelkova serrata* eradicated gradually Castanea crenata. In the east of the United States of America, when *Pinus taeda* (loblolly pine) and *Pinus echinata* (shortleaf pine) are mixed, *Pinus echinata* is eradicated (Smith, 1986). On the other hand, species which are ecologically very different can coexist in differentiated vertical strata for several decades or more. For example, if *Chamaecyparis obtusa* (hinoki) and *Pinus densiflora* (akamatsu) are grown together in Japan, the fast-growing, light demanding *Pinus densiflora* grows quickly, providing growing space and an environment suitable for the slow growing, light tolerant *Chamaecyparis obtusa*. A similar relationship is also found between birches and firs.

If a mixed stand of species with similar traits is required, it is preferable to plant small clumps of different species rather than evenly distribute all species. This ensures that inferior species survive, even though trees immediately adjacent to superior species will be eradicated. The number of trees of each species gradually decreases through intraspecific competition and the physiognomy of the stand changes from mixed clumps to a mixture of individuals. Generally, fewer of the superior species should be planted, because they suppress the inferior species and the individuals usually occupy a larger crown area. The size of the clumps is determined by the desired final tree height, growth rate of each species and the expected frequency of thinning. If the expected final tree height and growth rates are low and thinning is expected to be frequent, smaller clumps can be planted. If, for example, the final height is expected to be about 25 m, the growth rate expected to be average and the first thinning expected in 20-25 years, the clump should be at least 10 m long (on one side) and at least 25 trees should be planted to ensure that at least one or two healthy trees of the inferior species remain at the end of the rotation (Fujimori, 1991a).

Clumps do not have to be uniformly distributed, and in one method, clumps of one species are surrounded by another species (Figure 4-7). The size of the clump is determined by the objectives of management, traits of the species and the frequency with which thinning can be practiced.

There is insufficient experience and knowledge of establishing mixed stands to be definitive about their management, but the benefits of mixed stands for various purposes will be increasingly recognized in the future. Therefore, more experiments testing methods of establishing mixed stands need to be conducted. In natural regeneration of mixed stands, the proportion of each species can often be manipulated by controlling the size of cutting area, as discussed in Part III.

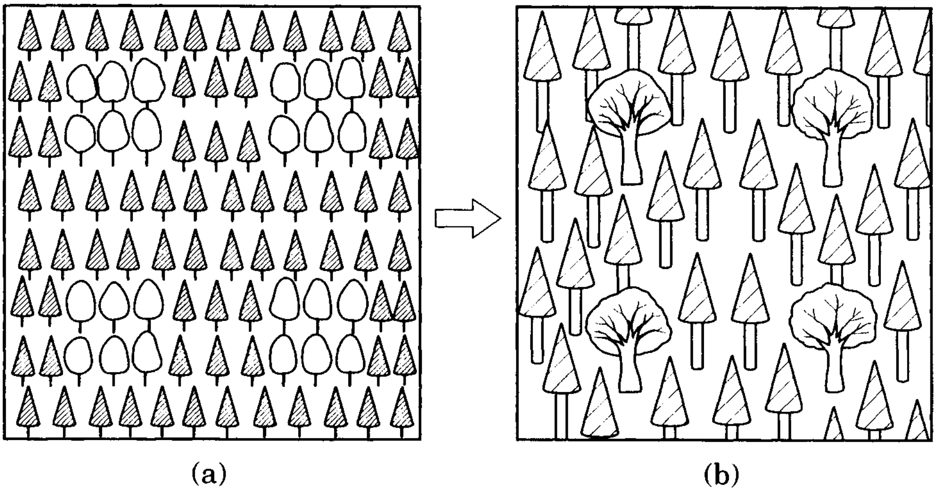


Figure 4-7 Alternative spatial arrangement for planted trees (Fujimori, 1991a)

4.5 Natural regeneration

Some aspects of natural regeneration techniques were discussed in Sections 4.2 (Regulation of regenerative canopy openings) and 4.3 (Site preparation) in this Chapter. Natural regeneration techniques are further discussed as part of each silvicultural method covered in Part III.

Chapter 5

Management to Control Interspecific Competition

One of the most important techniques for the success of regeneration and subsequent tending of crop trees is the control of competing vegetation. These operations are discussed in this Chapter.

5.1 Forest vegetation management

A silvicultural operation which suppresses undesirable vegetation to give sufficient growing space to planted or naturally regenerated desired trees is called vegetation management or vegetation control. In tropical rain forest zones, unwanted vegetation grows well and intensive vegetation management is indispensable for regeneration of desired species. In the summer humid areas in temperate and boreal forest zones such as eastern parts of Asia and North America, vegetation management is also indispensable (Tanimoto, 1982, 1983; Wagner, 1993; Mallik et al., 1997). Vegetation management can be the most expensive tending operation in forest management. Chemical herbicides have been widely used to control competing vegetation, but their use has being criticized as an environmental hazard, and there is a need to improve or restrict the use of herbicides (Jobidon, 1991; Wagner, 1993; Mallik et al., 1997). On the other hand, manual control of vegetation is labour intensive and therefore costly. In this context, alternative methods for vegetation control based on the ecology of the forest should become much more important. Knowledge of autecological characteristics of competing plants is required, and understanding their regenerative strategies following disturbance is especially important (Tanimoto, 1982, 1983; Wagner, 1993; Mallik et al., 1997). This is essential if sustainable forest management is to be achieved.

There are many terms for vegetation management, such as weeding, brushing, cleaning, climber cutting, and liberation, which are used according to the growing stage or size of the crop trees and competing vegetation. Smith (1986) defined weeding as the removal of all plants competing with the desired species, regardless of whether their crowns are above, beside, or below those of the desired trees. Ford-Robertson (1971) defined weeding as a cultural operation eliminating or suppressing undesirable, mainly herbaceous vegetation during the seedling stage of a forest crop. The term "brushing" used in Canada refers to the removal of competing vegetation from the immediate area surrounding seedlings (natural or planted) at the early stage in the tree life (2 to 5 years after regeneration) when competition is a very real threat to survival and growth of crop trees (Canada-British Columbia Partnership Agreement on Forest Resource Development, 1992). The definition of cleaning differs between countries, but according to Ford-Robertson (1971) and Smith (1986), the term cleaning is a cutting operation, undertaken before the end of the sapling stage to clear competing vegetation, mostly woody plants of a similar age, from around the desired species. However, the plants eliminated in cleaning may include not only overtopping trees of undesirable species but also poorly formed desirable tree species, climbers, overtopping shrubs, and sometimes herbaceous growth (Smith, 1986). In this context, cleaning is not usually distinguished from weeding. It is equivalent to the operation called "shitagari" in Japan, in which the removed vegetation can be either herbaceous or woody, and which is conducted continuously from the seedling stage to the sapling stage (2-3 m height). In many countries in the world, there are probably many terms for the operation similar to weeding, brushing, and clearing.

Therefore, it is practical to use the single term weeding for operations involving weeding, brushing, cleaning, or similar. In this book, the term weeding is defined as an operation during the regeneration phase in which undesirable competing vegetation in and around the same layer as the crown of the desired species is suppressed or eliminated so that the desired species can survive and remain healthy until they outgrow the undesirable vegetation.

5.2 Weeding

Plants compete for resources required for growth, such as light and water. In areas where water is not a limiting factor for growth, light is generally the most critical determinant of survival of competing plants. The most important traits enabling plants to survive competition are a high growth rate in the early stage and/or a high tolerance to light. Weed species generally have high early growth rates and most herbaceous species have a much higher growth rate than most tree species, especially desired tree species (Figure 5-1). Trees must develop attributes which confer a long life, such as protection from the cold and structural support for height growth, i.e., cells, tissues and organs must lignify, and a high proportion of biomass must be allocated to bark and the root system. In contrast, herbaceous species can grow larger without diverting energy and matter to attributes associated with long life. Therefore, herbaceous species can develop large above-ground organs using the abundant organic matter produced in wet and warm climatic conditions.

Weeding controls secondary succession, and effective weeding strategies should be based on the growth habits of the competing species. The production structures (Section 2.3.2) of plants with three contrasting growth forms are shown in Figure 5-2. In the *Erechitites hieracifolia* (benibanaborogiku) community, there is little difference in the leaf biomass

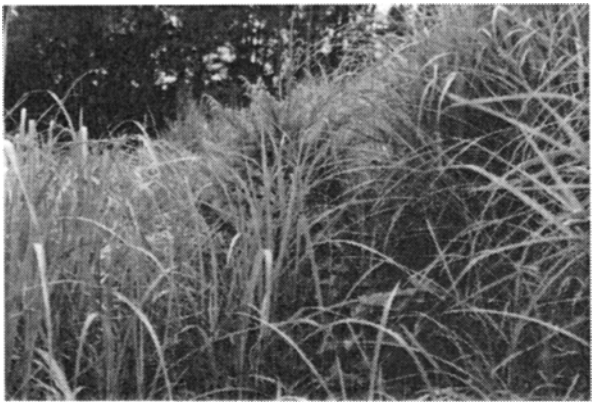


Figure 5-1 Planted trees and herbs in Ibaraki Prefecture, Japan. Four-year-old *Cryptomeria japonica* (sugi) seedlings on a site where *Miscanthus sinensis* (susuki) had dominated following clearcutting a few years prior to planting. Weeding has been practiced every year but if it is stopped now, the planted trees will be covered by *Miscanthus sinensis* within a year.

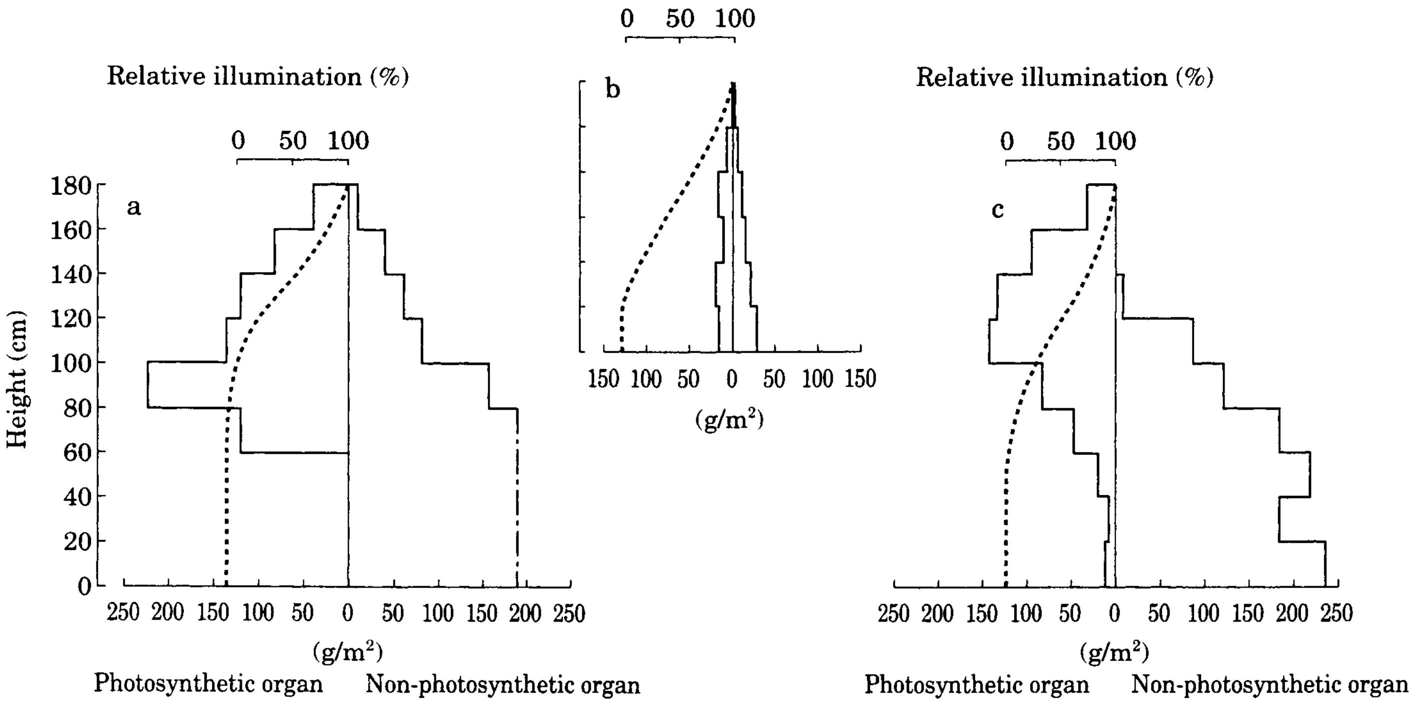


Figure 5-2 The production structure of some major herbaceous communities.
a: *Quercus glauca* (arakashi) community
b: *Erechtites hieracifolia* (benibanaborogiku) community
c: *Miscanthus sinensis* (susuki) community
·········: Relative illumination
(Tanimoto, 1982)

between each vertical stratum. In the *Miscanthus sinensis* (susuki) community, the greatest leaf biomass is in the highest stratum, and leaf biomass gradually decreases down the strata. In the *Quercus glauca* (arakashi) community, the greatest leaf biomass is also in the high strata, but the biomass decreases rapidly down the strata. The light regime in the *Erechitites hieracifolia* community is preferable for most forestry tree species, because there is good light penetration to the lower strata as a result of the low leaf biomass and consistent vertical distribution of leaves in each strata. For a species such as *Cryptomeria japonica* (sugi), the light regime is poorest in the *Quercus glauca* community, followed by the *Miscanthus sinensis* community and the *Erechitites hieracifolia* community.

Figure 5-3 is an example of the successional changes in production structures in the five years following planting of *Cryptomeria japonica* on a site previously occupied by a broad-leaved evergreen secondary stand in Shikoku, Japan. Weeding was undertaken annually. The production structure in the first year was that of the *Erechitites hieracifolia* type, by the third year *Miscanthus sinensis* became dominant, and then in the fifth year, broad-leaved evergreen trees dominated. Where weeding was not practiced, the plants were about 2.5 times as tall as in the area where weeding was repeated. However, the size of the *Cryptomeria japonica* in the unweeded area in the fifth year was similar to that in the weeded area in the third year, implying that growth of *Cryptomeria japonica* was faster when weeding is practiced.

The success of a species in the presence of interspecific competition on a given site depends on it having one of the following attributes:

- rapid height growth;
- rapid horizontal branch or leaf development; or
- tolerance of limited light conditions.

Species such as *Erechitites hieracifolia* (benibanaborogiku) have rapid height growth, species such as *Miscanthus sinensis* (susuki) have both rapid height growth and rapid horizontal development, and species such as *Quercus glauca* (arakashi) tolerate limited light and their sprouts have rapid height and branch growth. Thus, the sprouts of shade-tolerant species can be very competitive with desired species.

In *Erechitites hieracifolia*-type communities, weeding should be avoided in the year when seedlings are planted or in the second year because the light regime is not adverse for the planted species and elimination of *Erechitites hieracifolia* enhances the growth of *Miscanthus sinensis*, broad-leaved species and climbers which are very competitive with the planted trees.

Miscanthus sinensis-type herbaceous plants can be very competitive

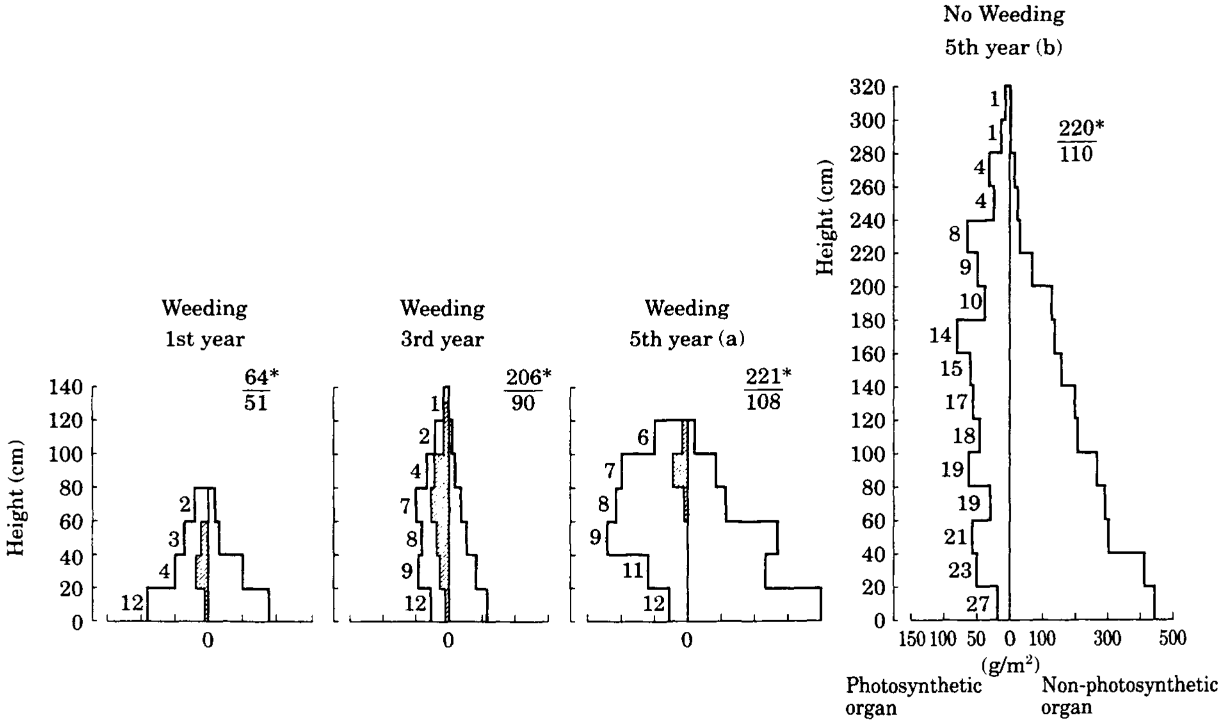


Figure 5-3 The change in the production structure of vegetation on a planted area. The figure in each stratum is the number of species found in the stratum. The hatched area denotes the leaf weight of the *Miscanthus sinensis* type.

* Height of *Cryptomeria japonica*

Maximum width of crown of *Cryptomeria japonica*

(Tanimoto, 1982)

with planted trees, because on hot, humid windless days the high humidity created by the density of *Miscanthus sinensis* can impede transpiration by the trees. In this respect, *Miscanthus sinensis*-type herbaceous plants are more competitive than broad-leaved species, although broad-leaved trees are more competitive for light. Therefore, the competitiveness of the surrounding species has several dimensions.

Mallik et al. (1997) classified potential competition strategies into two groups based on species regeneration strategies following disturbance. One is a vertical competition strategy (VCS) in which the weed species have overtopping effects because of their more rapid height growth following establishment. In this type of competition, the amount of light necessary for the growth of desired species (conifers) is reduced by species such as *Populus tremuloides* (trembling aspen) and *Prunus pennsylvanica* (pine cherry) overtopping the conifers. The other type of competition is horizontal competition strategy (HCS), in which weeds compete with the desired species in the horizontal plane, both above-ground for space and light, and below-ground for root space, nutrients and moisture. Examples include *Alnus viridis* (green alder) and *Corylus cornuta* (beaked hazel) which occur in clumps consisting of many short and massive stems above-ground and dense and robust roots and rhizomes below-ground. Mallik et al. (1997) suggest that weeding methods should be developed based on stem density and the proportion of VSC and HCS plants and population dynamics such as rate of clonal spread, height growth, stem mortality and recruitment.

If regenerating conifers occur on a nutritionally rich site with a large number of HCS plants and the conifer seedlings are above the canopy height of the competing plants, the site may not require any weeding operation. It is likely that although the conifers will initially face some below-ground competition for growing space from the HCS plants, they will eventually out-compete them owing to their taller structure. However, if the conifer seedlings are not above the canopy height of the competing plants, weeding may be necessary to release the seedlings (Mallik et al., 1997).

After clearcutting, herbaceous and woody plants recover in the cut area comparatively quickly, for example, within several month in Japan, if it is not winter. Nutrient uptake by the revegetating plants minimizes the loss of nutrient and helps restore the nutrient cycling to preharvest levels more quickly (Marks and Bormann, 1972; Likens et al., 1978; Outcalt and White, 1981; Boring et al., 1981; Gholz et al., 1985; Katagiri, 1986). Although weeding supplies nutrients to the soil, it may induce runoff of nutrients from the stand (Aiba et al., 1981, 1985; Haibara et al., 1983; Takahashi, 1996). Therefore, weeding should be practiced appropriately in consideration with effective vegetation control and minimizing runoff of nutrients.

If there is sufficient cheap labor, weeding can be completed as required. If it is limited, however, the most labor and cost efficient method must be selected on the basis of the development of the community surrounding the desired trees. Weeding can be achieved using physical, chemical or ecological methods, or a mixture of these methods.

5.2.1 Physical control

Physical weeding is the manual cutting of competing plants. It is the most reliable technique, although it requires a lot of labor.

The tools used for physical weeding include one-handed sickles, two-handed sickles, and motorized cutters (such as cleaners or brush cutters). The chosen tool is selected according to the size of the plants to be removed, the likelihood of damage to retained trees, labor productivity and site conditions. Sickles are used when the trees are still small and the weeds must be removed carefully. Scythes are used when the trees and competing vegetation are larger. Motorized cutters are the most productive, but are hard to use on steep or rocky sites, and can easily damage the retained trees, especially when they are small. Climbers close to the retained trees are often left to avoid injuring the trees. Therefore, it is desirable to use a combination of motorized cutters and sickles.

The best season for weeding may vary throughout the world according to the natural conditions. In temperate areas where the summer is wet, the best season my be in summer, when the competition of plants is most severe. In those areas, perennials and woody plants use organic matter stored during the previous year in their spring growth and begin to store organic matter for growth the following year from the end of the summer (Satoo and Takegoshi, 1952). In temperate areas where the summer is dry, the best season may be in spring, when both weeds and the desired trees are growing rapidly but before severe competition for moisture begins.

When establishing or regenerating a plantation after clearcutting, weeding is usually required for 5 to 8 years after planting in Japan (Japan Forest Technology Association, 1975). The duration of weeding depends on the planted and competing species, site quality, and the density and size of the planted trees. The faster the growth rate of the planted trees, the shorter the period of weeding. The period of weeding is also shorter if the site quality is higher, although two weeding operations a year are often necessary in the second and third years on good sites. On poor sites, the weeding period is longer but annual weeding is only necessary for the first half of the period. The period of weeding is also shorter if stand density is higher, or the planted trees are larger.

Partial cutting of vegetation around the planted trees (spot weeding) or strip cutting along the rows of planted trees (strip weeding) is sometimes adopted to reduce the cost of weeding. These techniques are effective for a short time, but the plants left uncut grow to suppress the planted trees within a few years and the cost of removing them is often greater. Climbers spread from the area left uncut and the removal of them becomes necessary. On the other hand, weeding by only selectively cutting plants directly affecting the planted trees in the first and second year is an effective way to control the growth of stiffer species including climbers. Generally, after the second year, weeding of the entire area is desirable.

5.2.2 Chemical control

Weeding using herbicides is an effective, labor-saving method. Herbicides must be used appropriately, however, as their misuse can damage the environment. Herbicides are available for each of the main types of competing vegetation. The herbicides contain inorganic or organic compounds, which have metabolic, photosynthetic, or growth regulatory effects on the weeds. The ecological traits of the main weed species and the properties of the herbicides must be understood to use herbicides effectively.

Asanuma (1987, 1988) studied the relationship between the traits of dwarf bamboos and the efficiency of herbicides. Tetrapion is a slow acting herbicide absorbed by the roots of dwarf bamboo which impedes cell division in the shoot apex. When pelletized tetrapion is sprayed at 3 kg (active ingredient) per ha, dwarf bamboo such as *Sasa nipponica* (miyakozasa), whose shoots and leaves have a one- or two-year life span, usually die within one or two years. Other species of dwarf bamboo such as *Sasa paniculata* (chimakizasa), whose leaves have a two- or three-year life span and the shoots a longer life span, do not completely die and resume growing about three years later. Therefore, the dosage of a herbicide must be determined according to the weed species and the desired degree of control.

Herbicides should only be used to control the growth of competing vegetation, not kill it completely. The aim should be to reduce the weed competition whilst retaining soil cover to prevent soil erosion and moderate the microclimate. Effective combinations of chemical and physical control have been proposed by Asanuma (1987). Herbicides should be used only by experienced people and new herbicides should be tested on small areas before being used on an operational scale.

5.2.3 Ecological control

The development of light-demanding vegetation can be controlled by retaining overstorey trees to maintain shade. Weeding can be reduced or eliminated by using harvesting systems such as the selection, two-storied or shelterwood methods. These methods are referred to as multi-storied forest methods in Japan (7.1.1). Weeding can also be reduced or eliminated by strip harvesting (this is also regarded as a multi-storied forest method) of old *Cryptomeria japonica* (sugi) and planting large size seedlings of *Cryptomeria japonica* or *Chamaecyparis obtusa* (hinoki) (80-100 cm height) (Yamamoto, 1986). Light-demanding competing vegetation is reduced because shady conditions are maintained in the strips. Multi-storied forest methods are particularly effective if comparatively shade-tolerant tree species are expected to regenerate. Should weeding prove necessary in a multi-storied forest, it can be effectively practiced in cool, shady conditions (Ando, 1985; Fujimori, 1991a).

Generally speaking, weeding should be done before the unwanted vegetation overtops the desired species. However, if light-demanding, fast growing pioneer tree species such as birches or pines invade the stand, there may be some merit in allowing them to coexist with the desired species. Light-demanding, fast growing species inhibit the growth of highly competitive species more than most desired species. Light-demanding species can also protect the desired species from frost damage in cold areas (Hara et al., 1995). Therefore, tending costs may be reduced if light-demanding species are retained until the desired species are well established. If the invading pioneer species is commercially valuable, such as *Betula maximowicziana* (udaikanba), the stand can be left to develop into a mixed stand of the planted and invading species (Figure 5-4).

Weeding can be completed earlier by planting at higher densities, although the cost of planting increases and more precommercial thinning is

Figure 5-4 Two storied forest of *Betula maximowicziana* (udaikanba) and *Chamaecyparis obtusa* (hinoki). *Betula maximowicziana* regenerated naturally soon after *Chamaecyparis obtusa* was planted and weeding stopped.

required. However, high quality timber with fewer knots and uniform annual rings can be produced by this method if repeated thinnings are conducted.

Exploitation of the phenomenon of allelopathy may be a promising method of biological vegetation control. Allelopathy is regarded as any direct or indirect harmful effect of one plant (including microorganisms) on another through production of chemical compounds that escape into the environment (Jobidon, 1991). According to Jobidon (1991), the presence of *Pennisetum clandestinum* (kikuyu grass) on sites of regenerating *Cunninghamia lanceolata* (Chinese fir) significantly inhibited the growth of competing weeds but did not reduce the growth of fir seedlings in Taiwan (Chou et al., 1987, 1989). In Quebec, Canada, Jobidon et al. (1989a, b, c) recognized that allelopathic mulches, such as barley, oat, and wheat straw, significantly reduced the number and height growth of competing vegetation [mainly *Rubus idaeus* (red raspberry)], although the planted *Picea mariana* (black spruce) was not affected by the straw. It was hypothesized that the straw mulches inhibited nitrification, which in turn impaired the establishment of *Rubus idaeus*, a notoriously nitrophilous species (Jobidon et al., 1989b). Allelopathy may be difficult to exploit in other circumstances, such as on sites where stiff plants prevail, but it does offer an additional tool for vegetation control.

5.3 Climber Control

There are many kinds of climbers in humid tropical areas, humid subtropical areas, and temperate areas with humid summers. Climbers often cause damage to trees. For example, in the Nagasaki Forestry District Office in the broad-leaved evergreen forest zone of southwestern Japan, where there is a large area of forestland, 43% of young, mostly coniferous, plantations which had been weeded completely were affected by climbers and required climber cutting. A high percentage of natural forests were also affected by climbers, although damage was not as serious as in the plantations (Arakawa, 1936). In the Kiso District Forestry Office in the broad-leaved deciduous forest zone of central Japan, climber cutting was conducted in 28% of all plantations and weeding was conducted in 24% (Osawa, 1937). In 7 *Chamaecyparis obtusa* (hinoki) plantation stands on the foot of Mt. Tsukuba in Ibaraki Prefecture in central Japan, which is a transition zone from the broad-leaved evergreen forest zone to the broad-leaved deciduous forest zone, 21 woody climber species and 11 herbaceous climber species were found (Suzuki, 1984). These figures show the prevalence of climbers and the importance of their control in these areas.

In tropical rain forest zones where vines grow luxuriously, vine management is a critical silvicultural treatment (e.g., Pinard and Putz, 1994; Vidal et al., 1997). Although the following discussion of vine control is based on data from temperate Japan, it will apply to vine control in tropical zones as well as other parts of temperate or even boreal zones.

5.3.1 Mechanism and types of damage caused by climbers

Climbers cause two types of damage; deterioration of wood quality and reduced growth caused by coverage of the crown (Figure 5-5). It is common for both types of damage to occur together. Climbers grow around the tree stem and cut into it as both the stem and the climber grow thicker, causing bends (Figure 5-6) or forks (Figure 5-7) in the stem, defects in the wood or killing the tree.

Climbers can affect trees before or after canopy closure. If climbers are not completely killed during the weeding period, they can produce many sprouts which later develop and can injure young trees until the stand is completely closed. Between 10% and 75% of trees in young *Abies sacharinensis* (todomatsu) plantations can become bound by climbers within 3 years of the last weeding and between 30% to 90% of trees can be bound within the next 5 years (Toyooka, 1977).

Climbers prevalent before stand closure include *Pueraria lobata* (kuzu), *Wisteria* spp. (fuji spp.) and *Akebia trifoliata* (mitsubaakebi). Most of these are vines which climb the tree stem, coiling around it and eventually strangling it. When the vine coils around the tree stem, the phloem is injured and the transport of photosynthates down the stem is interrupted. This causes abnormal thickening above the vine and the stem is deformed

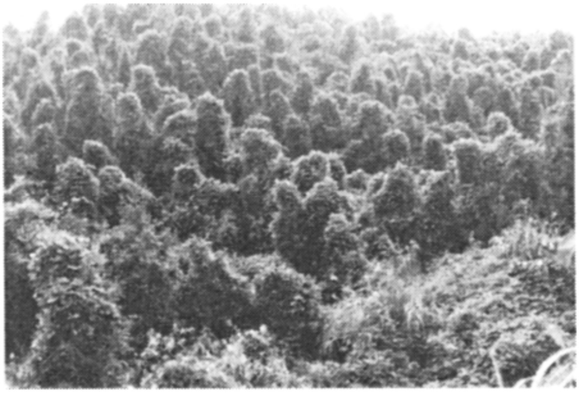


Figure 5-5 A plantation of *Cryptomeria japonica* (sugi) covered by *Pueraria lobata* (kuzu) in central Japan.

Figure 5-6 A crooked stem of *Larix kaempferi* (karamatsu) which was caused by a climber in central Japan.

Figure 5-7 A fork-shaped stem of *Chamaecyparis obtusa* (hinoki) which was caused by a climber in central Japan.

(Figure 5-6). The younger the tree and the faster its growth rate, the more serious the damage to the tree. Damage to younger trees is therefore more serious than that of older trees and early climber cutting is necessary.

The relationship between the degree of injury by climbers and the timing of climber cutting is shown in Figure 5-8. Serious damage to the tree stems occurs 3 or 4 years after binding, so damage can be avoided or minimized by cutting the climbers before then. Otherwise, irreversible stem damage occurs (Figure 5-9). If climber cutting is still not done, the stem is likely to break, fork or become extremely crooked as a branch takes over as the main stem (Figures 5-6, 5-7, 5-10). Logs produced from a tree whose damage has advanced to the abnormal thickening stage have no value or extremely limited yield. Usually, climber damage is most serious in the lower portion of the stem which would otherwise produce the most valuable first and second logs.

Climbers such as *Pueraria lobata* and *Vitis* species (budo spp.) prevail before stand closure and damage trees by densely covering their crowns with large leaves. This reduces the tree's capacity for photosynthesis and therefore reduces growth. Further damage occurs when the climber grows onto a neighboring tree, bending the shoot of the tree and causing a crooked stem.

Climbers such as *Schizophragma hydrangeoides* (iwagarami) and *Trachelospermum asiaticum* (teikakazura) usually invade in the mature stage, or after intensive improvement cutting or thinning. These climbers grow up the stem gradually and cover the crown. As it usually takes more than 15 years for the vines to reach the crown and reduce photosynthesis (Suzuki, 1989), climber cutting for these species is possible any time before that, although earlier cutting is desirable.

5.3.2 Methods of climber control

The best season for climber cutting is from the beginning to middle of summer in temperate areas, when the growth rate of climbers is rapid and capacity for regrowth limited because photosynthate reserves have not yet been stored. Vines should be cut near the ground so as not to injure the tree stem. If the stem is injured, discoloration of wood is caused (Section 6.1.7), which degrades the value of the wood. If the vine has not yet strangled the tree stem, it is sufficient just to cut it, but if the stem has been strangled even slightly, the vine must be removed immediately after cutting.

Climbers regrow by sprouting, so the most effective control is to pull them up within two or three years of them invading. This can be done at the same time as the forest floor is treated for regeneration, and again several years later. Although it may be better to avoid weeding in the year when seedlings are planted or in the second year, climbers and other

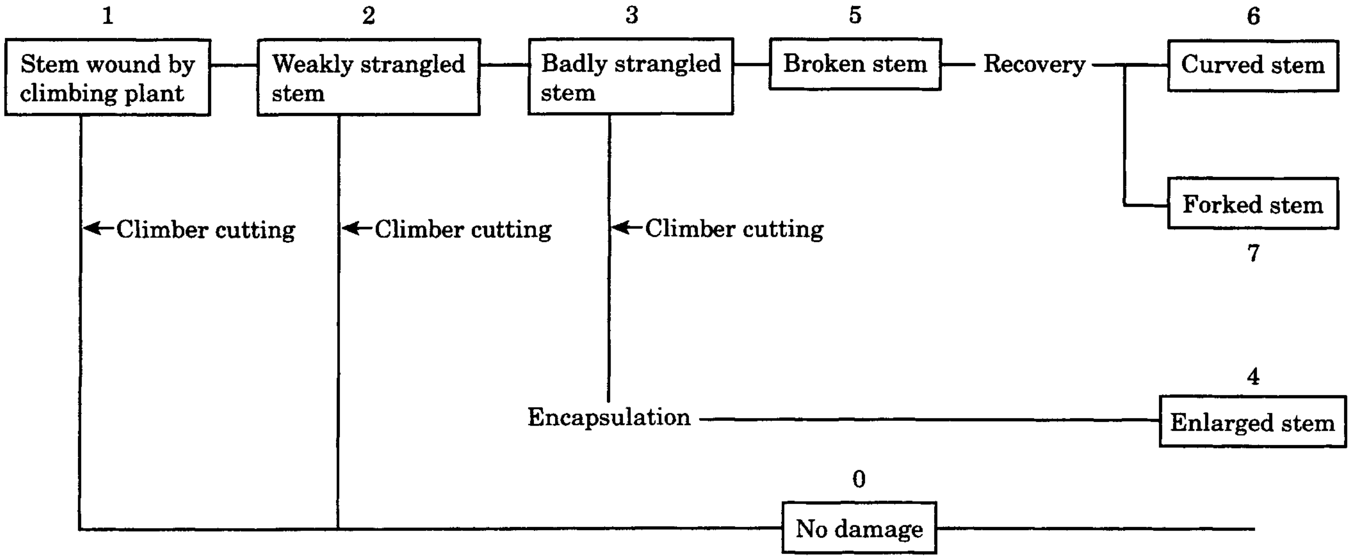


Figure 5-8 Flow chart showing the development and degree of damage caused by climbers. The degree of damage is represented by the numbers. (Suzuki, 1989)

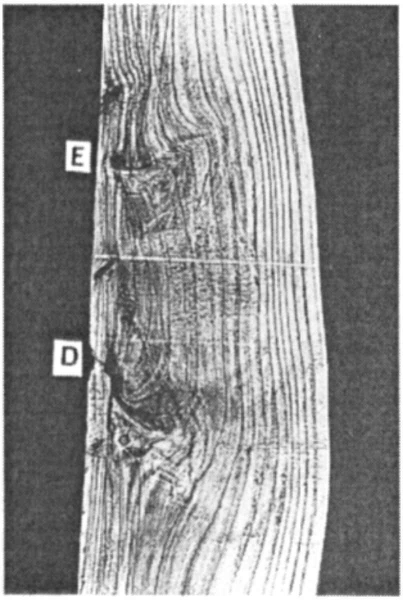


Figure 5-9 Stem abnormalities of *Chamaecyparis obtusa* following climber damage. The climber was cut 3 years after it began strangling the stem, but vine was left on the stem. D and E show the enlarged stem caused by abnormal growth after the damage occurred. (Suzuki, 1989)

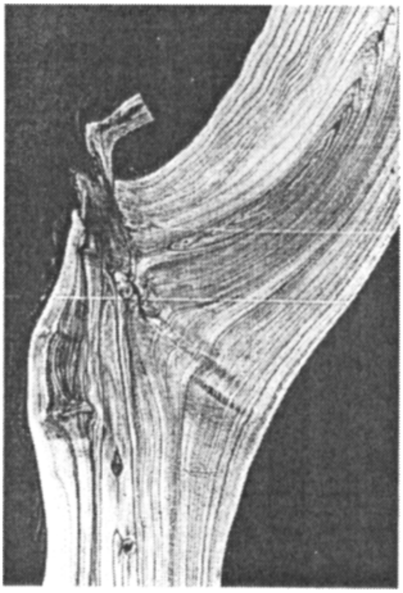


Figure 5-10 Crooked stem of *Chamaecyparis obtusa* which arose after the stem broke at the point where it was injured by a climber. (Suzuki, 1989)

plants directly affecting the trees should be removed (Osawa, 1937). As weeding creates conditions suitable for climbers to invade and grow rapidly, the growth of climbers must always be considered when planning weeding.

Herbicides are also effective for the control of climbers. The base of the vine is cut near the ground, a cross about 1 cm deep cut and herbicide injected into it.

Even if a genetically superior variety of tree is selected, good quality seedlings are planted, and adequate weeding is completed, if the tree is injured by a climber, the value of it is completely lost. Therefore, it is essential to control climbers if a healthy stand is to be established and quality wood produced. A strategy for the control of climbers must be included in all silvicultural systems in areas where climbers are prevalent.

5.4 Liberation operations

Liberation refers to the release of young stands, not past the sapling stage, from the competition of distinctly older, overtopping trees (Ford-Robertson, 1971; Smith, 1986). There are two cases, depending on whether overtopping trees are commercially valuable or not. If they are not valuable, they are cut and left on the stand floor or killed and left standing. Here, liberation to eliminate non-valuable, overtopping trees is discussed. The overtopping trees are not seed trees and liberation is not part of a shelterwood method. Liberation is used to a certain extent in the non-clearcutting methods described in Section 8.1.2. In this method, valuable trees are planted or naturally regenerated under a stand of low value trees to reduce the cost of weeding, to avoid the degradation of soils, or to protect valuable trees from cold damage during their juvenile phase. In this method, when the planted trees become large enough to compete with other plants or resist cold damage, the overtopping trees are cut or killed by girdling.

5.4.1 Cutting

Cutting overtopping trees is expensive and can cause a lot of damage to the young trees. Limbing must be done after the tree is felled so that the young trees are not crushed or shaded by the crown of the felled tree. The advantages of cutting are that the danger of limbs and snags falling following girdling and the sight of dead standing trees are avoided.

5.4.2 Girdling

Girdling is a method of killing a tree by severing the phloem and cambium (Figure 2-1), and sometimes the xylem, around the entire stem. By severing the phloem and cambium, transfer of photosynthate from the crown to the roots is interrupted and the roots gradually decline, reducing the availability of water and nutrients for the rest of the tree, and the tree then dies. One of the advantages of girdling is that sprouting is controlled by the decline of the root system. The most effective method of girdling with axes is double-hacking. In this method a horizontal line of chips is removed by striking two downward blows; the second is made about 6 cm above the other so that the chip may be pried entirely out of the cut with a twist of the axe handle. Using this technique, it is easy to verify that no strands of phloem or cambium remain (Smith, 1986).

Girdling is best done between spring and early summer, when the cambium is active and the bark is easily stripped off. Strips of bark at least 20 cm wide are peeled off after continuous cuts are made at the top and bottom of the strips (Smith, 1986).

Notch-girdling is also effective. In this technique, a series of close downward and upward, i.e., V-shaped, incisions into the sapwood is made (Ford-Robertson, 1971). This operation is hard to do with axes but is easy with motorized cutting devices. The tree dies quickly after the operation because water transportation to the crown is interrupted. The disadvantage of this method is that it results in vigorous sprouting.

Combined use of herbicides and girdling can be effective. This can be done by single-hacking, or frilling (a single line of overlapping axe cuts through the bark), followed by injection of herbicides into the cut (Smith, 1986). Single-hacking is less laborious than double hacking and the herbicides effectively kill the tree without sprouts being produced.

5.5 Improvement, Salvage and Sanitation Cuttings

5.5.1 Improvement cutting

Improvement cutting is defined as the elimination or suppression of less valuable trees in favor of more valuable trees, typically in mixed uneven-aged forest (Ford-Robertson, 1971). Improvement cuttings are made in older stands (i.e., past the sapling stage) for the purpose of improving species composition, growth increment or the quality of the growing stock by removing trees of slow growth, poor form, or unhealthy condition from the main canopy so that retained trees can become more productive (Smith, 1986; Matthews, 1989). The principal difference between improvement cutting and thinning is that main trees removed in improvement cuttings are unwanted species, while in thinning, they are the desired species.

Improvement cuttings are often required when tending natural stands, but not in the intensive management of plantations. The exception is the case of newly established plantations which have replaced natural stands, in which improvement cuttings are often needed if weeding is not adequate.

Improvement cuttings should be conducted before systematic thinning.

Only trees restricting the growth of desired trees should be removed and gaps which provide growing space for climbers should not be created. Subordinate trees which do not affect the growth of retained trees should be left to limit the production of epicormic buds on the trunks of the retained trees.

5.5.2 Salvage and sanitation cuttings

Salvage cutting is defined as the harvesting of trees that are dead, dying or deteriorating (e.g., overmature or materially damaged by fire, wind, insects, fungi or other injurious agencies) before their timber becomes worthless (Ford-Robertson, 1971). Pre-salvage cutting anticipates damage by removing highly vulnerable trees (Smith, 1986). The objective of these cuttings is to utilize the injured trees. Sanitation cutting is defined as the removal of dead, damaged or susceptible trees, essentially to prevent the spread of pests or pathogens and promote forest hygiene (Ford-Robertson, 1971).

Salvage cutting and sanitation cutting are different from thinning and improvement cutting in that their objective is not primarily to control competition between individuals in a stand. Salvage or sanitation cutting occurs only sporadically in response to damage, so they are not systematic operations like thinning. For example, when *Pinus densiflora* (akamatsu), *Pinus Thunbergii* (kuromatsu), or *Pinus luchuensis* (ryukyumatsu) trees die from pine wilt disease, sanitation cutting is necessary to prevent the disease from spreading. Matsunomadarakamikiri, a kind of beetle (*Monochamus alternatus*), lays eggs on dead trees, the larvae feed on the sapwood, and the adults fly away from the tree, carrying the pine wood nematode (*Bursaphelenchus xylophilus*). When the adults feed on the twigs of other living trees, the nematode invades the wood through the feeding wound, infecting another tree which finally dies. Therefore, to prevent the spread of disease, dead trees must be removed and burnt or chemically treated. In the past, when wood was used for fuel, using dead trees for fuelwood effectively controlled the disease.

Even though dominant trees lose their commercial value if damaged, they often remain dominant in the stand. For example, in plantations of *Cryptomeria japonica* (sugi) and *Chamaecyparis obtusa* (hinoki) the wood of dominant trees is often peeled off along the annual rings or chapped in severe swaying during typhoons. Such injuries do not heal, so damaged trees must be eliminated. Damaged trees can be identified by small horizontal splits in the bark. The elimination of such valueless but competing trees is not the same as salvage cutting nor sanitation cutting because the objective differs, but it is similar in that degraded trees are removed.

Declining and dead trees are important components of forest ecosystems, especially for biodiversity. However, if their presence conflicts with management objectives, salvage or sanitation cutting is necessary.

Chapter 6

Control of Individual Tree Growth and Quality in Relation to Stand Density

Individual tree growth and the quality of the wood can be regulated by thinning and pruning techniques. Thinning and pruning also contribute to modifying the light conditions of the understorey, which is important for enhancing understorey growth and the conservation of biodiversity and soil and water resources. Thinning is also important in providing intermediate income as well as heightening the resistance to wind and other disturbance agents.

6.1 Pruning

Most silvicultural techniques which are conducted between regeneration and stand establishment are techniques critical to successful establishment of a stand of a desired species. Pruning, however, is not necessary for regeneration or establishment of the stand, but it is often important to improve wood quality. Pruning is an aggressive technique of controlling wood quality as well as a technique for selecting trees to retain and trees to remove in thinning to control stand density. It also could be a significant contributor to ecosystem management because it allows the amount of light on the forest floor to be manipulated and therefore can be used to control the development of undergrowth during the young stage of plantations, which helps conserve the soil structure (Chapter 11).

Generally, dead branches of conifers are more persistent than those of broad-leaved species, so pruning is mainly conducted on conifers. As a result, there have been many studies of pruning in coniferous species, but few of broad-leaved species. Most of the information presented on pruning in this chapter refers to coniferous species.

6.1.1 Objectives of pruning

The main objective of pruning is to produce high quality knot-free timber or timber with no dead knots on the surface of sawn wood. Knot-free timber attracts a premium of up to two or three times depending on the condition of the knots on the surface of timber in Japan (Fujimori, 1984). Therefore, techniques which control the presence or size of knots are important.

Production of knot-free timber

The presence or size of knots in a stem can be influenced to some degree by controlling stand density. Natural pruning is encouraged if the stand density is high. However, control of stand density alone cannot prevent dead knots completely and the horizontal distribution of knots cannot be precisely controlled. These characteristics can be controlled by pruning. The effect of pruning on distribution of live and dead knots have been schematically shown on the basis of knot analyses (e.g., Henman, 1963, Fujimori, 1975). Figure 6-1 shows the effect of different pruning strategies on the distribution of live and dead knots. If live and dead branches in the shade crown or dead branches under the crown (Figure 6-1, II) are pruned, the distribution of live knots is similar to the case of no pruning (I), but there are fewer dead knots than without pruning. Dead knots are not completely avoided unless branches are pruned from the part of the functional crown (Section 6.1.2) where there are no dead branches (Figure 6-1, III). If green branches in the functional crown are pruned, dead knots are not formed, and the live knots are smaller, although there may be some loss of growth (Figure 6-1, III).

Production of timber with uniform annual rings

The width and straightness (angle to the vertical) of annual rings can be controlled by manipulating the growth of the stem by pruning. Uniform and straight annual rings, together with small or absent knots, are an important component of timber quality. They provide a record of tree growth and, unlike hereditary characteristics or damage by pathogens, can be controlled. Pruning reduces the amount of crown, which affects the width and straightness of the annual rings.

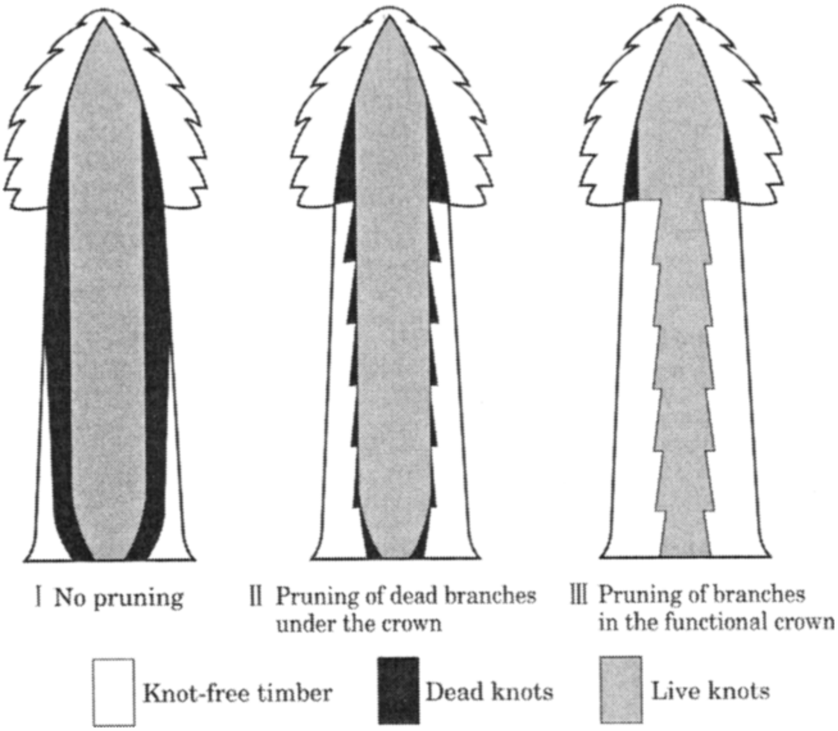


Figure 6-1 The effect of different pruning strategies on the horizontal distribution of knots in stems. (Fujimori, 1985)

Control the size of an individual in a stand

Control of an individual tree's crown by pruning effectively controls the size of the tree and enables all trees in a stand to be kept a similar size. Production of trees of a similar size that suits the target end-product maximizes the yield from a stand. For example, production of boxed heart square timber requires logs of a specified size and yield is maximized if as many logs of the required size as possible are produced from a stand.

Control of light condition in a stand

The illumination under the canopy of a young stand is usually too low to allow undergrowth to exist, and this can contribute to surface erosion of the soil. This is undesirable, but can be improved by pruning as well as thinning. This makes pruning an important tool for ecosystem management.

Protection of damage by disease and pests

Some pests and diseases that reduce wood quality enter the stem through dead branches. For example, the beetle suginoakanetorakamikiri

(*Anaglyptus subfasciatus*) lays eggs on the dead branches of *Cryptomeria japonica* (sugi), and the larvae bore into the xylem of the stem through the dead branch. The gallery made by the borer (larva) often decays and the value of the timber is greatly reduced. Larvae only ever bore into the stem about 20 cm. The borer does not enter through green branch stubs, so green pruning prevents borer damage and produces knot-free timber. Green pruning also helps to protect against the pathogen hiakagaresei-mizokusarebyo (*Fuscoporia punctata*), which invades the xylem of the stem from dead branches (Fujimori, 1985).

Improvement of working condition in young stands

Dead branches that remain on the stem near the ground are undesirable for workers who need to walk through and inspect the stand. The dead branches make it difficult to detect damage by disease or other agents and make it hard to select trees for thinning. Pruning avoids these problems and creates suitable conditions for tending operations.

Prevention of fire spreading from ground to crown

Pruning helps prevent fires spreading from the ground to the crown. Dead branches with dead leaves retained on the stem near the ground are especially flammable.

Controlling water use in agroforestry system

Pruning can be a powerful means of controlling water balance in agroforestry systems. In semi-arid areas, combining trees and crops on the same piece of land often leads to competition between trees and crops for available soil water, particularly in areas where the soil is shallow. Pruning to control water balance is practiced in agroforestry systems used by farmers in Kenya (Jackson et al., 2000).

6.1.2 Crown structure and stem growth

Knowledge about tree growth and architecture was reviewed in Chapter 2 but more specific information relevant to pruning is reviewed here. The organs of trees that are essential for growth are the leaves and fine roots. Growth of the stem is therefore controlled by controlling the leaves or fine roots. Although fine roots can be controlled in the nursery, it is impossible in the field. However, pruning can be used to manipulate the quantity and position (stratum) of leaves in the crown, and thus control stem growth.

A diagram which shows the relationship between the amount of light, photosynthetic organs (leaves) and non-photosynthetic organs (stems and branches) in each stratum is called a biological production structure diagram (Section 2,3,2). Figure 6-2 shows the relationship between crown structure and stem growth to age 51, and the production structure at age 51, of an "average" tree in the overstorey of an even-aged stand of pure

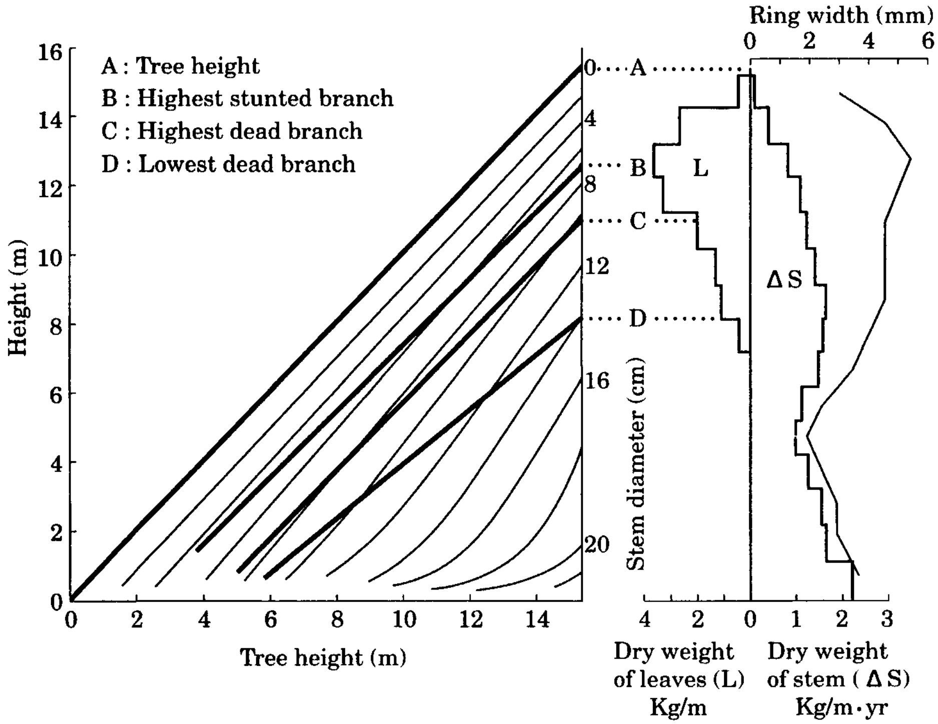


Figure 6-2 The history of crown structure development and stem growth in a tree from a 51-year-old *Chamaecyparis obtusa* (hinoki) stand. (Fujimori, 1993a)

Chamaecyparis obtusa (hinoki) in Japan.

In Figure 6-2, line A (at 45°, at the top) is the equivalent line of tree height. The lines beneath it are equivalent lines of stem diameter, i.e., the height at a given diameter at each growing stage. Thus, the equivalent line of tree height coincides with the line for which the equivalent stem diameter is zero. The three thick lines (B, C, D) beneath the equivalent line of tree height (A) demonstrate the dynamics of branches within the crown. The uppermost of these, (B), represents the height of the first stunted (dying) branch and is called the equivalent line of the highest stunted branch. A stunted branch is one that has ceased to form annual rings at its base. The next thick line, (C), is the equivalent line of the highest dead branch, and the lowest thick line, (D), is the equivalent line of the lowest live branch.

The distance between the equivalent lines of tree height and the lowest live branch is the crown depth at each tree height. The equivalent line of the highest dead branch defines the border between the functional crown (sun-exposed crown) and the non-functional crown (shade crown) (Fujimori, 1993a). The equivalent lines of stem diameter are almost parallel in the range of functional crown. Below that they become curves, and become further apart, except at the root-collar. The greater the distance between the equivalent lines of stem diameter, the less the taper of the stem.

The information presented in Figure 6-2 is derived by analyzing sections of logs as follows (Fujimori, 1993a). A stem including a knot is cut longitudinally to produce a section between the center of the knot scar and the pith of the stem (Figure 6-3). For each knot, the following parameters are measured: (1) height of each knot from the ground; (2) year when the branch emerged from the shoot apex, as determined by the number of annual rings in the stem at the height of knot; (3) year when the branch ceased to form annual rings at its base; (4) year when the branch died.

The year when the branch ceased to form an annual ring at its base is defined as Annual Ring A, and the year when the branch died is defined as Annual Ring B (Figure 6-3). When the branch dies, the annual rings adjacent to the dead branch curve toward the pith to begin the process of occluding the stub (Rapraeger, 1939). Many studies have reported this

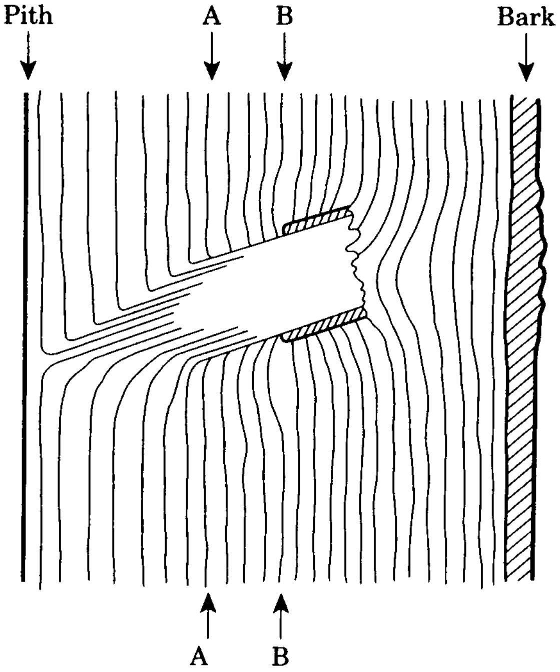


Figure 6-3 Radial section of stem showing a longitudinal section through a knot. A, the year when the branch ceased forming annual rings; B, the year when the branch died. (Fujimori, 1993a)

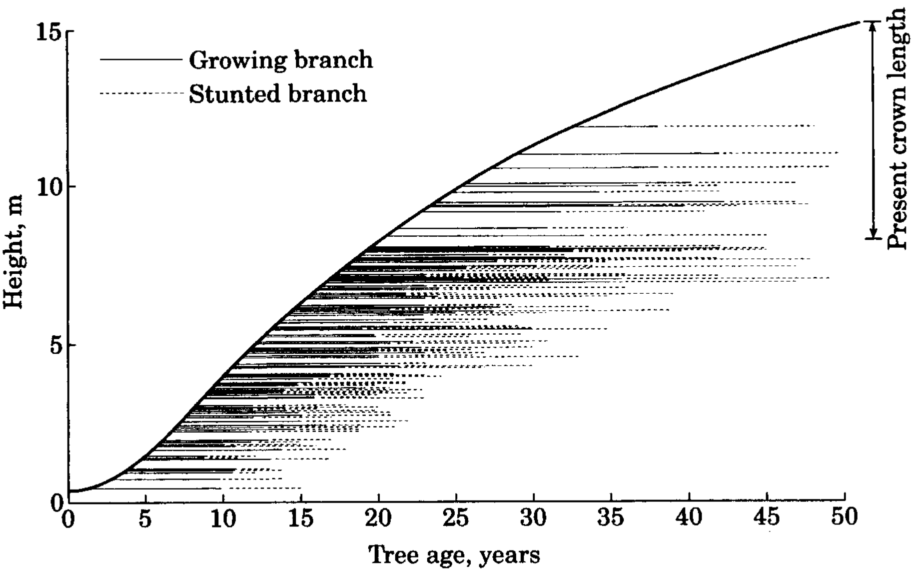


Figure 6-4 Dynamics of branch growth and mortality during the active growth of a tree in a 51-year-old *Chamaecyparis obtusa* (hinoki) stand. The curve shows the height growth of the tree with age. The point where a horizontal line extends from the height growth curve shows the tree age when that branch emerged and the height of the emergence of the branch. The change from a solid line to a dashed line indicates the tree age when a branch became stunted (ceased to grow). The right end of each dashed line shows the tree age when the stunted branch died. Present living branches were not drawn in this figure. They exist in the range of the present crown length shown in the upper right part of the figure. (Fujimori, 1993a)

phenomenon (Koide, 1941; Fujimori, 1975; Maguire and Hann, 1987). However, there is no such distinctive point to identify the year in which the branch ceased to form an annual ring at its base (A in Figure 6-3), although this can be identified with a hand lens. Annual rings A and B are most easily identified on the underside of the knot (Figure 6-3).

These types of data can be used to trace the life histories of branches, as shown in Figure 6-4. Branches emerge from shoot apexes at any height, and some years later they cease to form annual rings at their bases [these are defined as stunted branches (Fujimori, 1993a)]. Two to twelve years later they die, and this is indicated as the end of a dashed line in Figure 6-4. The fewer number of lines above 8 m indicates the presence of the live crown, which in this case commences at 8.2 m.

In Figure 6-5, total tree height is used on the X-axis instead of tree age, and the highest point of stunted branches, the highest point of dead branches, the lowest point of stunted branches, and the lowest point of dead branches, for each tree height, are plotted against it. The four lines corresponding to these points were obtained by regression analysis. Figure 6-2 was partly derived from this Figure. Equivalent stem diameters (the height of a given diameter at each growing stage) were added, and on the right side, crown structure and stem growth at 51 years are summarized to relate the past and present structure of the tree. The regression line for the lowest stunted branch was omitted from Figure 6-2 because it was similar to that of the highest dead branch. Figure 6-5 can be also modified to develop a diagram for pruning the non-functional crown, as shown in Figure 6-10.

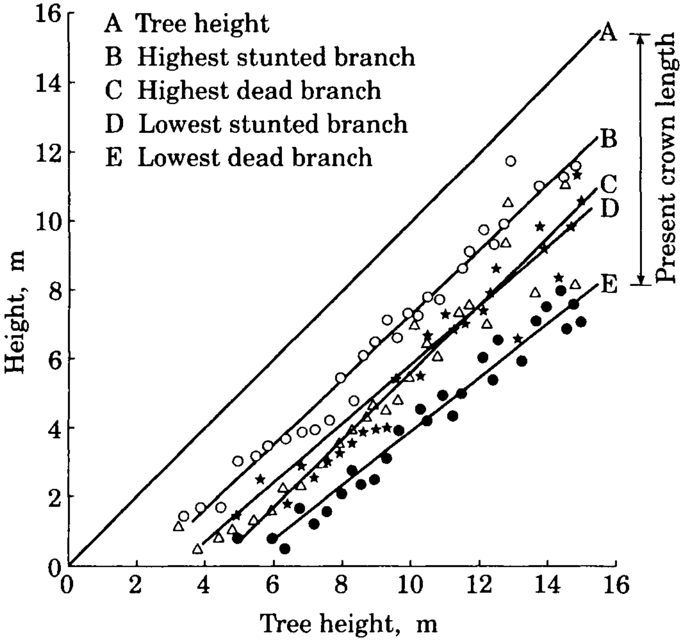


Figure 6-5 Relationship between tree height and crown structure of a tree in a 51-year-old *Chamaecyparis obtusa* (hinoki) stand. The highest point where a branch ceased to grow, the highest point where a branch died, the lowest point where a branch ceased to grow, and the point where the lowest living branch died were chosen for every 50 cm height range, and they are indicated by white dotes, black stars, white triangles and black dotes, respectively. (Fujimori, 1993a)

6.1.3 Effect of pruning on stem growth

Pruning has a negligible effect on stem growth if branches from the non-functional crown are removed, but the effects are large if the functional crown is pruned (Fujimori, 1975; Takeuchi and Hatiya, 1977a). The greatest effect is reduced stem diameter growth rather than reduced height growth except for extremely intensive pruning (Young and Kramer, 1952; Slabaugh, 1957; Henman, 1963; Barret, 1968; Fujimori, 1975). The diameter growth of the stem within the functional crown is not significantly affected, even if pruning is intense, but the growth beneath the crown is greatly reduced and the magnitude of the reduction increases down the stem (Figure 6-6).

6.1.4 Pruning as a crown control technique

Pruning should be considered together with stand density control and

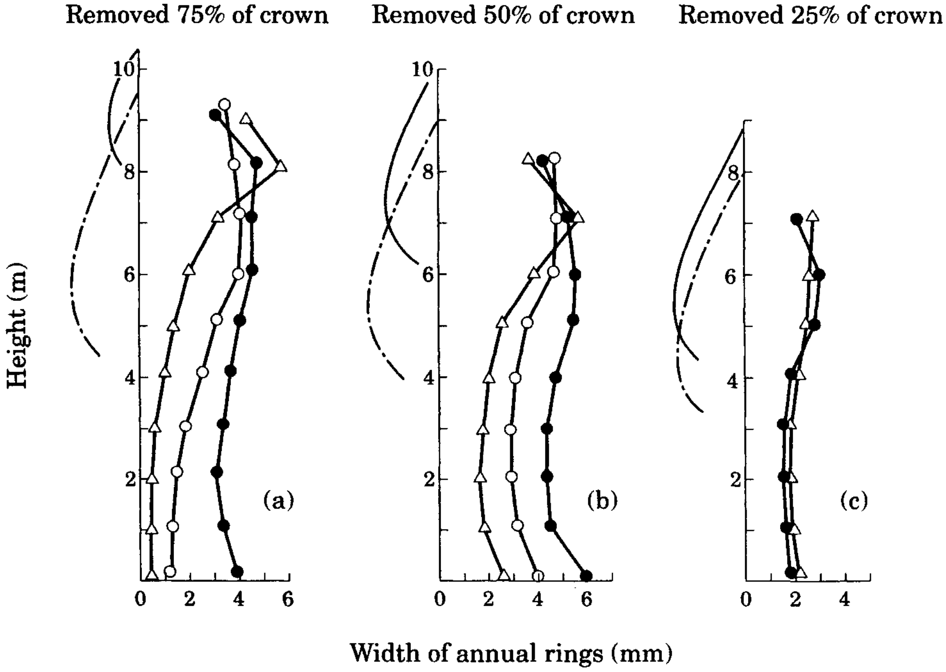


Figure 6-6 The effect of pruning intensity on diameter growth with height and in relation to crown position in *Chamaecyparis obtusa* (hinoki). Dashed lines and solid lines on the left-hand side of vertical axes denote the crown positions just before and after the pruning.

●–● Two years before the treatment
△–△ Two years after the treatment
○–○ Three and four years after the treatment
(Onaka, 1950)

thinning, because pruning can control stem growth and therefore the quality and quantity of wood, by manipulating the crown. Stem growth is also controlled by manipulating stand density and therefore available growing space for each crown. Therefore, effective tending systems combine pruning and stand density control.

As stand density decreases, pruning becomes more intense if pruning to a fixed diameter. If pruning is done on a tree with thick branches, operational productivity drops, the stem is easily injured, causing discoloration of the wood, and the stubs become longer, increasing the diameter of knotty wood. If pruning is conducted in stands of low density where individual trees have well developed crowns, epicormic shoots (Section 2.3.2) can develop in some species.

If pruning is done repeatedly, leaving the same depth of crown on each tree, the growth of each tree becomes similar and the stand will be composed of trees of the same size (Fujimori, 1972). If thinning to remove larger or smaller trees is combined with this type of pruning, a uniform stand is created. Such stands are found in advanced forestry areas of Japan, where forests are managed intensively to produce high quality knot-free timber of *Chamaecyparis obtusa* or *Cryptomeria japonica*. The Kitayama forestry area (Figure 6-7) is noted for its uniform stands where

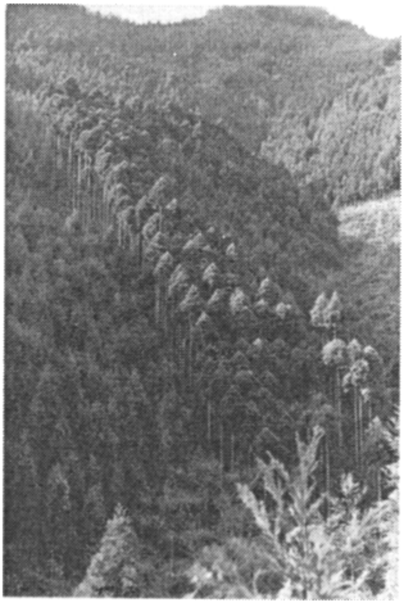


Figure 6-7 Uniform stand of *Cryptomeria japonica* (sugi) to produce high quality knot-free timber for ornamental boxed-heart pillars in Kitayama forestry area in Kyoto Prefecture, Japan.

high quality knot-free logs for boxed-heart pillars are produced.

6.1.5 Pruning regimes to meet production objectives

Factors affecting the decision of stem size for pruning

Pruning regimes should be determined according to the production objectives. The key decisions are the stem diameter required at the bottom of the crown to produce knot-free timber of a specific size, and the minimum target diameter for pruning which does not overly affect growth. The amount of branches which are removed at each operation is then determined by the distance between these diameters.

A precise regime is required to produce knot-free logs for boxed-heart pillars. Figure 6-8 shows the factors which affect the diameter of the stem and which determine pruning if knot-free square timber is to be produced. When the stem is straight (Figure 6-8b), if the side of the square timber to be produced is y cm, then the minimum diameter of the stem (z) which can produce this size timber is shown in Figure 6-8a and is defined as:

$$z = \sqrt{2} \cdot y \qquad (6.1)$$

If the surface of the square timber of side y cm is to be knot-free, the pruning stubs must be sealed by the time the diameter of the stem reaches y cm. Therefore, pruning must be done before the stem reaches the diameter x [y cm minus stub length (d) of both sides] (Figure 6-8a). In effect, pruning must be done before the stem has a diameter of x, where:

$$x = y - 2d \qquad (6.2)$$

The stub length (d) is determined by a) how much injury of stem wood is allowed, b) the form of the branch base, c) the skill of the pruner, and d) the tools used for pruning.

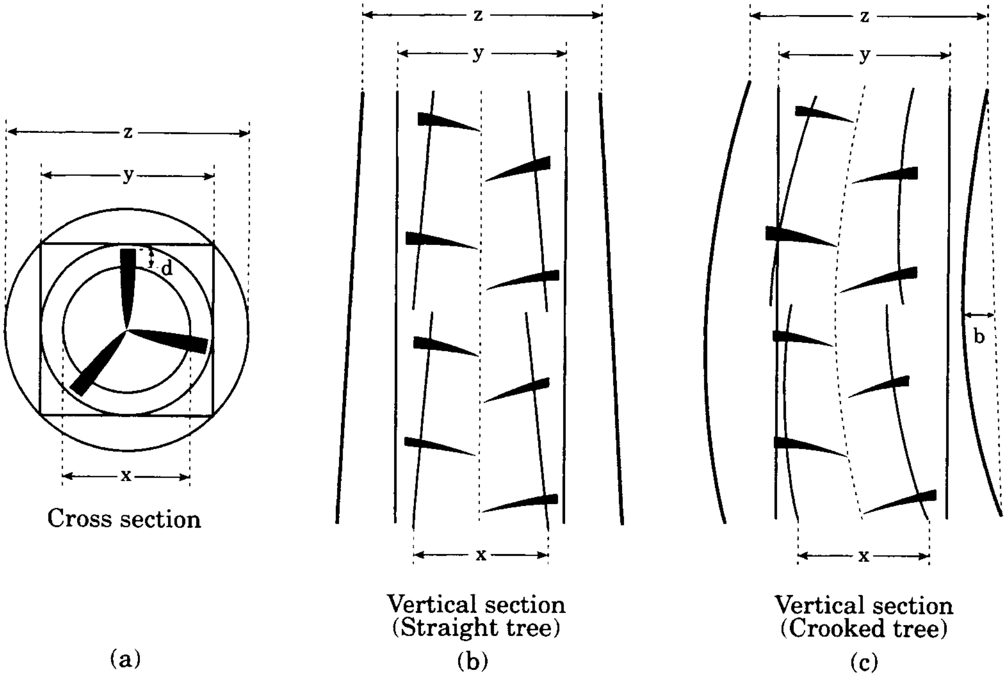
In the case of pruning to produce coniferous boxed-heart square timber with a side length of less than 12 cm, the branches are generally less than 2 cm in diameter when the stem diameter is the right size for pruning. The stub length will then be less than 0.5 cm normally, and at most will be 1 cm. If d=1 cm in Equation 6.2, pruning must be conducted by the time stem diameter is 2 cm less than the size of the end-product.

The above calculation assumes that the stem is straight. Even in stems which seem to be straight, a bend of 1 or 2 cm is usually found within the 3 or 4 m length required for a minimum length pillar. If the bend is b cm (Figure 5-5c), the target stem diameter for pruning is given by

$$x = y - 2d - b \qquad (6.3)$$

For example, if the stub length and bend are 1 cm and 2 cm respectively, then the target stem diameter for pruning is 4 cm smaller than the size of the end product. Therefore, to produce knot-free timber which is 10.5 cm or 12 cm square (the standard sizes in Japan), the target pruning diameter must be 6.5 cm or 8 cm respectively.

The minimum depth of crown required for normal growth of young



Cross section

(a)

Vertical section
(Straight tree)

(b)

Vertical section
(Crooked tree)

(c)

Figure 6-8 Factors for deciding the target diameter for pruning.
x: Diameter at the base of the crown at pruning
y: Length of one side of boxed heart square timber
z: Least stem diameter required to yield y ($z = \sqrt{2} \times y$)
d: Stub length
b: Degree of bend
(Takeuchi and Hatiya, 1977b; Fujimori, 1984)

Cryptomeria japonica or *Chamaecyparis obtusa* is 3 m. The diameter at the base of a 3 m deep crown is about 4.5 cm. There is usually about 1.5 m of crown between the 6.5 cm and 4.5 cm stem diameters. As stub length and bend decrease, the target pruning diameter increases and the depth of the retained crown is increased. It is therefore advantageous to grow straight trees which are easy to prune.

The intensive pruning regime as described above is not necessary if larger logs are produced, because different sizes of boards and square timbers can be sawn according to the log size. Nevertheless, pruning should still be conducted as early as possible without inducing unnecessary stress on the tree, so that as much knot-free timber can be produced as possible. This can be achieved by repeatedly removing the non-functional crown. Therefore, pruning should be done just before the bottom of the crown begins to die and dead branches accumulate, as explained later.

6.1.6 Model diagrams of different pruning regimes

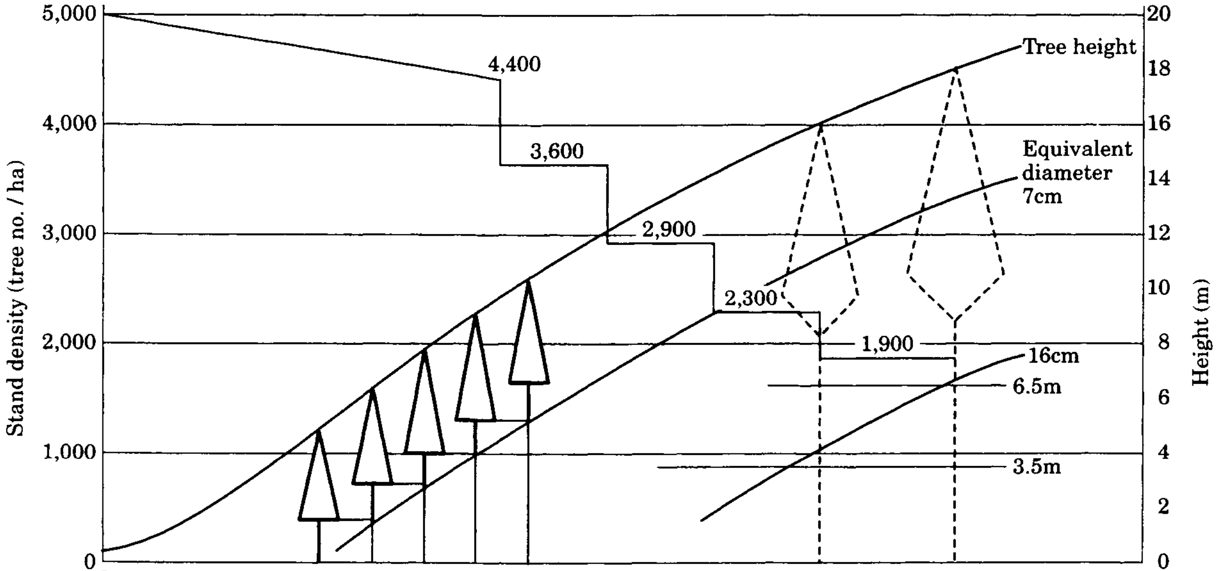
Model for the production of boxed-heart square timber

After defining a production objective, pruning to a target diameter should be repeated until a length of stem satisfying the production objective is pruned. For example, if the objective is to produce two logs for knot-free boxed-heart square timber, each with 10.5 cm side and 3 m length, then the target pruning diameter is 6.5 cm (equation 3). The target pruning diameter is normally rounded up to 7 cm for convenience.

The pruning regime is closely related to the stand density regime. In *Cryptomeria japonica*, the ideal number of trees for efficient pruning is about 5000 per ha, because at this density, the growth of the branches is controlled so that the diameter at the base of the crown is the same as the target pruning diameter (7 cm) at the time of pruning. If the stand density is lower, pruning must be more intense and live crown must be removed. If the stand density is greater, the base of the crown will be above the target pruning diameter of 7 cm when pruning is conducted.

Figure 6-9 is a model diagram of the pruning regime for *Cryptomeria japonica*, based on data from stands on a class 1 site in the Kansai region, Japan. These types of diagram vary according to species, the production objectives, site class and stand density. In Figure 6-9, the following conditions apply: a) the objective of production is two logs for knot-free boxed-heart square timber; b) the site is class 1; c) the initial stand density is 5000 and thinning is frequent; d) the target pruning diameter is 7 cm based on Equation 6.3; and e) the retained crown after pruning must be at least longer than 3 m deep. Figure 6-9 was derived from the stem and knot analyses described in Section 6.1.2 (Fujimori, 1975).

In Figure 6-9, the stepped line running downward from the top left



Stand age	0	5	10	15	20	25	30	35
Mean DBH (cm)		3.3	6.4	9.9	13.6	17.3	20.4	22.7
Mean tree height (cm)		2.7	6.3	9.6	12.5	14.9	17.0	18.8

Pruning						
	Time	1	2	3	4	5
	Tree height	4.9	6.3	7.8	9.0	10.2
	Clear length	1.5	3.0	4.0	5.2	6.5

Harvesting knot-free logs
for 10.5 × 10.5cm × 3m log
1 log 2 logs

Figure 6-9 A model pruning regime for production of knot-free boxed heart square timber in *Cryptomeria japonica* (sugi) for a class 1 site near Kyoto Prefecture, Japan. (Fujimori, 1976) represents stand density. The equivalent line of diameter 7 cm is the line connecting the height of diameter 7 cm at each stand age. The equivalent line of stem diameter 16 cm is the maximum diameter (under bark) required to produce a boxed heart square timber of side 10.5 cm (minimum diameter under bark is 14.8 cm). The horizontal lines crossing the 16-cm equivalent line give the length of the log to be harvested. The length 3.5 m is 3 m of log plus 0.5 m of stump and the length 6.5 m is two 3 m logs plus 0.5 m stump. The solid stepped line from 8 years upward represents the pruning regime. Five prunings are required between years 8 and 16, at 2-year intervals. One 3 m log for 10.5 cm square timber can be harvested at 26 or 27 years. Two logs can be harvested at 32 years, and if the remaining trees are grown to a large size, they will become high quality trees with a high percentage of knot-free wood which can be sawn in a variety of ways, depending on demand.

Model for producing large-size logs

If the management objective is to produce large-size logs from which a high percentage of knot-free wood can be obtained, pruning of the non-functional crown is effective. Removal of the non-functional crown does not reduce the growth of the tree, but the number and size of dead knots can be still controlled. Figure 6-10 shows a diagram for pruning the non-

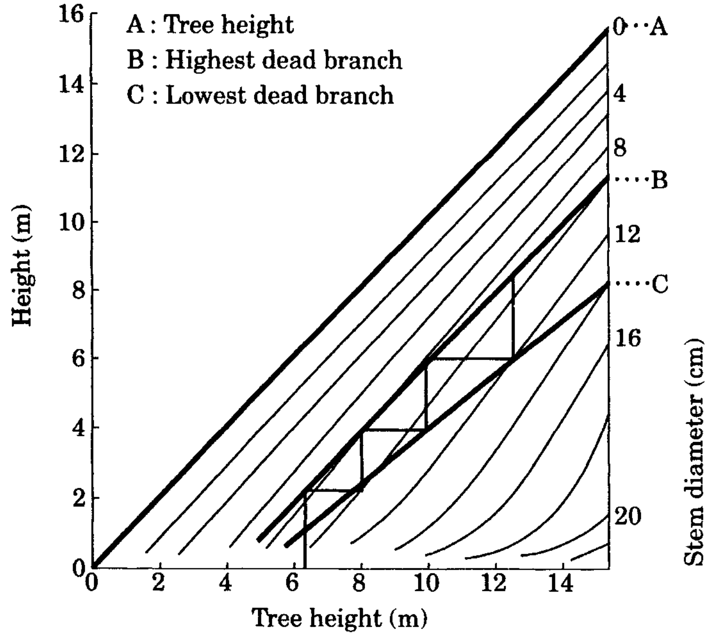


Figure 6-10 A model for pruning the non-functional crown in *Chamaecyparis obtusa* (hinoki). (based on Fujimori, 1993a)

functional crown of *Chamaecyparis obtusa*. The diagram is based on Figure 6-2 and assumes that pruning the non-functional crown does not affect the growth of the tree. The diagram also assumes the following silviculture: a planting density of 3000 to 4000 stems per hectare; two thinnings and residual stocking at 51 years of 1200 trees per hectare. The diagram is representative of average dominant trees on a class 2 site in the Kyoto Prefecture.

Figure 6-10 represents either natural pruning (loss of dead branches beneath the crown), or pruning the branches in the non-functional crown (under the equivalent line of the highest dead branch). The non-functional crown is between the equivalent line of the highest dead branch (B) and the equivalent line of the lowest living branch (C). The stepped line represents the pruning regime. The first pruning, to 2 m, occurs when the tree is 6 m tall and subsequent prunings are conducted until the required pruned log length is achieved. The trees is pruned to about 9 m, and the greatest diameter of the pruned stem is 12 cm. Thus, knots are confined to about 12 cm within the stem.

6.1.7 Injury of stem wood and discoloration

Injury to the xylem during pruning causes discoloration which devalues the timber. If the xylem is injured, phenolic compounds and resins are formed around the injury and the parenchyma dies, causing discoloration (Osako et al., 1974, 1978; Nobuchi et al., 1976). This is a similar phenomenon to the darkening of sapwood as it changes to heartwood, but the discoloration caused by injury is darker and irregularly distributed. This response to injury is confined to inside the cambium and does not occur to the outside.

Such physiological discoloration can also result from chemical reactions which protect the xylem from fungi. However, if wood-staining fungi do invade, the discoloration is darker and larger, and the wood becomes almost worthless. In most conifers, even if the stem wood is injured, fungi seldom cause serious degrade. However, some hardwood species are vulnerable to fungal infection, so preliminary investigations are necessary before pruning species which have not been pruned before.

The most common injuries to the xylem which occur during pruning is damage of the swollen (branch) collar and bark tearing (peeling the phloem or cambium) (Fujimori et al., 1984). As shown in Figure 6-11, the branch collar comprises the branch (knot) and the stem xylem which covers the branch. If the collar is injured, the stem xylem is also injured, resulting in discoloration and slowing healing of the pruning wound. Bark tearing tends to occur when trees are growing vigorously, so pruning should be avoided during the growing season.

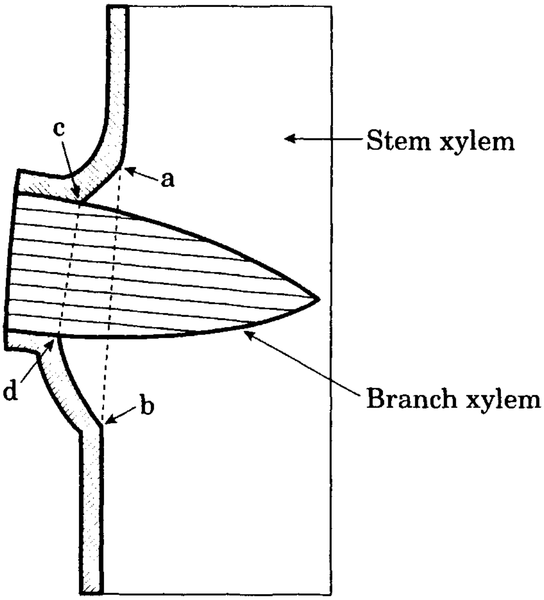


Figure 6-11 Vertical section of branch, knot, and branch collar. The part surrounded by a, b, c, and d is the branch collar. (Fujimori, 1985)

6.1.8 Pruning techniques

Position of branch to be cut

The position of the branches to be cut is determined by the production objectives and the following factors: a) how much stem damage, and therefore discoloration is allowed; b) the minimum stub length; and c) how fast the pruning cut is sealed.

Discoloration should not matter for the production of boxed-heart square timber, because if pruning is conducted according to Equation 6.3, the discoloration will not appear on the surface of the sawn timber. In the production of this type of timber, therefore, some stem damage is allowed and the stubs should be pruned as short as possible. Figure 6-12b shows the ideal pruning cut for this scenario. If, however, larger logs are being grown to produce various kinds of sawn timber, pruning injuries should be avoided in order to avoid discoloration of the stem wood. In these cases, branches should be cut as shown in Figure 6-12a.

Techniques for removing branches

There are various techniques for removing branches, depending on the

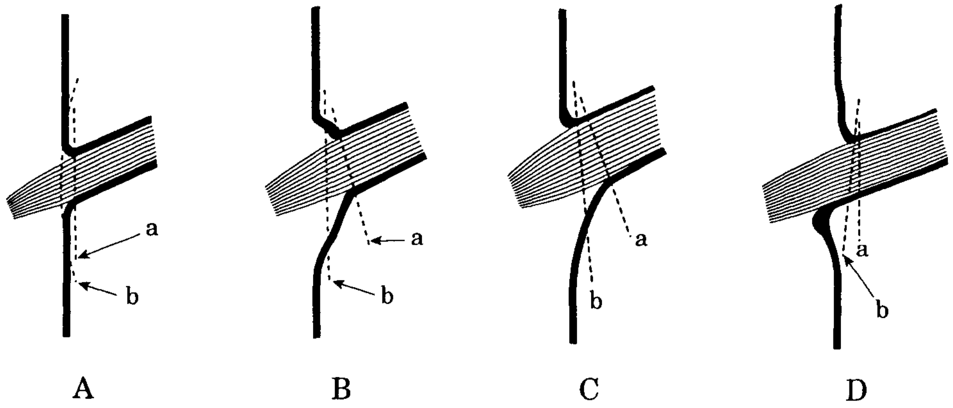


Figure 6-12 Position of cutting branches.
a: Position of cut to avoid discoloration of the stem xylem
b: Position of cut for the shortest stub, even if discoloration occurs
(Fujimori, 1985)

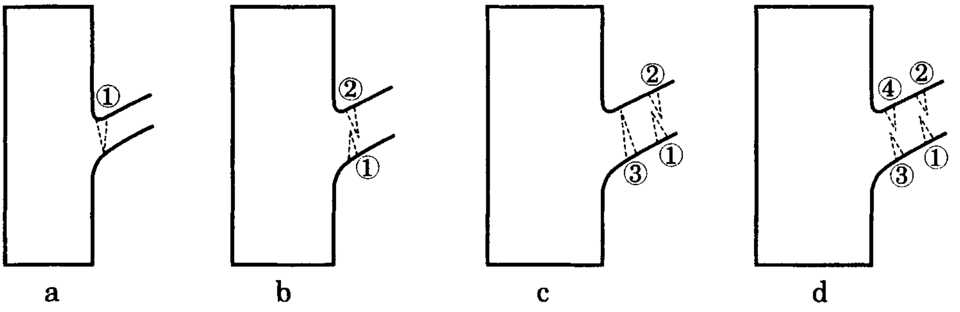
thickness of the branch (Figure 6-13). Small branches can be cut in a single operation (Figure 6-13a). A thicker branch is first cut upward, then the branch is removed by cutting downward (Figure 6-13b). This avoids bark tearing injuries. If the branch is very thick (>4 cm diameter), the branch is first removed by cutting away from the base of the branch, and then the remaining stub is removed by cutting upward (Figure 6-13c) or cutting first upward, then downward (Figure 6-13d).

Pruning tools

There are many kinds of tools for pruning such as saws, shears, axes, hatchets, and sickles. All of these tools have been modified to suit pruning. Saws are easy to use and give the most control. Old saws did not cut branches smoothly and productivity using old saws was low. However, with improved setting of the teeth, saws are now generally the best tool to use, and the operation is precise, safe, and easy, and productivity is the same as with other tools. Shears are also easy to use and the productivity is high, although they cannot be used on thicker branches.

An axe is good for cutting tough branches, because it has a thick and heavy edge. Hatchets are thinner and longer than axes and can be used for both thick and thin branches. Sickles are the thinnest and lightest tools, so can only be used for thin branches.

Tools with long handles are used to reach higher branches. Long



Thin
branch
<1.5 cm

Thick
branch
1.5-2 cm

Very thick
branch
>4 cm

Figure 6-13 Pruning methods for removing branches of different sizes. (Fujimori, 1985)

handled sickles, saws and shears can be used for pruning to greater heights. However, because it is hard to place the tool at the right position, pruning tends to be rough, especially for the sickle and sometimes for the saw. Long handled tools are also more tiring and dangerous to use.

Mechanized tools include a small round saws with short handles provided by a light engine. These are carried by the worker and can be operated with one hand, which allows ladders to be used. These saws cut smoothly, can be positioned correctly and are highly productive. An alternative mechanized tools comprises a combined saw and engine which climbs the tree itself, pruning as it climbs to the designated height. A worker can set the machine at the base of tree and then operate it by remote control. This is good for removing branches a long away up a tree, but is less effective for short lifts to about 2 m, because of the work involved in carrying the comparatively heavy machine from tree to tree, and setting it up. These machines also tend to injure the stem. They are also limited by only being able to climb to a minimum stem diameter of 7 cm, whereas the target pruning diameter for some products can be less than this. On the other hand, the maximum diameter by which the machine can be set up is limited to about 35 cm. These machines need further development before they fully meet pruning requirements.

6.2 Thinning

Thinning removes competing trees to expand the available growing space of trees which will be harvested later or which will be retained for some other objective. In this section, thinning for wood production is discussed. Usually, thinning of young stands involves the removal of trees of poor form, but in older stands, the trees removed can be large enough to harvest a product. Thinning is distinguished from improvement cutting because in improvement cutting, the trees removed are mainly different species, while in thinning they are mainly the same species as the residual trees (Smith, 1986). Thinning is an important component of stand density control systems.

6.2.1 Objectives of thinning

Maintaining resistance to destructive agencies

After a stand closes, the growing trees begin to compete for growing space and competition can become severe. Even though stand density will be reduced by self-thinning, this tends to result in the stand becoming susceptible to strong winds or wet snow, or to pests and diseases. This is especially true for even-aged plantations of single species. Thinning can help maintain or improve a stand's resistance to damaging agents because individual trees are prevented from developing an excessively low ratio of crown depth to tree height or high ratio of tree height to DBH.

Control of wood quality

Apart from hereditary and damage factors, wood quality is mainly determined by the presence of knots and the width and uniformity of annual rings, which are the integration of a tree's growth throughout its life. Therefore, wood quality can be controlled by controlling the crown structure through thinning.

Increasing the percentage yield

It is still a matter of debate whether the total production of a stand is increased by thinning. Experiments testing this have differed in site, species, production objectives and thinning regimes. Also, total biomass production must be distinguished from the total yield of a product or total stem volume. The difference between total production and yield is partly dependent on the product. For example, in forest management for fuelwood production, production and yield are relatively similar, but in forests managed for sawlog production, the values can be very different. The yield of sawlogs is increased by thinning because the proportion of total production that can be harvested is increased by judicious selection of trees in thinning, as long as an adequate stand density is maintained. The yield is further increased if the retained trees are straight, have less taper and have stems clear of branches.

Improved light conditions in the understorey

When a stand is in the young stage, the closed canopy prevents light reaching the forest floor (Section 2.4.4). This is unfavorable for the conservation of soil and biodiversity, so should be avoided whenever possible. Thinning helps improve light penetration through the canopy and therefore improves the vertical structure of the forest. The relationship between stand density and coverage of undergrowth or seedlings of crop trees is important for conservation of soil and biodiversity and for regeneration of crop trees. Repeated thinnings can create conditions suitable for regeneration by shelterwood or selection methods (Section 8.1.2).

Successive harvesting within a stand

The primary objective of thinning is to improve the growing space of the best trees, but in many cases, thinning is also an opportunity for harvesting. Sustainable forest management and ecosystem-based management is favoured by silvicultural systems with long rotations and frequent thinnings.

6.2.2 The relationship between growth and thinning

The relationship between stand development stage and thinning

As discussed in Section 2.4.4, stands follow a typical stand development pattern following large-scale disturbance, as long as another destructive disturbance does not occur. Within this sequence of development, thinning can play its most important role during the young stage when intraspecific or interspecific competition is most severe. In temperate zones, this stage is generally between 15 and 50 years old in both plantations and natural forests. Thinning is particularly important during the early period of the young stage, as tree form is determined at this stage. In the young stage, comparatively frequent thinning is required as stands close again quickly (Kiyono, 1990).

Even if thinning is not conducted during the young stage, the trees will continue to grow and dominant trees will develop until, in the early mature stage, there is space between the crowns (Kiyono, 1990). However, as the ratio of crown length to the tree height decreases and stem taper increases in the absence of thinning, thinning during the young stage enables individual trees to grow faster and develop resistance to various destructive agents such as wind.

The quantitative relationship between mean growth and total growth of a stand

One of the most important relationships between thinning and stand density is that between the mean growth of individual trees in a stand and the total growth of the stand. Across the range of stand density, excluding full density, mean stem volume increases as stand density decreases, while total stem volume per unit area increases as stand density increases

(Figure 6-14).

The qualitative relationship between mean growth and stand density

Qualitative and quantitative growth are closely related, and the relationship between both qualitative and quantitative growth and stand density can be summarized (Hatiya, 1970) as:

- The mean height of dominant trees is little changed by stand density as long as the stand is not too dense;
- The mean stem diameter decreases as stand density increases;
- The degree of taper decreases as stand density increases;
- The length of clear stem increases as stand density increases;
- The diameter of knots decreases as stand density increases; and
- The horizontal distribution of knots decreases as stand density increases.

6.2.3 Stand density management

Stand density management determines thinning regimes. The basic theories of the relationship between stand density and plant growth and the forest stand density management diagram were developed in Japan in the early 1960s (Kira et al., 1953, 1954, 1956; Shinozaki and Kira 1956, 1961; Yoda et al., 1963). Stand density management theories were developed from these (Ando, 1968) and have been applied and further developed around the world wide since (Newton, 1997).

The relationship between individual growth and the total growth of a stand

The mean weight and number of individual trees are related by the Competition-Density (C-D) effect. If conditions for growth are identical throughout time, growth of all trees starts at the same time and the only variable is stand density; then the relationship between mean weight (w) and the number of individual trees (ρ) after a certain period of time is defined as:

$$1/w = A\rho + B \tag{6.4}$$

A and B are coefficients that are a function of time (t). Equation 6.4 is called the reciprocal Competition-Density (C-D) equation (Shinozaki and Kira, 1956, 1961).

There is also a relationship between weight per unit area (y) and stand density, namely

$$y = w \times \rho$$

Substitution of this relationship into Equation 6.4 results in:

$$1/y = A + B/\rho \tag{6.5}$$

This relationship is the Yield-Density effect (Y-D effect), and Equation 6.5 is the reciprocal Yield-Density (Y-D) equation (Shinozaki and Kira, 1956, 1961). Yield as used here is equivalent to production. Equations 6.4 and 6.5 are applicable to either the whole tree volume or stem volume.

The C-D and Y-D effects on stem volume are shown for *Cryptomeria japonica* (sugi) in Figure 6-14. Figure 6-14a shows the reciprocal C-D relationship of Equation 6.4, and shows that at low stand densities, individual tree volume increases with time independently of stand density, but if the stand density exceeds a certain level, the growth of individuals is checked by competition. Figure 6-14b shows the relationship between yield and density and is almost symmetrical to Figure 6-14a. At low densities, yield increases in proportion to density, but at high densities, yield is limited until at the highest density, the yield approaches a constant level.

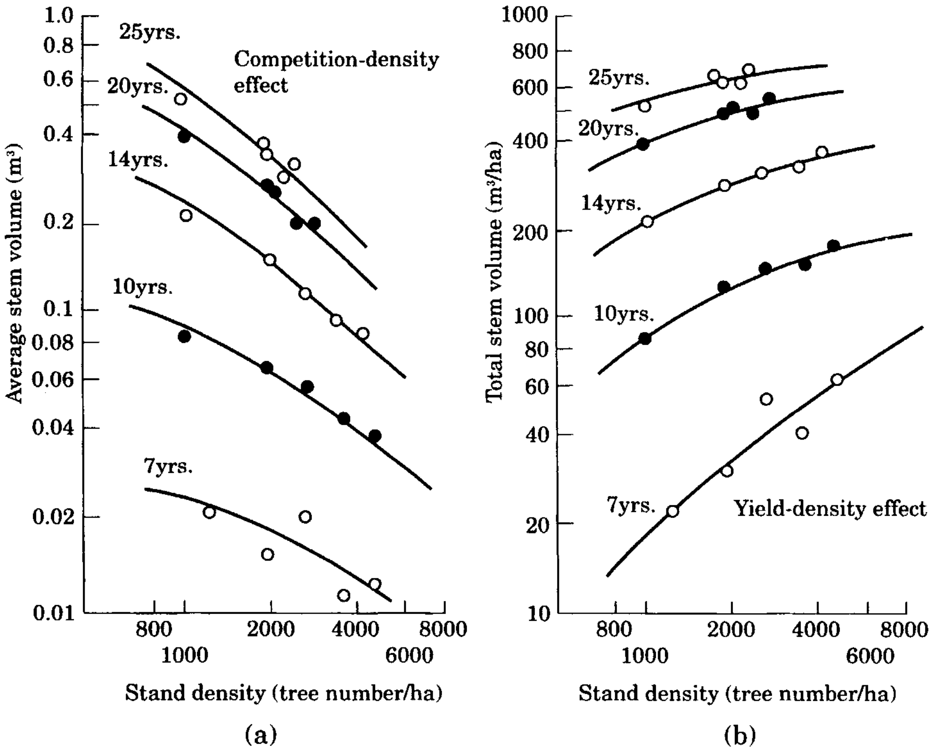


Figure 6-14 The effect of stand density on stem volume in *Cryptomeria japonica* (sugi). (Hatiya, 1970; figure after Shu, 1957)

Full density

In any stand there is a limit to the number of trees which can coexist at each growing stage. As a pure even-aged stand grows, competition among individuals becomes severe and self-thinning occurs. In a closed stand in which self-thinning is taking place, the following relationships are found amongst stand density (ρf), mean individual weight (w) and the yield per unit area (y):

$$w = k\rho f^{-a} \tag{6.6}$$

$$y = k\rho f^{1-a} \tag{6.7}$$

where, k and a are coefficients. The coefficient k changes depending on species, and the coefficient a is usually around 3/2 (Kira, 1957; Shinozaki, 1959). For this reason, this relationship is called the 3/2 power law. The curve describing Equations 6.6 or 6.7 is called the full-density curve (Kira, 1957). Figure 6-15 shows the process of self-thinning and the full-density

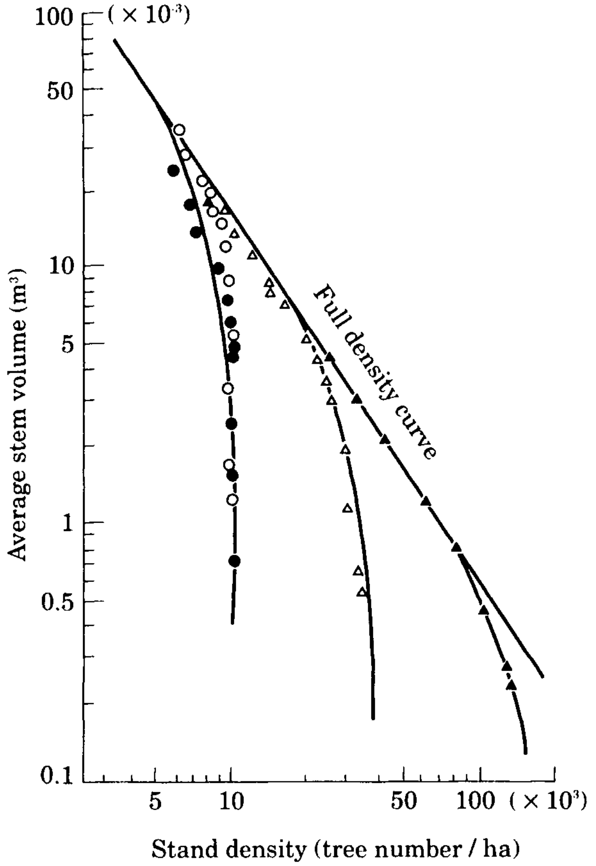


Figure 6-15 Self-thinning and full density curves for *Pinus densiflora* (akamatsu) stands. (Ando et al., 1962; Tadaki et al., 1979)

curve according for each growing stage of a natural stand of *Pinus densiflora* (akamatsu). The curve of self-thinning is expressed by the following equation:

$$1/\rho = A'v + B' \qquad (6.8)$$

where, ρ, v and A′, B′ express, for a given time, stand density, mean volume, and the coefficients of the full-density curve and initial planting density, respectively (Tadaki, 1964).

Stand density management diagram

Stand density management diagrams are developed by combining the yield-density curve (Figure 6-14), the full density curve, and the self-thinning curve (Figure 6-15) on a log-log graph (Ando, 1968). The Forestry Agency of Japan (1978-1983) produced a series of diagrams for the 5 main coniferous species for each region in Japan. Figure 6-16 shows, as an example, the stand density control diagram for *Cryptomeria japonica* for national forests in Shikoku district. This diagram can be interpreted as follows:

- Equivalent mean height line: Each line which runs from the lower left to the upper right represents the relationship between stand density and stem volume per ha according to the mean height of the dominant trees (marked in m).
- Full-density line and self-thinning line: The oblique line at the upper right is the full-density curve, and the curves from it down to the x-axis of the graph are the self-thinning curves.
- Equivalent mean diameter line: The lines from the full-density curve to the lower left part of the diagram are the mean diameter lines relative to mean height and stand density (marked in cm).
- Yield index line: Each line running parallel to the full-density curve expresses the yield index (Ry) corresponding to the ratio of the stem volume of a stand at a certain density to that at full density, when mean tree heights of the stands are identical.

Various relationships between stand density, stem volume, mean tree height and mean diameter of a stand can be interpreted at any given time, and the future growth of the stand under different stand density control options can be estimated.

For example, the line A-F on Figure 6-16 traces a course of stand density management (Ando, 1994). At planting, the stand density was 3000 stems per ha, but assuming that 10 % of the trees die within several years of planting, stand density starts at 2700 stems per ha (F). The relative stand density (Ry) was maintained between 0.8 and 0.7, and the first thinning conducted when Ry reaches 0.75 (E). At the first thinning, about 300 trees were removed (D). The second thinning occurred at point C

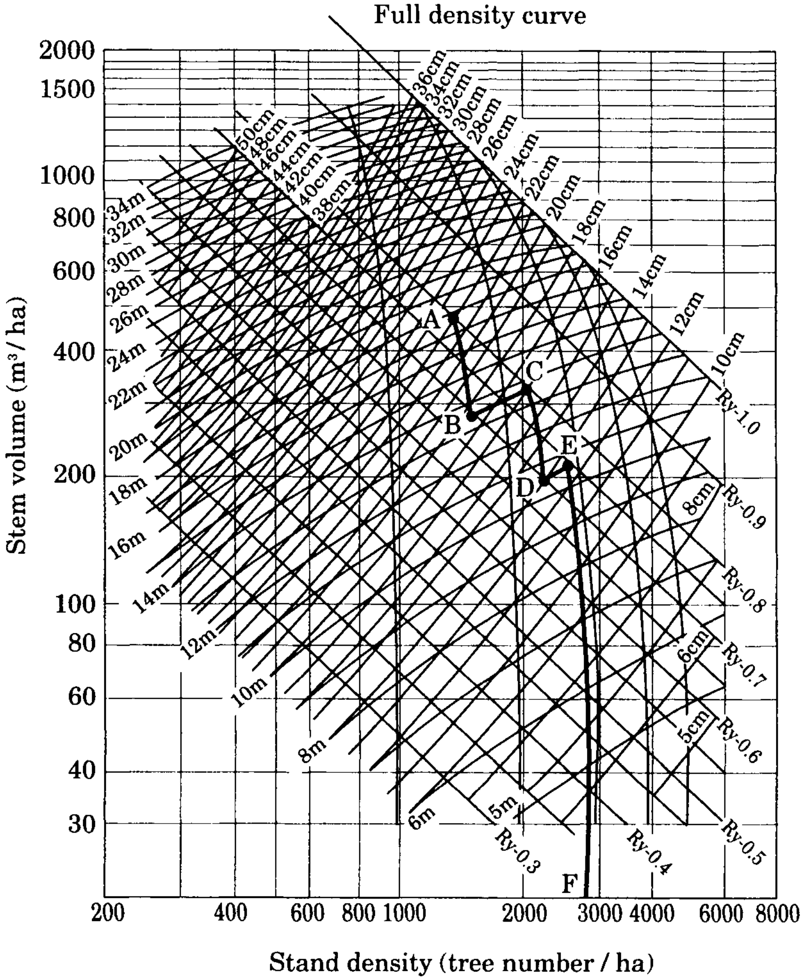


Figure 6-16 A stand density control diagram for *Cryptomeria japonica* (sugi) stands in the National Forest of Shikoku Region. (Forestry Agency of Japan, 1979; Ando, 1994)

when the mean tree height and mean diameter were 13 m and 16 cm, respectively. At this point, logs suitable for a single pillar length could be harvested. About 500 trees, or 30 m^3 per ha, were harvested at the second thinning (B). The final harvest occurred at point A when mean tree height and mean diameter were 18 m and 22 cm, respectively. At this stage, the logs were big enough to yield two pillars. About 1400 trees, or nearly 500 m^3 per ha, were harvested at the final cutting. This technique can be used to evaluate various silvicultural options and compare the value of harvests under each option.

Stand age is not included in the stand density management diagram. If information on stand age is required, it can be obtained using the general yield table for the same district used for the stand density management diagram. The yield table enables mean tree height, mean diameter, stand density and stem volume per ha to be determined according to stand age and site index.

The stand density management diagram is a useful tool for forest management, but there are some limitations to its application. The diagram provides mean stand values, but individual tree values are required for thinning. Another disadvantage of the diagram is that it is only suitable for thinning from below, because the diagram is derived from the law of self-thinning. Therefore, these diagrams should only be applied to planning operations of thinning from below in single-storied pure stands.

During the 1970s and 1980s various modifications to the original modeling approach were proposed including the replacement of the reciprocal equations with empirical-based volume-density functions, employing different relative density indices and size varieties, and incorporating forest production theories (Newton, 1997). Drew and Flewelling (1977) defined the phase of stand development between the initiation of density dependent mortality and the asymptotic volume-density relationship during self-thinning as the zone of imminent competition-mortality.

Drew and Flewelling (1979) continued their work and developed a stand density management diagram for *Pseudotsuga menziesii* (Douglas-fir) (Figure 6-17). This diagram illustrates the relationship between stand density and mean tree volume according to mean tree height or mean stem diameter. The three relationships on the diagram, that is, the maximum size-density line, the lower bound of the zone of imminent competition mortality, and the line of crown closure (relative density of 0.15) are the basis of this density diagram. The relative density index is defined as the ratio of the observed stand density to the maximum stand density attainable in a stand with the same mean tree volume. The relative density index corresponding to Figure 6-17 is shown in Figure 6-18. They demonstrated the process of heavy and light thinning on the diagram. Many stand density management diagrams derived from the achievements outlined above were reviewed by Newton (1997).

Yield-Density diagram

Stand density management diagrams are not applicable to managing stands with a large range in individual tree size, as is common in natural broad-leaved forests. In these situations, it is more useful for sawlog

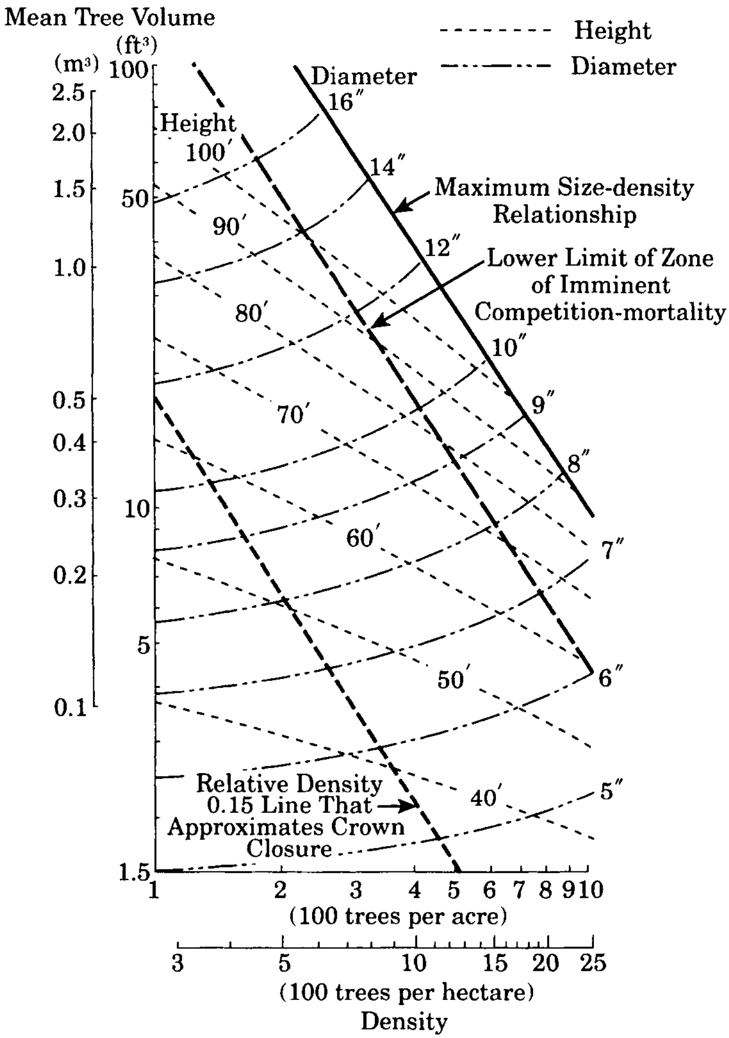


Figure 6-17 Stand management diagram for *Pseudotsuga menziesii* (Douglas-fir). (Drew and Flewelling, 1979)

production to understand the growth of individual trees. The most important information is the number of trees above a critical size and their likely future growth. Kikuzawa (1978) devised a yield-density diagram for such stands (Figure 6-19) based on the frequency distribution of the volume of individual trees in the stand (Hozumi et al., 1968). The diagram is composed of following factors.

- Y-N curve: this curve is hyperbolic, and is derived from the

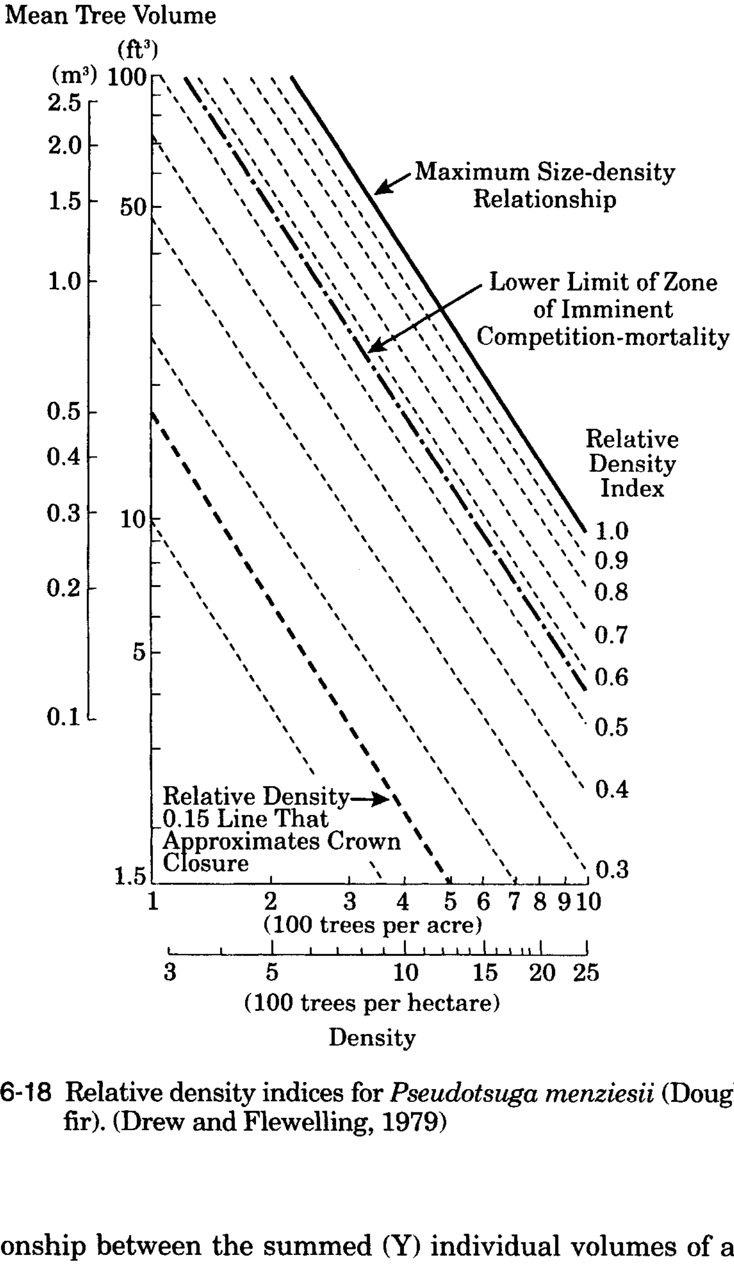


Figure 6-18 Relative density indices for *Pseudotsuga menziesii* (Douglas-fir). (Drew and Flewelling, 1979)

relationship between the summed (Y) individual volumes of all trees (the values are summed consecutively from the largest value to the smallest) and number (N) of these trees. In Figure 6-19, each line which runs from the lower left to the upper right is a Y-N curve. Y-N curves are derived from an analysis of the distribution function of individual tree volumes in a stand (Hozumi et al., 1968): They are expressed by the following equation:

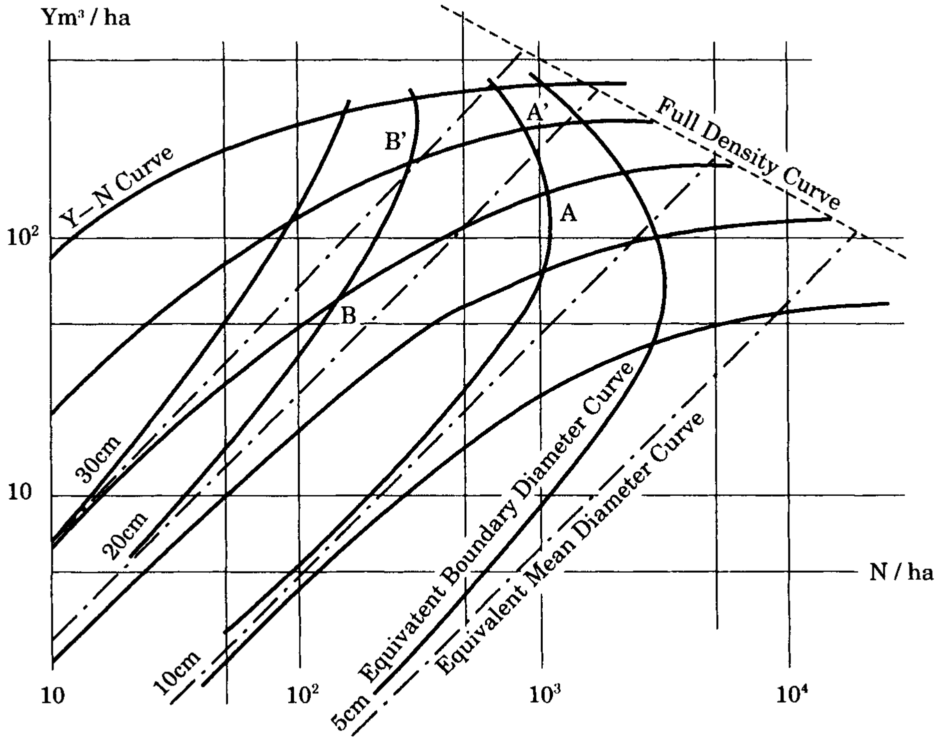


Figure 6-19 Yield-density diagram for natural deciduous hardwood stands in Hokkaido, Japan. (Kikuzawa, 1978)

$$1/Y = B/N + A \tag{6.9}$$

Where, A and B are constants.

- Equivalent boundary diameter curve: The point marked A in Figure 6-19 is the number of trees with diameters over 10 cm (boundary diameter) and their total stem volume. The equivalent boundary diameter curves shown in Figure 6-19 are curves combining the boundary diameter for each Y-N curve. These are hyperbolic curves which are convex at the upper right. These curves represent the number of trees larger than the boundary diameter. For example, if the boundary diameter is 10 cm, the number of trees over 10 cm initially increases during the young stage, reaches a maximum, then decreases because of self-thinning as the stand age increases. Throughout all stages, the stem volume of the stand continues to increase irrespective of the number of trees whose diameter is over than the boundary diameter.

- Equivalent mean diameter line: If the same mean diameters from a range of stands are plotted on the number-yield graph, they form a straight line called the equivalent mean diameter curve.

Yield-Density diagrams such as that shown in Figure 6-19 are used as follows. Point A is where the Y-N curve for a stand crosses the 10 cm equivalent boundary diameter curve. At this point, there are about 1000 trees with diameters greater than 10 cm and the total volume of the stand is about 110 m^3 per ha. Following this Y-N curve to the left, it crosses the 20 cm equivalent boundary diameter curve at point B. At this point, there are about 110 trees with diameters over 20 cm. Thus, the Yield-Diameter diagram provides information about tree number per unit area, stand volume and distribution of diameter classes.

The Yield-Density diagram allows the yield from each diameter class to be predicted from the upper Y-N curves. For example, when the stand grows and reaches the upper Y-N curve, the number of trees with diameters over 20 cm (B′) reaches 300 and the number of trees over 10 cm diameter (A′) has decreased to 950; suggesting that if as many trees as possible are to be harvested from this class, harvesting should occur earlier.

As the Yield-Density diagram is based on the normal frequency distribution of the volume of individual trees in a stand, this diagram is only applicable if thinning is conducted in such a way that the trees to be removed are selected in proportion to their frequency.

6.2.4 Methods of thinning

An essential part of thinning is selecting which trees to leave and which to remove. This depends on the management objectives and the conditions of the stand, and will determine the method of thinning. Thinning methods can be classified into four types (Smith, 1986):

1) low thinning or thinning from below;
2) crown thinning or thinning from above and/or thinning of the dominants;
3) selection thinning; and
4) geometric thinning or mechanical thinning.

Figure 6-20 illustrates the diameter distributions of removed and residual trees for each method. It is also useful to recognize a fifth method, free thinning, which is the combination of the other four methods applied simultaneously (Smith, 1986).

The characteristic pattern of thinning which is found in very intensive forest management in Japan is the removal of dominant and suppressed trees, leaving average size trees to harvest for uniform boxed-heart logs for pillars. This could be classified as free thinning, but as the thinning regime

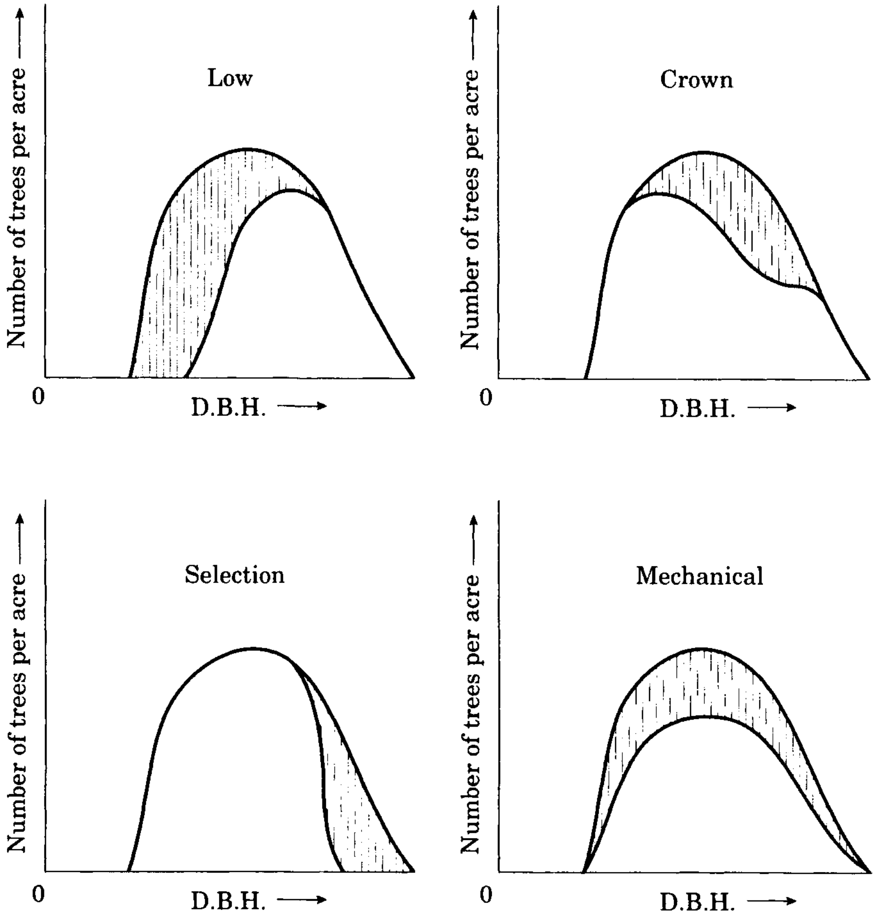


Figure 6-20 Diameter distribution of removal and residual trees for four different methods of thinning. Cross-hatching shows the part that would be removed. In each case about one-third of the basal area is represented as having been removed. It is assumed that the stands have not been treated previously, and that D.B.H. is clearly correlated with crown class. (Smith, 1986)

is distinct, this should be recognized as one method called combined thinning from above and below. This method is discussed later.

An essential part of selection of trees for thinning is the consideration of the growing space freed for the retained trees. Thus, selection of trees to be thinned must include both stand density and spacing considerations.

6.2.4.1 Thinning from below

This method of thinning favors dominant trees and removes trees from the lower crown classes. Crowns or trees are usually categorized into one of four classes such as those defined by Smith (1986), i.e., dominant, co-dominant, intermediate, or suppressed. Trees in the suppressed and intermediate crown classes usually die by self-thinning if they are not thinned, so the effect of thinning on the growth of the residual trees is small and the canopy soon closes again. Therefore, some co-dominant trees must be removed along with the lower crown classes if the growth of the residual trees is to be improved. Thinning from below usually removes suppressed, intermediate, and some co-dominant trees (Figure 6-21). The more co-dominant trees that are removed, the greater the effect of the thinning. As with any type of thinning, the selection of trees to be removed must be done relative to the adjacent trees.

Stands which have been thinned are susceptible to strong wind (Fujimori, 1992a; Isamoto and Takamiya, 1992) or wet snow in the subsequent two or three years. One of the greatest advantages of thinning from below is that the thinned stand is more resistant to such damage than stands subjected to other thinning methods.

Another advantage of thinning from below is that it is relatively easy to select the trees that are to be removed. However, it is often found that the growth subsequent to low thinning is less than predicted because workers are hesitant to cut co-dominant trees. This shortcoming could be corrected by recognizing the significance of thinning. If the effects of thinning are to be maximized, thinning from below should be conducted as early and as frequently as possible to ensure that the stand density and tree size required for utilization is produced. Thinning from below should be also done before the trees degrade or decline, if they are large enough to yield a product.

6.2.4.2 Thinning from above

Thinning from above favors the most promising trees by eliminating the most competitive trees (Figure 6-22). Potential crop trees are usually dominant but sometimes codominant. Any competing trees are removed but the most competitive dominant trees are removed preferentially. This method is usually called “crown thinning,” but is also referred to as “high thinning” and “thinning of the dominants” (Smith, 1986). One of the characteristics of thinning from above is that the bulk of the intermediate and suppressed classes are left (Figure 6-22) to restrict epicormic branching on the residual stems and/or prevent deterioration caused by the sudden increase in direct sunlight. Retaining intermediate and suppressed trees is especially important if the crop trees are capable of profuse epicormic shooting. In this context, intermediate and suppressed trees are called trainers. Hardwood species usually require a large growing

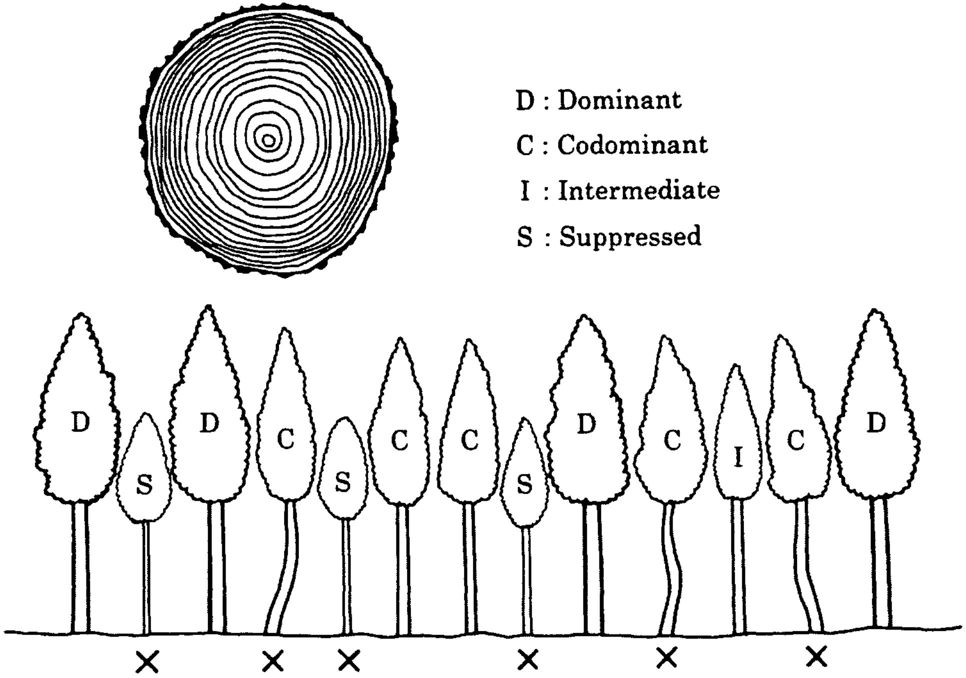


Figure 6-21 The removal trees in thinning from below and the width of annual rings in stem from a stand where thinning from below was practiced. The removal trees are shown by cross mark. (Fujimori, 1996)

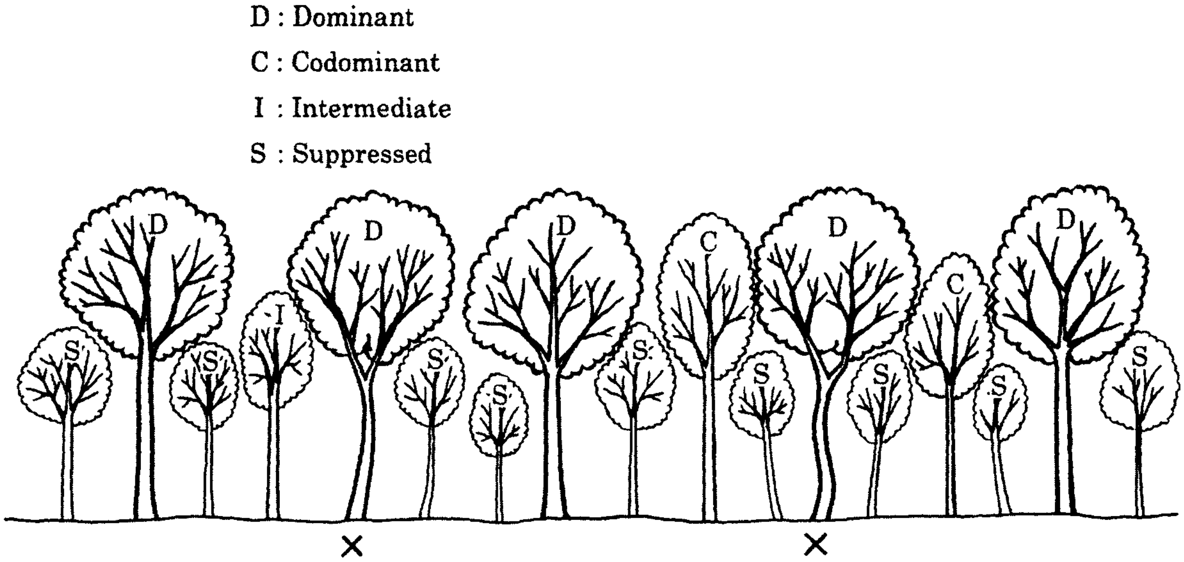


Figure 6-22 The removal trees by thinning from above which are shown by cross mark. (Fujimori, 1996)

space to develop into valuable dominants and they tend to produce epicormic shoots if the illumination suddenly increases, so thinning from above is more commonly used in hardwood stands than in coniferous stands.

Crop trees must be selected by their potential value relative to adjacent trees and with consideration of the distance between selected trees to ensure they have sufficient growing space until the next thinning or final cutting (Ushiyama, 1954, 1955). Crop trees are usually selected from dominants, but in coniferous stands, they are often selected from co-dominants or even from intermediates in the young stage if the stand is not susceptible to wind or wet snow. This is because one of the factors contributing to high timber quality in conifers is uniform annual rings of moderate width. This is best achieved by giving more growing space to trees which have been moderately restricted during the young stage and which are able to grow better during the later stage.

An important advantage of thinning from above is that the crop trees can grow to a given size in a shorter time. This advantage is more readily achieved in hardwood stands, because hardwood species generally require a wider growing space for fast growth. The growth rate of hardwood deciduous species is generally low (section 3.4), so accelerating the growth of crop trees by thinning is very useful. The total yield from stands that have been thinned from above is not generally greater than stands that have been thinned from below, and the thinning ratio as measured by the number of trees removed is generally lower in thinning from above than thinning from below, but the ratio as measured by stem volume is often greater in crown thinning. If thinning is delayed, thinning from above becomes difficult because the residual stand will be susceptible to strong wind or wet snow, and intermediate or suppressed trees cannot act as trainers as they may have been eliminated by self-thinning. Thinning from above is generally most effective if it is conducted at a relatively young stage (by 30-40 years old).

6.2.4.3 Thinning of dominants or selection thinning

This method of thinning removes dominant trees to stimulate the growth of promising smaller trees, most of which are co-dominants or intermediates (Figure 6-23). Thinning of dominants is also called selection thinning (Smith, 1986). In Japanese, Yuseiboku kanbatsu (thinning of dominants), Seiboku tekibatsu (harvesting trees of a usable size) and Nasubigiri (harvesting trees of a usable size) would be equivalent or similar terms to thinning of dominants or selection thinning. In this type of thinning, dominant trees are harvested when they reach a minimum commercial size. Removal of the dominant trees provides growing space for the smaller retained trees.

This method of thinning is useful for controlling the width of the

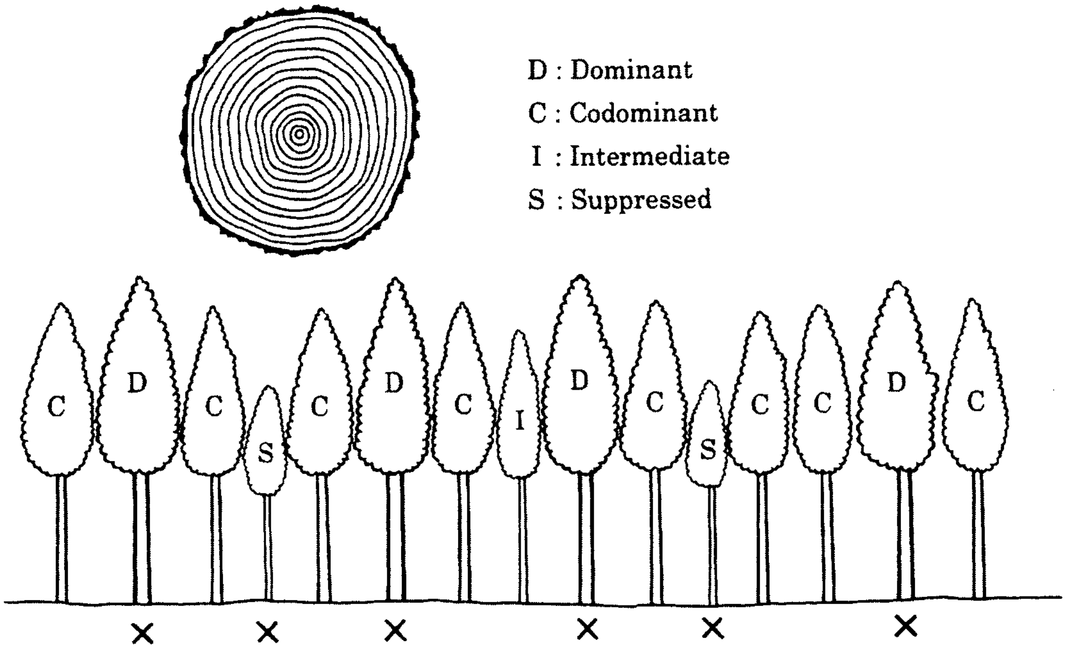


Figure 6-23 The removal trees by thinning of dominants and the width of annual rings in a stem from a stand where thinning of dominants was practiced. The removal trees are shown by cross mark. (Fujimori, 1996)

growth rings. Larger trees can be thinned and used for boxed-heart square timber, leaving smaller trees to grow more quickly, so their subsequent annual rings are a consistent and moderate width (Ando, 1984). If smaller size trees (DBH < 25 cm) are used to produce boxed-heart square timber, they must be particularly straight. Dominant trees usually are straight, so they are well-suited to this end-use. Even if the retained trees are less straight than the removed dominant trees, their form will improve as they grow and their diameter will become large enough (DBH > 40 cm) for processing into timber products such as boards and squares.

If this method of thinning is managed well, many subordinate trees which would otherwise die or be deformed can be grown to a size where they have some value, and trees harvested later will have greater value. Leading forest managers in Japan, such as Ishihara (1980), have evaluated this thinning method commercially and adopted it. However, this method can be only used in forestry areas where the natural and social conditions allow intensive management. It is not suitable in areas where strong winds or heavy wet snow falls are common, as the retained trees generally have relatively slender stems with less developed crowns, making them more susceptible to strong winds or wet snow. It is also not appropriate unless there is an established market relying on a constant supply of products. If thinning is delayed, the residual trees are prone to deformation to an extent which cannot be recovered even after the thinning. Therefore, the timing of thinning is particularly important in this type of thinning.

In a stand of a single species, thinning of dominants is only applicable if it is a shade-tolerant species. It can also be used in mixed stands, where comparatively light-demanding, fast growing species are removed. For example, it is used in mixed stands of moderately shade-tolerant *Chamaecyparis obtusa* (hinoki) and very intolerant *Pinus densiflora* (akamatsu).

Leaving slower-growing trees is undesirable from a genetic perspective. Therefore, seeds or scions should not be collected from the stands where thinning of dominants has occurred. They should be collected from seed orchards or scion gardens.

6.2.4.4. Thinning from above and below

This type of thinning has a special purpose in production forests. Trees which have reached the minimum size suitable for utilization are thinned out with the aim of harvesting similar sized trees in the final harvest. This method can also be called "thinning to leave average trees." It is used in advanced forestry areas in Japan, although its use has not been widespread. The method is described here because it is one of the fundamental types of thinning, it is theoretically clear, and it has been used and proved effective.

This method of thinning is used to produce as many high quality logs for standard size ornamental pillars as possible. A typical example of its use is in Kitayama forestry area in Kyoto Prefecture, Japan (Figure 6-7), where very intensive management produces polished logs of *Cryptomeria japonica* for ornamental pillars. Typically, these logs are 3 m long and 10-13 cm in diameter at the top end. One log from each tree is harvested at earlier thinnings and two logs from each tree are harvested at later thinnings and the final harvest. To harvest the greatest possible number of standard size logs from a given area, it is best to frequently harvest those trees which have reached the required size and retain those trees that are not yet the required size until final harvest. The total biomass of leaves per unit area can be defined for each species at canopy closure, and this can be used to determine the greatest number of trees of a specified size that can be produced. To satisfy the demand for consistently sized trees, it is best to reduce the deviation in tree sizes in the stand at final harvest. At each thinning, therefore, the trees to be removed should be selected from the largest and smallest trees, leaving average size trees. In the initial thinning, neither the large nor the small trees have a commercial value. At the second thinning, the larger trees do have a commercial value, but the smaller trees do not until later thinnings. In intensive forest management, if intensive pruning to a specified crown length is repeated, the standard deviation in tree size in the stand becomes much smaller, as seen in Kitayama forestry area (Section 6.1.4).

Thinning from above and below is also in *Chamaecyparis obtusa* used to produce knot-free boxed-heart square timber for pillars. The common sizes of square timber in Japan is 10.5 × 10.5 cm or 12 × 12 cm by 3 or 4 m length. The tree must be about 22 cm DBH to harvest two logs of this size. Forest managers who want to harvest two logs from each tree at the final harvest can use thinning from above and below for the same reasons as it is used to produce polished logs. In this context, the number of logs of a specified size that are harvested is more important than the total volume per unit area. This thinning method is characteristic of the most intensive management in plantations in Japan.

6.2.4.5 Geometric thinning

In this method, trees are removed or retained according to simple criteria such as a defined distance or a defined number of rows. There is no consideration of the trees' position in the canopy. The term, "mechanical thinning" seems to be more popular than "geometric thinning," but it is sometimes misunderstood to mean thinning using machinery, so it is better to use the term, "geometric thinning."

Geometric thinning cannot be unconditionally recommended because it does not necessarily satisfy the principle objectives of thinning. However, in some cases, it is better to use this method than not to thin at all. In cases where initial thinning is difficult because the trees are relatively small and have little value but the stand needs to be thinned to improve its health and individual tree growth, geometric thinning can be adopted. This method is also effective if the felled trees are transported using machines. Geometric thinning has advantages in young and dense stands such as naturally regenerated stands or regular and uniform-sized plantations.

In naturally regenerated dense stands, spacing thinning or strip thinning is usually applied. In spacing thinning, trees at specified intervals are retained and all others are removed. In plantations, row thinning is most easily applied. In this method, every third row is usually removed. This level of thinning (33%) is in the normal range for a young stand but the residual trees are only given more growing space on one side. This results in the development of lopsided crowns which may lead to the production of knotty stems, or in many species, leaning stems. Hardwood species are particularly prone to leaning, so use of row or strip thinning in hardwood stands should be avoided. Row thinning is improved if particularly poor trees are removed from the residual rows during the thinning operation.

Row or strip thinning has advantages for transporting the felled trees, but in stands on relatively steep slopes, there are disadvantages in soil protection. This can be overcome by thinning across the slope, but this loses the transport advantages. A compromise of the two techniques can be achieved by felling the trees in a herring-bone pattern (Figure 6-24). If felled trees are left in the stand, row or strip thinning should only be applied horizontally.

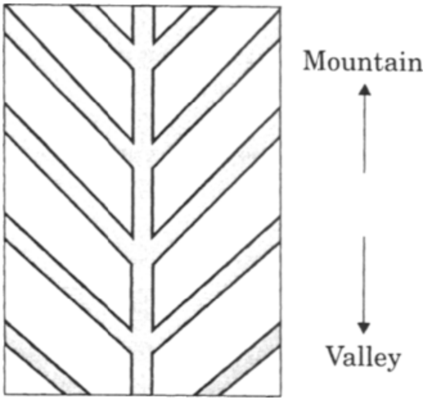


Figure 6-24 The herring-bone pattern of thinning, where trees on the dotted lines are removed.

6.2.4.6 Free thinning

Cutting which releases favorable trees without considering their position in the canopy is referred to as free thinning, because it is not constrained by adhering to any one of the other methods of thinning (Smith, 1986). In many cases, free thinning is a modification of the other methods or a combination of other methods. It is mainly used in stands with irregular composition. As the term free thinning is vague, it is better to use more informative terms such as "modified crown thinning" if the technique is a version of a defined technique (Smith, 1986).

6.2.5 Season for thinning

Thinning should not be conducted in the season when the trees are physiologically active. During this period, the residual trees are susceptible to injury from the impact of fallen trees, which causes wood degradation.

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Part III

Silvicultural Systems and Methods for Sustainable Forest Management for Wood Production

A silvicultural system is the combination of all the silvicultural methods used to achieve the objectives of forest management, and each silvicultural method is composed of individual silvicultural techniques. Individual silvicultural techniques function efficiently only if they are coordinated and directed towards achieving the management objectives. Silvicultural systems and methods originated in Germany and central or northern European countries, and have been further developed in other countries, mostly in temperate and boreal zones (Smith, 1986; Benecke, 1996). However, in many areas outside Europe, traditional silvicultural systems and methods must have existed and been developed to suit local natural and social conditions. The information from such systems should contribute to the development of new silvicultural systems and methods at both local and international levels. As it can be difficult to distinguish between the terms "system" and "method," the term "method" is mainly used in this book, and includes systems except in special cases.

The objectives of traditional silvicultural methods are biased towards the production of wood, despite the insistence of some scientists, such as Möller (1922), that ecological requirements need to be considered and the forest should be regarded as complex and dynamic living community.

The recent world-wide shift towards sustainable forest management requires that new silvicultural methods must be developed. In this Part, traditional silvicultural methods are classified according to their potential role in sustainable forest management. The application of these methods for wood production in given conditions is then discussed, and other forest functions such as conservation of biodiversity, soil and water resources briefly considered. Silvicultural strategies specifically focused on enhancing other functions of forest such as biodiversity are discussed in Part IV.

Chapter 7

Classification of Silvicultural Methods

7.1 Criteria for classifying silvicultural methods

The traditional silvicultural methods that originated in Germany were classified by the height of the stand and the spatial or geometric regeneration method. However a broader range of criteria is required to classify silvicultural methods for sustainable forest management and for their practical implementation. The following factors are considered important:

1. stand structure;
2. regeneration method;
3. tending methods (intermediate operations);
4. rotation period;
5. objectives of the management;
6. the potential natural vegetation (forests) and present forest type (including stand development stage or successional stage);
7. social circumstances; and
8. the desired forest type or stand development stage required to fulfil the desired forest function or objectives of forest management (target stand structure).

7.1.1 Stand structure

Stand structure is the most important factor for classifying silvicultural systems, because functions of stands are most dependent on their structure. Stand structures, such as even-sized stands and uneven-sized stands or pure stands and mixed stands, are the result of the regeneration and tending methods applied, and/or the rotation period.

7.1.2 Regeneration methods

One of the most important factors used to characterize silvicultural methods is the method of regeneration and this also determines the spatial pattern of cutting. Methods of regeneration can be classified into a few broad categories. Smith (1986) classified regeneration methods in relation to stand structure, as used in North America, into the following categories:

High-forest system - producing stands originating from seed.

a) Even-aged stands:

- *Clearcutting method* - removal of the entire stand in one cutting with regeneration obtained artificially or by natural seeding from adjacent stands or from trees cut in the clearing operation.
- *Seed-tree method* - removal of the old stand in one cutting, except for a small number of trees left singly or in small groups as a source of seed.
- *Shelterwood method* - removal of the old stand in a series of cuttings, which extend over a relatively short portion of the rotation, by which essentially even-aged regeneration is established under the partial shelter of seed trees.

b) Uneven-aged stands:

- *Selection method* - removal of mature timber, usually the oldest or largest trees, either as single scattered individuals or in small groups at relatively short intervals, repeated indefinitely, by which continuous regeneration is encouraged and an uneven-aged stand is retained.

Coppice-forest system - producing stands originating primarily from vegetative regeneration.

- *Coppice method* - any type of cutting which depends mainly on vegetative regeneration.
- *Coppice-with-standards method* - production of coppice and high forest on the same area with the trees of seedling origin carried through to a much longer rotation than those of vegetative origin.

Matthews (1989) classified the regeneration systems used in Europe into the following categories:

High forest systems - Crops normally of seedling origin.

a) Felling and regeneration concentrated on part of the forest area only:

- Old crop cleared by a single felling; resulting crop even-aged -

Clearcutting method

- Methods of successive regeneration fellings. Old crop cleared by two or more successive fellings; resulting crop more or less even-aged or somewhat uneven-aged – *Shelterwood methods*
  - Regeneration fellings distributed over whole compartments or sub-compartments:
    - Opening canopy even; young crops more or less even-aged and uniform – *Uniform method*
    - Opening of canopy in scattered gaps; young crop more or less even-aged – *Group method*
    - Openings in canopy irregular and gradual; young crop somewhat uneven-aged – *Irregular shelterwood method*
  - Regeneration fellings confined to certain portions of compartments or sub-compartments at a time:
    - Fellings in strips – *Strip method*
    - Fellings begin in center of strip and advance outwards in wedge formation – *Wedge method*

b) **Felling and regeneration distributed continuously over the whole area:**

Crop wholly uneven-aged (irregular) – *Selection method*

- Accessory systems arising out of other methods:
  - Form of forest produced by introducing a young crop beneath an existing immature one – *Two-storied high forest*
  - Form of forest produced by retaining certain trees of the old crop after regeneration is completed – *High forest with reserves*

Coppice systems – Crops at least in part originating from stool shoots (coppice) or by other vegetative means:

- Crop consisting entirely of vegetative shoots:
  - Crop removed by clear felling; even-aged – coppice method
  - Only a portion of the shoots cut at each felling; crop uneven-aged – *Coppice selection method*
- Crop consisting partly of vegetative shoots, partly of trees generally of seedling origin – *Coppice with standard method*

In Japan, silvicultural methods (systems) have been classified as either clearcutting or non-clearcutting methods since the 1970s (Sakaguchi, 1975). Non-clearcutting methods include the selection method, long-term two-storied forest method (two-storied high-forest method), and short-term two-storied forest method (Waseda, 1975; Ando, 1985; Fujimori, 1989a, 1991a). The shelterwood method could be included in the short-term two-storied forest method. In Japan, a non-clearcutting method is defined as any method in which the stand is regenerated without exposing the soil surface (Fujimori, 1991a). In this context, the shelterwood method is regarded as a non-clearcutting method in Japan, although elsewhere it is often regarded as a clearcutting method because overstorey trees are removed within a short period. In this book, the shelterwood method is regarded as a non-clearcutting method.

It is important to recognize that most two-storied forests do not maintain a two-storied structure throughout the whole rotation, i.e., the stand reverts to a single storey after the overstorey is cut.

Non-clearcutting methods are usually called multi-storied forest methods in Japan (Waseda, 1981; Working Group on Multi-storied Forests, 1983; Ando, 1985). The relationship between common silvicultural systems in Japan and in North America and Europe is as follows. The terms in brackets are those used in Japan.

High forest methods: Mainly for the production for sawn timber for construction, furniture, etc. or for other objectives excluding wood production.

a) **Clearcutting methods** (Single-storied forest method)
- *Clearcutting method*
- *Strip clearcutting method*
- *Seed-tree method*

b) **Non-clearcutting methods** (Multi-storied forest method)
- *Shelterwood method* (Short-term two-storied forest method)
- *Two-storied forest method* (Long-term two-storied forest method)
- *Selection method* (Perpetual multi-storied forest method)

Coppice methods: Mostly used for production of pulpwood, fuelwood, and mushroom bed logs.
- *Coppice method*
- *Coppice-with-standards method* (Multi-storied forest method)

Even-aged multi-storied mixed species forests which develop a multi-storied structure because of differences in growth rates between the species despite regenerating at almost the same time after clearcutting do not meet the above classification. In Japan, a multi-storied forest method is an alternative name for a non-clearcutting method, but in this case, the method is a clearcutting method even though a multi-storied forest results.

Silvicultural systems are often classified according to the regeneration method, as above, because use of an appropriate regeneration method is the most important factor determining the success of a silvicultural system. However, it should be acknowledged that regeneration methods are not silvicultural methods in themselves. An essential part of any silvicultural method is the objective of management, and silvicultural methods are a combination of regeneration and tending methods which meet the management objectives. In many cases, tending methods more strongly characterize the silvicultural methods. This is especially true in intensive forestry management.

7.1.3 Tending methods

In forestry for the production of sawn wood, thinning and/or pruning methods are instrumental in producing the desired quality and volume of timber and the specific approaches are important for differentiating silvicultural methods. The famous forestry areas of Japan noted for the quality of the wood they produce are characterised by specific silvicultural methods, which are distinguished by the number of planted trees, and the thinning and/or pruning methods applied. These techniques and methods are designed to meet specific timber production objectives. Therefore, tending methods become more important components of silvicultural methods as the production objectives become more specific.

If thinning is practiced frequently and yields products, the stand structure required for regeneration will, in many circumstances, gradually develop. This can be observed in forests such as those in Japan and the southern bottomland hardwood forests in the United States of America (Meadows and Stanturf, 1997). In these cases, there is no distinction between the thinning for tending and harvesting and that for regeneration, and the thinning methods are closely related to regeneration.

7.1.4 Rotation period

The rotation age is an important criterion for classification of silvicultural systems because the composition and function of forest stands, and their ability to meet the production objectives, differ greatly depending on the stand development stage (Section 2.4.4).

When the objectives of forest management are being determined, it is important to decide on the stand development stages which will be maintained. If the objective is to maintain biodiversity or maintain or enhance soil and water resources, it is best to let the stand develop to the old-growth, or climax stage and then maintain it. If the objective of management is extended to include production of wood with conservation of biodiversity, soil and water resources, then the rotation should extend to the end of the mature stage.

Figure 7-1 shows a model of the relationship between stand age, stem volume growth and the value of wood in a *Cryptomeria japonica* (sugi) plantation. Although this model was based on data from *Cryptomeria japonica* plantations, the pattern is probably true of many other even-aged coniferous plantations or even other forest types in temperate and boreal zones. The line which decreases from the upper left side to the lower right side like a staircase shows the change in stand density. In this model, 3000 trees per ha are planted, thinning is practiced at about 15 year intervals and a 35% thinning ratio (in both tree number and stem volume) is used until the fifth thinning. After the fifth thinning, thinning is practiced at 20 year intervals using 20-25% thinning ratio. The stem volume growth of the stand usually peaks between 20-40 years and then gradually decreases

(Kira and Shidei, 1967; Tadaki and Hatiya, 1968; Osumi et al., 1995).

The rotation which maximises volume production occurs at the age when the mean annual growth is the largest. This usually occurs a little later than the peak of stem volume growth. However, because the commercial value increases as stem diameter increases (Forestry Agency of Japan, 1982), it is worth extending the rotation. After the second thinning, thinned trees have commercial value. When thinning is repeated as shown in Figure 7-1, the number of trees falls to 180 at 130 years, and as this seems to be the lowest number of trees which can effectively utilize solar radiation, it might be best for the next cutting to be the final cutting. However, if the interval between thinning is extended and the thinning ratio is reduced as the stand ages, then the rotation can be extended. If the overstorey trees are no longer efficiently using the solar radiation, and if it is desirable to avoid clearcutting, then the stand can be converted to a

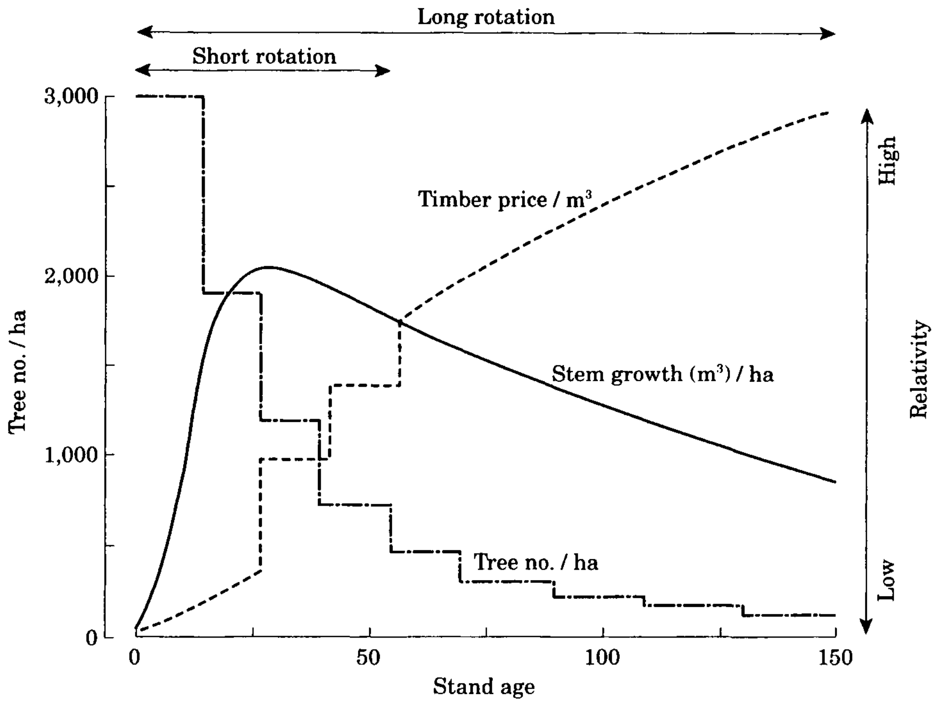

Figure 7-1 A model of the relationship between stand age, structure, timber price, and biological values of *Cryptomeria japonica* (sugi) or *Chamaecyparis obtusa* (hinoki) plantation. The stepped line from the upper left side to the lower right side shows the change in stand density with successive thinnings. (Modified from Fujimori, 1991a)

multi-storied forest by planting seedlings in the gaps during the mature stage.

Figure 7-2 shows a model of the relationship between stand age and resistance to wind and snow for plantations of *Cryptomeria japonica* or *Chamaecyparis obtusa* (hinoki) following clearcutting and regeneration, and the general trend of leaf and branch litter accumulation (thickness of organic layer) for various types of forest following clearcutting. This is a hypothetical model based on limited data and observations, but the general trends in the response of each function to stand age can be seen. The relationships between stand age and biodiversity and water yield are shown in Figures 10-2 and 11-3 respectively. Figure 10-2 shows the relationship between stand development stage and the species diversity of mammals in the natural forests in the Pacific Northwest of the United

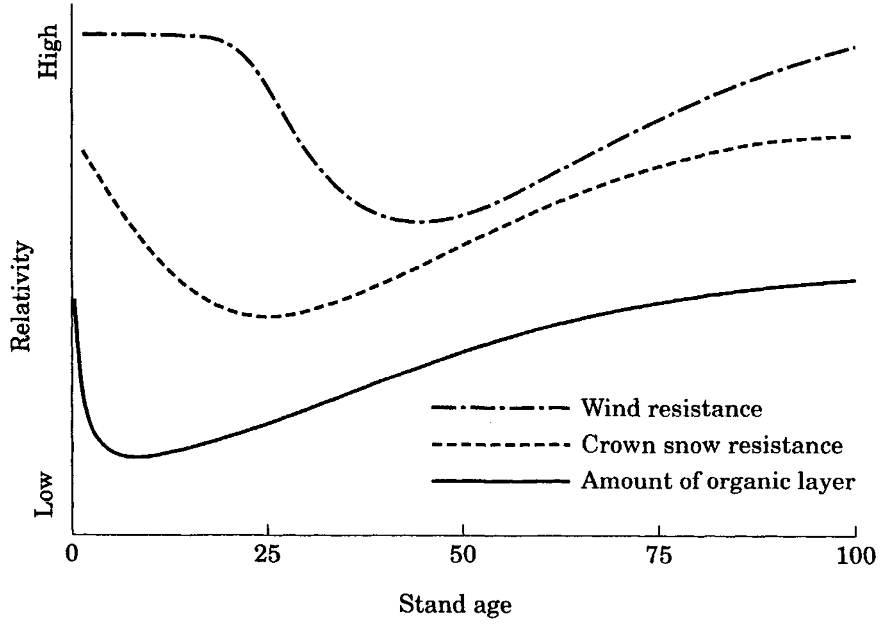

Figure 7-2 Hypothetical relationships between stand age and wind resistance, crown snow resistance, and accumulation of litter. The relationship for wind resistance is based on coniferous plantation in Japan (Fujimori, 1995), that for snow resistance on plantation of *Cryptomeria japonica* (Saito et al., 1986), and that for litter accumulation on broad-leaved deciduous secondary forest in eastern United State of America (Covington, 1981).

States of America and Figure 11-3 shows the relationship between stand development stage and water yield in eucalypt forests in southeastern Australia. More data including biodiversity and water yield is urgently needed to describe these trends and develop the models in more detail, because this information is essential for deciding the rotation period. These relationships are shown together in Figure 16-1 and strategies for enhancing these forest functions are summarized in Chapter 16.

In coniferous plantations, the wind resistance of a stand is usually high until age 20 or 25 years, decreases until about age 50 years, then increases until about age 100 years, although the information for stands over 100 years old is limited (Fujimori, 1995). For wind resistance, then, a rotation of 100 years, or even 150 years will be safer than a rotation of 50-60 years.

The snow resistance of saplings and young trees of conifers is low. The snow resistance shown in Figure 7-2 is crown snow damage. In snowy areas, many planted trees on a slope are pushed down by snow pressure, and *Cryptomeria japonica* (sugi) is most prone to injury from 5 to 15 years after planting. Young *Cryptomeria japonica* stands between 10 and 30 years old are most susceptible to crown snow damage (Fujimori, 1987b). *Chamaecyparis obtusa* is very susceptible to snow pressure but has more resistance to crown snow damage than *Cryptomeria japonica*. Thus, frequent, short rotations will not have much protection from snow damage.

Nutritional status and soil structure change as a stand develops (Tsutsumi, 1989; Yamaya, 1993). The change in thickness of the organic layer over time is shown in Figure 7-2, and this contributes to the nutritional status and soil structure of the stand. The organic layer decreases rapidly soon after clearcutting and then begins to recover, only achieving its former thickness after many years. Although not shown in this Figure, the accumulation of litter is often delayed in the young stage, due to the shortage of undergrowth, especially in *Chamaecyparis obtusa* stands. In the young stage, the undergrowth is poor due to the lack of the light on the forest floor and the surface soil is prone to disturbance from the impact of water dripping from the crown or rain drip. Overland flow carries the litter down the slope, as there is nothing to stop this movement of the litter on the floor. Undergrowth is important in preventing this type of runoff of litter or surface soil (Tsukamoto, 1963; Akai et al., 1981; Yoshimura et al., 1981; Kiyono, 1990). Thinning and/or pruning are effective ways to improve the light condition of the young stage (Fujimori and Kiyono, 1983). During the mature stage, the organic layer stabilizes but the soil structure continues to develop. This suggests that frequent repetition of short rotations is deleterious for soil and water conservation.

7.1.5 Objectives

Typical objectives of forest management would be production of wood, maintenance of biodiversity, maintenance of soil and water resources, enhanced recreational services, or the co-ordinated fulfilment of all these objectives. However, the specific objectives of production can vary and the silvicultural methods employed will differ accordingly. For example, wood production may be for different products, such as boxed-heart square pillars, boards or fuelwood, and specific silvicultural methods must be used for each product.

7.1.6 Natural conditions

The potential natural forest type of an area is a good model for an objective stand structure, because it is the result of adaptation to the natural conditions of the area. As climatic, geological, and topographical conditions become more severe, it will become increasingly more important to have forests which are resilient to such changes.

Natural disturbance is an important factor to consider when selecting silvicultural methods. In fire climax forests, the choice of silvicultural method is constrained by the fire disturbance regime. In southeastern Australia, the mean interval between tree-killing fires for *Eucalyptus regnans* (mountain ash) forests is reported as between 75 and 150 years (McCarthy et al., 1999). The silvicultural method for such forests is clearcutting followed by burning to produce stand-replacement conditions and reduce the level of combustible materials (Attwill, 1994). A rotation period within the mean fire disturbance interval may be desirable.

In Japan, typhoons are the most significant type of disturbance, and it is important to have a strategy to cope with them. Wind resistance varies with the stand development stage (Section 7.1.4), suggesting that the appropriate rotation for coniferous plantations which must be resistant to strong winds is at least 100 years. It is important to clarify the wind resistance of stands beyond 100 years and to adjust the rotation period accordingly. In natural forests mainly composed of hardwoods, wind damage is low until the stands are about 150 years old, then susceptibility increases (Fujimori, 1995). Therefore, the most appropriate rotation for managed hardwood natural forests which must be resistant to wind damage is up to about 150 years. Adequate thinning can reduce wind damage, but a stand in which intense thinning is suddenly conducted is susceptible to damage (Fujimori, 1992a; Isamoto and Takamiya, 1992).

The Japan Sea side of middle to northern Honshu in Japan is renown for its heavy snow. Regeneration generally takes longer than in other areas, and the labor costs are high, but stand growth is rapid after the young stage. Therefore, long rotations are appropriate for these areas. The area and technique of harvesting should be selected carefully for stands on steep slopes in snowy areas to prevent creeping of snow. On steep slopes, the area harvested should be as small as possible to avoid soil erosion, and if possible, non-clearcutting methods should be used.

7.1.7 Social circumstances

The social demands from a forest are largely determined by the natural circumstances. In and around areas susceptible to natural disasters such as surface landslides, the demands for forests to provide protection are high. Likewise, the demand for forests to fulfil recreational functions is high in and around urban areas. Historically, forestry production areas which produced wood for traditional uses developed near areas of demand, but transportation systems have developed such that it is no longer necessary for production areas to be located near their markets. However, if silvicultural systems based on sustainable production are to be used, constant demand for timber is necessary. The objectives of forest management and choice of silvicultural methods also depends on the ownership, land area and capital of the owner.

7.1.8 Forest type

In natural conditions in Japan, *Cryptomeria japonica* (sugi) and *Chamaecyparis obtusa* (hinoki) usually dominate at relatively low quality sites as a result of interspecific competition (Section 2.2.2). If they are planted and tended on better sites, both species show higher growth. A key objective of any plantation is to ensure high productivity of the selected species in both individual and total stand volume. Plantations are an effective way of increasing productivity, but care must be taken not to overly reduce biodiversity. A mosaic of plantations and natural stands or unmanaged patches would be required to maintain biodiversity.

Elsewhere in the world, there are many areas where introduced exotic species have been successful and have become the most important species for forestry. Examples include the introduction of *Pinus radiata* (radiata pine) from California, the United States of America into New Zealand (Figure 7-3), Australia, Chile, and South Africa; *Pinus elliottii* (slash pine) and *Pinus taeda* (loblolly pine) from the southeastern part of the United States of America into Argentina and Uruguay; eucalypts (*Eucalyptus* spp.) from Australia into South American countries and South Africa; *Pseudotsuga menziesii* (Douglas-fir) from the western part of the United States of America and Canada into New Zealand and western Europe; and *Picea sitchensis* (sitka spruce) from the Pacific Northwest of North America into western Europe. The common condition of the areas where these species have been successfully introduced is the similar, and comparatively mild climates. The introduction of an exotic species for intensive forestry in Japan has not been successful. This emphasizes the unique characteristics of the Japanese climate.

Silvicultural methods differ considerably between hardwood forests and coniferous forests. Most hardwood species have a decurrent growth form (Section 2.3.2), and if they are given enough open space, tend to develop a short, single straight stem with big branches emerging relatively

Figure 7-3 *Pinus radiata* (radiata pine) forest in New Zealand. The exotic species radiata pine grows well in New Zealand and is that country's most important species for wood production, grown on a rotation of 25-30 years.

low on the stem. Therefore, if timber is to be produced from such species, stands must be regenerated at a high density to encourage natural pruning and develop tall, single stems. This is why natural seeding is usually used to regenerate hardwood forests managed for sawn timber production. In contrast, species with excurrent growth form grow symmetrically, maintaining a limited crown width, and such species can be planted at lower stand densities. Most conifers and some hardwood species have an excurrent growth form.

Thinning techniques must be selected according to whether the species tends to produce epicormic branches or not (Section 2.3.2). For species which do produce epicormic branches, abrupt intense thinning should be avoided, and it is important to retain trainers around promising trees at thinning (Section 6.2.4.2).

7.2 New classification of silvicultural methods

As discussed in the previous section, the following are the main factors used to classify silvicultural methods.

Objectives of management

Production of wood
  Production of large sawn timber
  Production of small sawn timber

    - Production of logs for fuel, pulp, and other chemical use.
    - Production of non-wood products such as mushrooms, herbs, and animals such as fur bearers
  - Conservation of biodiversity
  - Water and soil conservation, and land protection
  - Recreation and culture
  - Enhancement of the contribution of the forest ecosystem to the carbon cycle

Regeneration method and geometric structure of forest
  - The classifications by Smith (1986) and Matthews (1989) as shown in the previous section.

Forest type
  - Species composition
    - Coniferous pure forest, Hardwood pure forest, Mixed forest
  - Natural forest or plantation
    - Natural forest, Plantation
  - Managed forest or unmanaged forest
    - Managed forest (Plantations and managed natural forests), Unmanaged forest (Natural forests)

Rotation Period
  - Long rotation, Short rotation

Tending methods
  - Characteristics of stand density control, thinning and/or pruning regime.

Each of these factors must be known before an appropriate silvicultural method for a particular forest can be determined. However, if all factors were considered separately, there would be too many silvicultural methods. So, in this book, in cases where the management objective is wood production, traditional classifications of silvicultural methods based on high forest or coppice systems and regeneration methods are used. In addition, factors such as rotation period and tending methods are used to discriminate between the traditional silvicultural methods for the production of different types of wood.

Objectives of forest management other than wood production, such as conservation of biodiversity, enhancement of recreational capacity, land and watershed protection, and enhancement of carbon sequestration and pooling need new systems and methods to be developed. Silvicultural applications or strategies to meet these objectives are discussed individually in Part IV.

Chapter 8

Silvicultural Methods for Wood Production

World-wide, the paradigm of forest management has shifted from a focus on sustainable wood production to emphasizing sustainable forest ecosystem management. Therefore, even for wood production, maintenance of, and harmonization with, other functions of the forest ecosystem must always be considered, both within each stand and across forest stands at a landscape scale. This shift requires that traditional silvicultural systems and methods for wood production be reconsidered, and become more ecologically sensitive. This Chapter reviews and discusses the silvicultural methods that have developed in Europe since the 19th century, the modifications of these methods that have been made in many parts of the world, and some of the methods characteristic of different countries or regions. Amongst these methods, there are silvicultural methods and techniques which are appropriate to, or may be adapted for, sustainable forest management.

The Chapter mostly covers silvicultural methods that were established or implemented in the temperate and boreal forest zones, as per the classification discussed in Chapter 7. This classification mostly includes silvicultural systems which originated in Europe, but in each method described in this chapter, various modifications and characteristic methods that have developed elsewhere are discussed.

Traditional silvicultural systems are classified mainly according to regeneration method. However, rotation period is an important factor influencing the conservation of soil and water resources, the conservation of biodiversity, and the maintenance of health and vitality of the forest ecosystem. Therefore, rotation period as well as regeneration method is emphasized in this book. The rotation period not only reflects the maturity of the ecosystem and its suitability for fulfilling other functions of the forest, but it also impacts on the conditions that develop for regeneration. Other activities, such as thinning regimes, also impact on the rotation period and the conditions that develop for regeneration.

Traditional silvicultural methods are frequently based on forest operations developed for the optimization of financial return, with little or no consideration given to the sustainability of the ecosystem. The forester, with his specialist knowledge, should be able to adopt the traditional silviculture to specific sites, species and to various social requirements; taking commercial and economic realities into account within the framework of sound ecological practice (Piussi and Farrel, 2000). In many cases, financial assistance may be required to implement ecosystem-based silviculture as part of the establishment of a sustainable society. Provision of such financial assistance is a social issue.

As noted in Chapter 1, alternative systems or concepts that enhance sustainable forest management such as new forestry and ecosystem management (Franklin, 1989; Swanson and Franklin, 1992; Franklin, 1997), diversity-oriented forest management (Fujimori, 1991a), nature-oriented silviculture and diversity-oriented silviculture (Lähde, 1992, 1993; Lähde et al., 1999), and sociological ecological silviculture (Benecke, 1996) have recently become of increasing interest. The Dauerwald concept advocated by Möller (1922) is the underlying concept to all of these alternative systems. Dauerwald means continuous cover forestry (Benecke, 1996) or permanent, perpetual, continuous, or sustainable forest cover (Schabel and Palmer, 1999). Silvicultural methods important to this system include selection methods which maintain a diverse-sized stand structure. This is one of the important options, especially in Europe or areas with similar conditions to those of Europe. Worldwide, however, more diverse silvicultural methods will be required for sustainable forest management.

The new systems require the appropriate use of methods such as single-tree selection, group selection, patch cutting, small-scale clearcutting, or combinations of these methods, depending on various natural and social factors such as the ecological traits of the primary species, site and economic conditions, and the technical capacity of foresters and workers. This Chapter discusses implementation of these types of silvicultural methods at a stand level, and implementation at a landscape level is discussed in Part IV.

The major objective of producing wood can be refined according to the type of wood produced: large (larger than about 40 cm DBH) and middle-size (about 20-40 cm DBH) logs used mainly for sawn timber; and small-size (less than about 20 cm DBH) logs or poles for uses such as fuel, pulp, and tools. Although the specific production objectives may change in time and in different areas of the world, these size-classes are likely to be typical.

In this book, a long rotation is regarded as at least 50-60 years, but may be longer than 70-80 years if this is the length of time required to achieve a bigger tree size. These rotation periods may differ between regions or countries. Ecologically, a long rotation is one in which final cutting is done in the mature stage (understorey reinitiation stage) of the stand (Section 2.4.4). A short rotation is one that is generally less than 40-50 years, or in which the final cutting is done during the young stage (stem exclusion stage). Very short rotations are between less than 10 and about 20 years long, and are generally for biomass production or fuelwood.

8.1 High-forest methods (Production of large or middle-size logs mainly for sawn timber; long rotation and short rotation)

8.1.1 Clearcutting method

8.1.1.1 Pure clearcutting method

In this method, all trees over a considerable area are cut at one time. An even-aged stand is established, usually by planting, or by natural seeding, or sometimes, by artificial seeding or a mixture of seeding, sprouting and/or planting. The simple coppice method could be defined as a clearcutting method, because all trees are cut and regenerated at one time. Historically, however, the coppice method has been distinguished from the clearcutting method because regeneration is from sprouting. Therefore, the coppice method is considered separately in the next section.

The clearcutting method (Figure 8-1) is simple and easy to implement, so has been widely used in most countries in the world. The clearcutting method is the most efficient for felling, extraction, and establishing a planned stand quickly. The quality of the trees (i.e., the bole length and stem taper) can be easily controlled by stand density management. Clearcutting can be the ecologically most appropriate silvicultural system in fire climax forests, such as *Eucalyptus regnans* (mountain ash) forests in southeastern Australia, as such forests depend on catastrophic fires to regenerate naturally and clearcutting most closely replicates the regeneration conditions created by fire (Attiwill, 1994; McCarthy et al., 1999).

Clearcutting, however, also has several drawbacks, particularly in

Figure 8-1 Clearcut area within a *Cryptomeria japonica* (sugi) plantation in Ibaraki Prefecture in central Japan.

terms of the production and social environments. Clearcutting is a major anthropogenic disturbance that can result in a decline in the hydrological and biochemical cycles in and around the forest ecosystem which take a long time to recover (Borman and Likens, 1979; Vitousek et al., 1979; Kobayashi, 1982; Nykvist and Rosén, 1985; Arimitsu, 1987; Hornbeck et al., 1987; Emmett et al., 1991; Larsen, 1995). The sudden exposure of the forest floor can destroy the structure of the surface soil through the impacts of direct rain drip, increased groundwater flows, direct sunlight, frost heaving, and direct winds. As a result, the water holding capacity declines and the capacity of the forest to control floods declines. Nutrients in the soil are generally lost as the rate of decomposition rapidly increases, leaching by ground water is increased, and nutrient cycling is disrupted by the destruction of microorganisms and a decline in mycorrhizae.

Planted stands generally contain trees that are uniform in size, and such stands are susceptible to wind storms or wet snow unless appropriate thinning is practiced (Fujimori, 1991a, 1995). The understorey of many planted stands is generally poorly developed during the young stage (stem exclusion stage) (Section 2.4.4, Figure 2-22), especially in evergreen coniferous stands of species such as firs, spruces, *Cryptomeria japonica* (sugi), and *Chamaecyparis obtusa* (hinoki), unless proper thinning is practiced. A lack of undergrowth in a stand can limit soil development and increase susceptibility to soil erosion (Section 11.3).

Another disadvantage of the clearcutting method is that there is generally a high labor requirement for weeding (Section 5.2), climber cutting, and cleaning in the herb/brush stage (stand initiation stage), which can make consistent management difficult, especially in regions where the summer is humid and labor costs are high. However, in regions with moderately dry summers such as southeastern Australia, natural regeneration following clearcutting is generally successful and weeding is seldom required (van der Meer et al., 1999; Ashton and Martin, 1996).

The suitability of the clearcutting method for sustainable forest management varies according to the rotation period and the area that is cut. Generally, long rotations are desirable because it becomes easier to combine wood production with other functions of forest ecosystem (Section 7.1.4, Figure 7-1 and Figure 7-2). Clearcutting over smaller areas is preferable for environmental reasons, including the conservation of soil. However, regeneration of shade intolerant *Quercus nuttallii* (nuttall oak) in the southeast bottomland hardwood forests in the United States of America requires that at least 1 ha is clearcut (Johnson and Krinard, 1989). Very shade intolerant species such as pine and birch may require a minimum area of about 1-2 ha to be cut. Therefore, clearcutting is necessary for the regeneration of shade intolerant species, but in these cases, the cutting area should be as small as possible to enhance other environmental values. In eucalypt forests in the fire climax areas of southeastern Australia, clearcutting is probably necessary, although there are a range of views on the appropriate size of cut areas (Attiwill, 1994; Lindenmayer, 1995; Lindenmayer and Franklin, 1997; McCarthy et al., 1999; van der Meer et al., 1999).

The rotation period of spruce plantations managed under a clearcutting system in Germany and Finland is generally 90-100 years (Iwai, 1992). The rotation period for *Pseudotsuga menziesii* (Douglas-fir) in Washington State, the United States of America is about 60 years (Oliver, 1992) (Figure 8-2). In Japan, the rotation period of *Cryptomeria japonica* (sugi) used to be about 60 years, then was shortened to about 40 years during the 1950s and 1960s when demand for wood was high, and is now being lengthened to 80 years or more to balance the costs and environmental benefits. In New Zealand, the rotation periods of *Pinus radiata* (radiata pine) are between 25-30 years, and trees are harvested when they are 40-60 cm in diameter. In Uruguay, *Pinus taeda* (loblolly pine) and *Pinus elliottii* (slash pine) stands grow to about 18 m in height and 30 cm in DBH in 13 years, and the rotation period is about 20-25 years (Fujimori, 1991b). These pine plantations with short rotations are typically monocultures, and are cut while still in the young stage. However, many of these plantations have been established on pastures or farmland, and can be considered to have enhanced these environments. Despite this, it may still be desirable to extend the rotation period in a proportion of the area to enable conservation of biodiversity.

Figure 8-2 *Pseudotsuga menziesii* (Douglas-fir) stand regenerated by planting after clearcutting, mixing with naturally regenerated saplings in Washington State in the United States of America.

The advantages and disadvantages of the clearcutting method need to be evaluated with respect to both ecological and economical aspects, including rotation period and the area of cutting.

a) Regeneration by planting

Coniferous species

After a stand is clearcut, the microclimate is often too harsh for seedlings of commercially valuable tree species. Those species which can grow in these conditions are usually suppressed by light-demanding fast growing species within a few years. The best method of regenerating these areas, therefore, is to plant nursery stock that can tolerate the environment and competition with other species. Nursery stock is raised in nursery beds where the environment is better than the field (Section 4.1), until they are sufficiently developed to resist the harsh conditions and are large enough to either survive the competition or be easily identified during weeding (Section 4.4). However, aerial seeding of *Pinus banksiana* (Jack pine) and *Pseudotsuga menziesii* (Douglas-fir), is done in North America (Cafferata, 1986).

The advantages of planting include the ability to select the best species or varieties, and precisely control the density and spacing (Sections 4.1 and 4.4). The spacing can be planned to allow the use of machinery. A stand regenerated by planting evenly quickly closes its canopy. After clearcutting, planting should be done as soon as possible (during the first suitable season following clearcutting) so that the planted trees can better compete with weeds or other woody plants.

In the Pacific Northwest of North America (including Oregon and Washington, the United States of America and British Colombia, Canada), coniferous forests composed of such species as *Pseudotsuga menziesii* and *Tsuga heterophylla* (western hemlock) are widespread. As *Pseudotsuga menziesii* is a shade intolerant species, the forests are usually clearcut (Figure 8-2). In Oregon and Washington, natural regeneration was initially the only method used, and its success was variable. Attempts to achieve more successful natural regeneration were made by using seed tree methods, alternative cutting patterns, and varying the timing of harvesting. Later, direct seeding became the main method of regeneration, and the helicopter became routinely used for this purpose. Hand planting of seedlings gradually replaced direct seeding, because the regeneration was more predictable and more rapid. Today, all methods are used in various combinations, but hand planting is the most common technique for *Pseudotsuga menziesii* stand establishment (Cafferata, 1986).

The typical planting stock for *Pseudotsuga menziesii* regeneration in Washington and Oregon is barerooted 2+0 seedlings (Section 4.1.4). The seedlings are typically planted at densities between 250 and 1500 trees/ha. The lower stocking rates are used if the stand will not be able to be thinned, and the higher rates if stands can be thinned (Cafferata, 1986). Thinning usually occurs when the stands are 20- to 30-years-old, and pruning at this stage is recommended. If both thinning and pruning occur at this stage, high quality timber can be produced by age 60 (Oliver, 1992). In Oregon and Washington, dispersed clearcutting has been widespread, but it has been pointed out that the resulting patch mosaic produces environmental conditions unfavorable for the species with strong interior-forest microclimatic requirements (Swanson and Franklin, 1992). This is discussed further in Chapter 10.

A typical long-rotation silvicultural method used in Japan was illustrated in Figure 7-1. As of 1995, 41% of forests in Japan was plantation, of which 98% is coniferous. More than 70% of the coniferous plantations is composed of *Cryptomeria japonica* (sugi) and *Chamaecyparis obtusa* (hinoki) (Forestry Agency of Japan, 1997). Plantation management techniques have been developing for about 300-400 years (Yamauchi and Yanagisawa, 1973a, 1973b) and the clearcutting method has been the most common. The most common silvicultural method used for *Cryptomeria japonica* following World War II was to plant about 3000 trees per ha, weed 5-10 times until 5-8 years after planting, and cut climbers about twice following weeding. Precommercial thinning occurred about 15 years after planting (several years after canopy closure, retaining between 1300 and 1800 trees per ha). A commercial thinning was conducted at about age 30 years and, the final cutting occurred at age 40-50 years (Japan Forest Technology Association, 1975). Prior to World War II, the rotation length was more variable and the average rotation was longer, around 60 years. Recently, the average rotation length has begun to increase and this trend is expected to continue for sustainable forest management. Tending has also become more intensive. Pruning began to be used in the 1970s. Commonly, pruning is conducted at least twice to produce a 3 m log for boxed-heart timber (Section 6.1.5). Figure 8-3 shows a typical tending regime for early management of a *Cryptomeria japonica* (sugi) plantation. At the time of the commercial thinning, one length of boxed-heart timber can be harvested from each tree, and by the final harvest, two boxed-heart timber lengths are harvested.

An important consequence of this approach to tending is that most of the standing trees have commercial value when their diameter reaches about 21-22 cm. If the stems are straight with no defects, they have commercial value for boxed-heart-timber. From a single tree of this size, two lengths of boxed-heart timber of the standard size (10.5 cm × 10.5 cm ×

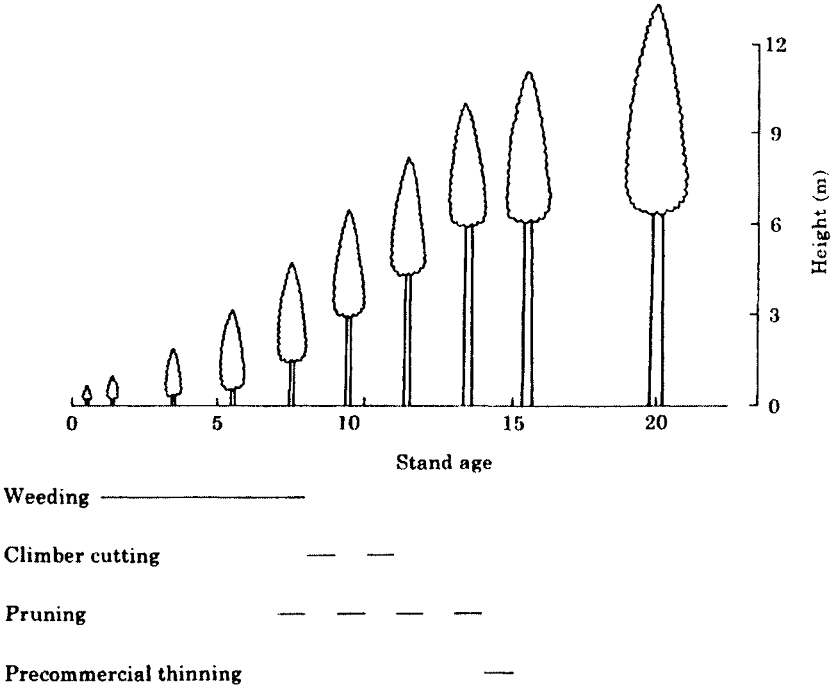

Figure 8-3 A common tending regime for the early stage of a *Cryptomeria japonica* (sugi) plantation. Up to about age 15 years, a clear bole to a specified height is obtained by maintaining a high stand density and pruning. Aggressive thinnings then occur, retaining promising trees which further develop their crowns so that they can produce high quality timber earlier and develop resistance to windthrow and crown snow damage.

3 m) can be produced. The average stand density at the time of thinning is about 1300, so about half of the trees planted are commercially valuable.

Another feature of this tending regime is that there is a high proportion of commercially valuable trees at the first commercial thinning. At this time, a single standard size of boxed-heart timber is produced from each tree. The average diameter of each tree is about 17 cm and there are about 1800 stems per ha. Such intensive management aims to maximize the number of trees which are commercially valuable, unlike more standard methods which produce more variable trees.

These intensive management techniques require a high level of weeding, and there is a lot of debate within Japan on how this might be reduced. One suggested strategy is to extend the rotation length as far as possible and convert from a clearcutting system to a selection system or other non-clearcutting system (Section 5.2.3). This could enhance the cost-benefit ratios as the costs of site preparation, planting and weeding would be offset by improvements in the value of the wood and the ability to meet other objectives of sustainable forest management, including the conservation of biodiversity and soil and water resources.

Extended rotations would require modifications to the tending regime. A possible regime for a species such as *Cryptomeria japonica* could be as follows (*Chamaecypsris obtusa* would be similar, although the rotation and thinning intervals may be longer). Pruning would continue to be conducted to meet timber quality requirements. More thinnings would need to be conducted, and the thinning ratios adjusted to suit the preferred rotation period. Up to 4 or 5 thinnings might be conducted. The first would be a precommercial thinning some years after canopy closure, in which about 35% of trees would be removed. A second thinning removing a further 35% of trees would be conducted when the average tree diameter is about 17 cm and one length of boxed-heart timber can be harvested. The third thinning removing a further 35% would be conducted when the diameter is about 22 cm and two lengths of boxed-heart timber can be harvested from each tree. Traditionally, this would have been about the time of final harvest. After the third thinning, the stocking would be about 750 stems per ha. About 15 years later, a fourth thinning could be conducted, when the bottom log has a small-end diameter of more than 28 cm. Further thinnings could then be conducted at intervals of 15-20 years, with a removal ratio of 20-30%, until final harvest at about 150 years. A management model show in Figure 7-1 is similar to this tending regime.

The combination of thinning and pruning in the young (stem exclusion) stage can contribute to improved light conditions on the forest floor, which enables undergrowth to survive or invade (Fujimori and Kiyono, 1983). In the later part of the rotation (for example, after 100 years), shifting to non-clearcutting methods such as the selection method, group-selection method, or strip-selection method could be considered.

As sustainable forest management is implemented, more aggressive thinnings may be required to induce greater crown development in the crop trees, and so increase the resistance of monoculture coniferous plantations to strong wind (Fujimori, 1995). After a certain length of branch-free stem is obtained in the early young stage by means of stand density effect and/or pruning, crowns of individual crop trees should be developed by maintaining a crown ratio of about 60% in consideration with a report by Burschel and Huss (1987) cited in Benecke (1996). Figure 8-4 is an example of 70-year-old *Chamaecyparis obtusa* (hinoki) plantation where aggressive thinnings were repeated once a certain length of branch-free stem is obtained. These management enhancements not only increase the resistance to wind damage but also produce high quality large diameter timber with uniform annual rings. It also enhances conservation of biodiversity and conservation of soil and water resources by enabling the development of various strata of hardwood species and herbs. This type of stand structure may be ideal for sustainable forest management.

An alternative strategy to help overcome the intense weed control requirements is to use an extensive establishment method. In this approach, about 1000-2000 stems per ha are planted, with the objective of producing at least 400 trees with a diameter of at least 40 cm at the time of

Figure 8-4 A 70-year-old *Chamaecyparis obtusa* (hinoki) plantation showing crop trees with diameters of 50-70 cm. The crowns of these trees were released to give additional growing space once branch-free stem had developed as a result of stand density management and pruning during the early young stage.

harvest. Under this regime, a large proportion of the planted trees is expected to be eliminated or degraded by interspecific competition. If any commercially valuable hardwood species regenerated naturally amongst the planted trees, they would be retained, and the number of planted trees that are harvested might be reduced, depending on the proportion of hardwood species which can be harvested. This greatly reduces the cost of weeding and climber cutting. If the naturally regenerated hardwood species are not commercially valuable and there are sufficient healthy planted trees, the hardwood species might still be retained because of their contribution to the stand's biodiversity and soil condition.

This approach is already used in parts of Japan. In the broad-leaved deciduous forest zone, valuable species such as *Quercus crispula* (mizunara) and *Magnolia obovata* (honoki) often grow amongst planted *Cryptomeria japonica* or *Chamaecyparis obtusa* (Figure 8-5). When this occurs, a single pruning to the height of one log length is conducted on selected planted trees and sometimes on invading trees. The pruning is conducted in such a way that the growth of the selected trees is not reduced. The first thinning at about 15 years is designed to optimize the

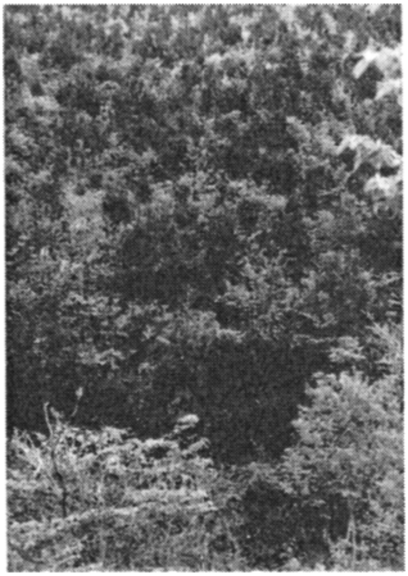

Figure 8-5 A mixed stand of planted *Cryptomeria japonica* (sugi) and naturally regenerated hardwood species in Iwate Prefecture in northeast Japan. Weeding stopped a few years after the *Cryptomeria japonica* was planted to allow to growth of commercially valuable hardwood species such as *Quercus crispula* (mizunara).

proportion of each species in the stand and to ensure that the retained crop trees are evenly distributed and have sufficient growing space. Trees which affect the growth of the selected trees are then removed. At the time of second thinning (about 15 years later), dominant trees which are not crop trees are removed, as long as a large gap is not created. Thinned trees often have commercial value. Intermediate and suppressed, or some codominant trees, are left to prevent epicormic buds developing on the selected trees or a rapid change in the forest ecosystem.

Hardwood species

Plantations of hardwood species are not as common as those of softwood species, although plantations of fast growing hardwood species such as *Eucalyptus* are found in many areas in the tropics, the sub-tropics and areas with Mediterranean climates. In general, because broad-leaved species tend to have a decurrent form (Section 2.3.2), plantations are established at a high density to ensure the development of a straight clear bole. In Denmark, beech was planted at densities as high as 40,000 trees per ha, and frequent thinnings produced straight boles and beautiful forests (Kondo, 1951), but it is uncertain if such intensive management is still undertaken. Regeneration of hardwoods usually relies on natural seeding because a very dense occurrence of seedlings can be expected. Some of the finest young stands of beech in the Austrian mountains were established on clearcut areas (Wessely, 1853; cited in Matthews, 1989), and the fine mature beech in the Forêt de Soignes near Brussels in Belgium was also established following clearcutting (Anderson, 1949).

In Japan, plantations of hardwood species are found in many places, but they tend to be small in area and many of them have not been systematically managed. The species most commonly planted is *Zelkova serrata* (keyaki) (Figure 8-6), the timber of which is highly valued in Japan. *Zelkova serrata* is a moderately shade-intolerant species which requires rich soil. Most plantations have not been very successful because of inadequate silviculture, particularly thinning. More recent studies on *Zelkova serrata* have provided better information and better silvicultural methods are developing (Maeda et al., 1989; Tanimoto, 1990; Fujimori, 1991a; Arioka, 1994).

The most common silvicultural regime for producing high quality *Zelkova serrata* is to plant at a high density (over 5000 trees per ha), conduct a low intensity thinning to remove poorly formed dominant trees, then thin heavily once the crown is above 5-6 m. Several thinnings may be conducted, but with a single heavy thinning, at least two logs of 2.1 m length (the standard length of hardwood logs in Japan) can be harvested from about 200 trees per ha. If thinning is delayed until the crown is higher, the crown might not be able to recover even if a large growing space is released by thinning (Yokoi, 1997). There is also a risk of epicormic buds

Figure 8-6 A 70-year-old *Zelkova serrata* (keyaki) plantation in Shimane Prefecture in western Japan (Photograph by T. Arioka).

developing. Pruning of crop trees may be conducted while the stand is still young, but less than 25% of the crown should be removed so that growth of these trees is not slowed. Wolf trees which significantly affect the growth of crop trees may also be roughly pruned. Competition control in *Zelkova serrata* plantations is also important, and weed and climber control is carried out the same way as in conifers, although care has to be taken that the competition, not the planted trees, are controlled.

As an alternative to intensive plantation management, more extensive silvicultural methods could be used. One option would be to plant several hundred *Zelkova serrata* per ha, in a mix with other broad-leaved trees regenerated by natural seeding or sprouting. Any trees suppressing the *Zelkova serrata* would be removed, but the rest would be retained to help control branching. This would avoid the need to prune the *Zelkova serrata* trees.

b) Regeneration by natural seeding

Regeneration by natural seeding in clearcut areas is used for light-demanding pioneer species such as pines and birches. A well-known example of natural regeneration following clearcutting is the *Pinus pinaster* (maritime pine) forests of the coastal dunes of Landes in southwestern France. Large areas of 80 to 100 ha are clearcut, and there is abundant natural regeneration from seed, some of which is already on the ground, but much of which is released from the cones of felled trees in April or May. Natural regeneration is successful because the pine has an abundant annual seed crop, the loose sandy soil favors seedling establishment, and clearcutting provides the full exposure to light required by this species for regeneration. Following harvesting, the residual branches are spread evenly over the site to distribute the cones and seed and achieve an even stocking of the area. After 4 years, weeding is conducted, reducing the stocking to about 10,000 plants per hectare or a spacing of about one meter square (Lanier, 1986; cited in Matthews, 1989). Although the ecological basis for the size of the clearcutting area used for *Pinus pinaster* in southern France is uncertain, a minimum area may be required on such sites. The most suitable size will depend on the site characteristics and species requirements.

In the Pacific Northwest coast region of North America, clearcut areas of *Pseudotsuga menziesii* (Douglas-fir) and other coniferous species can be regenerated by planting or naturally, from seeds blown in from areas surrounding forests (Figure 8-7). Dry summers give regenerating conifers an advantage because competitive weeds and shrubs are eliminated by the dry conditions

Site preparation by scarification (Section 4.3.2) can be important for successful regeneration. Scarification is usually done by raking the litter

Figure 8-7 Natural regeneration of *Pseudotsuga mensiesii* (Douglas-fir) with retained snags and fallen logs in Washington State, the United States of America (Photograph by J. F. Franklin).

away in strips, which results in alternate strips of litter and scarified soil. The spacing of naturally regenerated trees is generally denser but more variable than that of planted trees, and early stand density control is usually dependent on self-thinning.

8.1.1.2 Strip-clearcutting method

Strip clearcutting method or seed-tree methods have been used in many parts of the world. The area of the clearcut must be smaller than the distance within which seed can be disseminated from the seed trees or surrounding forest. Harvesting should occur following seed dispersal in a mast year.

Strip-clearcutting is often used to naturally regenerate light-demanding species. In the alternate-strip method, the stand is clearcut in two stages (Smith, 1986; Matthews, 1989) (Figure 8-8). This method is often used to regenerate species such as pines or birch. The strips cleared during the first cutting are regenerated from seeds originating from the retained strips. When these seedlings are established, the retained strips are cut. The strips cut in the second harvest are regenerated from their own seeds or, if this is unsuccessful, by artificial regeneration.

Strip-clearcutting with three or more strips at different stages is called the progressive-strip method (Smith, 1986). If the number and stages of strips increases and the width of the strip decreases, the progressive-strip method becomes similar to the strip-selection method. If shade effects are expected in the strip-clearcutting methods because the strips are narrow

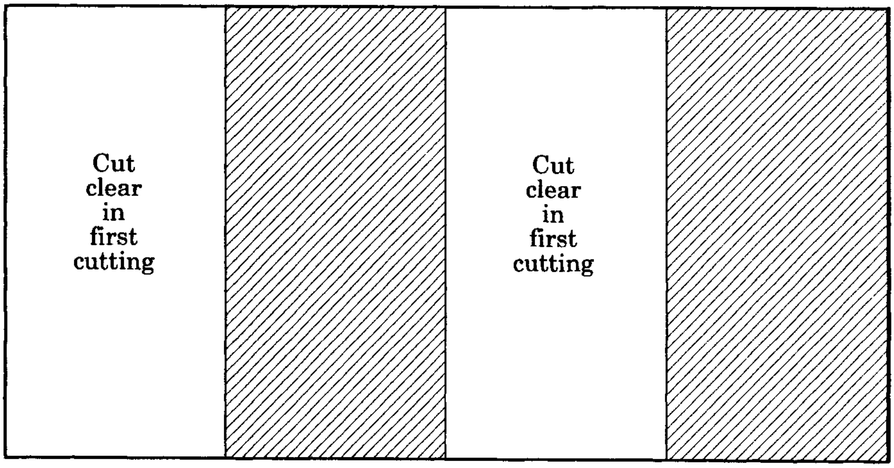

Figure 8-8 The alternate-strip method. (Smith, 1986)

(i.e., about 20-30 m), it is no longer a strip-clearcutting method, but should be referred to as one of the non-clearcutting methods.

In Europe, strip clearcutting followed by natural regeneration from adjoining stands or belts is widely used for *Pinus sylvestris* (Scots pine), and has been applied to other conifers including *Pinus nigra* (Austrian pine) (Matthews, 1989).

For these methods, the optimum width of the strip is determined by the effective dispersal distance of the seed and the light conditions required by the species for good growth. Orientation of the strips should take into consideration the sun-angle and, if seeds are dispersed by wind, the direction of the prevailing winds. Preferably, strips should be aligned at right angles to the winds and sun, but this is not always feasible, especially on mountainous slopes. Therefore, the width and orientation of the strips should be adjusted to suit the conditions. For the very shade intolerant species *Pinus densiflora* (akamatsu) in Japan, the average width of strips is 3-5 times the height of the trees in the retained strips, or 2-3 times tree height if the retained strip is only on one side (Uesugi, 1953; Sato, 1962; Kato, 1971, 1975; Aomori Regional Forestry Office, 1974). For birch, which is also very shade intolerant, the strips are generally about 70-100 m wide (Nakano, M., 1971). The top height of birch stands is about 20-25 m, so this equates to a strip width of about 3-5 times the height of the retained trees.

8.1.1.3 Seed-tree method

In this method most of the trees in a stand are removed in a single harvest, leaving a small number of seed trees. Once the new generation is established, the seed trees are removed. The seed-tree method is similar to the shelterwood method, but because the microclimate of the regenerating stand is more like that of a clearcut stand, it is usually regarded as a kind of clearcutting method. The seed trees are generally isolated and evenly distributed.

One of the important considerations of this method is to decide the number of the seed trees to be retained. This mainly depends on the level of seed production, the dispersal distance of the seed and the light conditions required by the regenerating seedlings. Superior trees should be selected as seed trees, in the hope that some of their superiority is genetic in origin. On some sites, the wood quality of retained seed trees may degrade as a result of their exposure to winds or other meteorological events. It is therefore desirable to minimize the number of seed trees and thereby initially harvest a larger number of good quality trees. However, if there are fewer seed trees, the damage to the retained trees may increase. The susceptibility of the seed trees to exposure might be able to be reduced if appropriate thinnings are conducted throughout the growing phases of the stand.

In *Pinus densiflora*, the optimal number of seed trees is about 20-40 per ha, although this is partly dependent on tree height (Kato, 1975). If the seed trees are about 20 m tall and the number of seed trees exceeds 40, the growth of the regenerated trees is reduced (Uesugi, 1953).

The seed-tree method was attempted for beech (*Fagus crenata*) on harsh mountainous sites in Japan. However, it was not successful for a number of reasons. Beech is a shade-tolerant species, with relatively slow growth. The sudden exposure of seed trees to wind, heat and sunlight resulted in serious degradation of the wood quality and a reduction in seed production. Considerable weeding was required, both because of the relatively slow growth of beech seedlings, and because if harvesting did not occur in a mast year, then there was a greater presence of weeds. A more appropriate silvicultural method for beech is the shelterwood method or some modification of it (Kataoka, 1982).

8.1.2 Non-clearcutting methods

8.1.2.1 Shelterwood methods

The shelterwood method is often regarded as a clearcutting method, because all the trees of the overstorey are cut within a relatively short period. However, this definition only considers the overstorey, and does not consider the understorey or impacts on the soil. In shelterwood methods, the soil is not fully exposed and disturbance is minimized. Although limited scarification may be used to improve regeneration, the soil continues to be protected by the retained overstorey and regenerated seedlings and saplings. Therefore, the shelterwood method should be classified as a non-clearcutting method.

Shelterwood methods were developed in Germany and elsewhere in Europe during the 19th century (Nakamura, 1956). Shelterwood methods are characterized by the staged removal of the old trees in two or more harvests. The retained trees provide a source of seed and/or protection for the regeneration. The harvests are usually done in a sequence of preparatory cutting, seeding cutting (establishment cutting) and removal cuttings (secondary cuttings) (Ford-Robertson, 1971; Smith, 1986; Matthews, 1989). The preparatory cutting may not be essential if thinnings have been conducted, and the removal cutting can be conducted several times in which case the last removal cutting is called the final cutting. In some parts of the world, where adequate advanced growth is already present, the old trees may be removed in a single cut; in Malaysia this is termed the Malayan Uniform system, and in North America it is called the one-cut shelterwood method (Ford-Robertson, 1971). The cuttings usually resemble a heavy thinning, and, under intensive practice, regeneration by the shelterwood method logically follows a series of thinnings (Smith, 1986). As the intermediate operations enhance the conditions for regeneration, the intermediate operations and regeneration operations can be regarded as a continuous series of forest management operations (Fujimori, 1991a; Clatterbuck and Meadows, 1993; Meadows and Stanturf, 1997). This concept is important for silvicultural strategies for sustainable forest management.

The objective of preparatory cutting is to promote crown development, seed production and more rapid decomposition of humus layers which are unfavorable for the regenerating seedlings. However, if adequate thinning has been practiced, the dominant trees will be vigorous enough to produce the seed required and decomposition of humus layers will be accelerated. Buffet (1980, 1981; cited in Matthews 1989) pointed out that crown development is not achieved if the cutting is done a short time before the seeding cutting (establishment cutting). Crown development is promoted if cutting is done throughout the greater part of the life of the crop from the small pole stage onwards. In France, the 'coupe preparatorire' is now understood to mean the last thinning done before the seeding cutting (Matthews, 1989).

Seeding cutting (establishment cutting) opens up the canopy to provide sufficient light for seedlings to germinate, survive and grow adequately in the understorey. It is best done during mast years (good seed years) of the desired species; otherwise, it will enhance the growth of competing vegetation rather than the desired species. At the same time as the seeding cutting, the competing undergrowth may need to be controlled and the soil scarified to improve the environment so that the seedlings can grow well.

The removal cuttings should be timed to suit the growing space requirements of the seedlings. As seedlings grow, they require more light to maintain their growth. If the overwood is retained for too long, the light reaching the seedlings will gradually decrease as the crowns of the retained overstorey expand. If the final cutting is conducted when the seedlings are still small and not very dense, the seedlings will tend to be suppressed by the competing vegetation. On the other hand, if the seedlings or saplings become too large, they are prone to be injured when the overstorey is harvested.

An important objective of the shelterwood method is to enhance the growth of the high value trees of the overstorey during the regeneration period. Vigorous and better-formed individuals are therefore usually retained until the final cutting. However, continued intermediate cuttings (thinnings) are important for development of the crowns of the regenerating crop, because if the crowns develop a poor shape they cannot recover. If an appropriate series of thinnings is undertaken, a seeding cutting may not be necessary for successful regeneration, and instead, the removal of competing vegetation and/or removal of suppressed and intermediate trees might be all that is required (Buffet, 1980, 1981; cited in Matthews 1989; Fujimori, 1991a; Meadows and Stanturf, 1997).

In general, shelterwood methods depend on natural regeneration (Matthews, 1989). In Japan, however, the natural regeneration is not always sufficient because of the persistence of the competing vegetation. This is especially true of coniferous species, and in these cases, artificial regeneration by planting is often used.

8.1.2.1-1 Uniform method

The term uniform method (system) is an abbreviation of 'shelterwood uniform system' (Matthews, 1989). In the uniform method, old trees and regenerated trees are evenly distributed within a stand.

a) Hardwood stand

Regeneration by natural seeding

The regeneration of oak and beech in Europe provide a good example of this method (Matthews, 1989). In a stand's early stages, from 3 to 10 m top height, improvement cutting is practiced. In this operation, competitive unwanted species and dominant, poorly formed trees of the desired species are removed. The improvement cuttings are kept to a minimum in order to maintain as dense a stand as possible to control side branches and encourage the development of clean stems.

Periodic thinnings to remove poorer stems and favor the better trees begin when the crop reaches top heights of 10 to 14 m for beech and 10 to 16 m for oak. Crop trees are selected when the whole crop has reached a top height of 15 m for beech and 18 m for oak. The thinnings aim to stimulate crown development so as to maintain diameter growth and encourage seed production. However, it is equally important the canopy should remain continuous at this stage, as permanent breaks in the canopy are likely to result in strong growth of undergrowth which may prevent natural regeneration of desired species when it is wanted.

As the crop approaches the age at which it will be felled and regenerated, it should consist of trees with long, straight stems free from branches and with well developed crowns forming a complete canopy and capable of producing abundant seed. Trees with good crowns will have correspondingly well-developed root systems, so that when the crop is opened out they should be reasonably wind-firm.

When it is time to initiate regeneration, a series of seeding and secondary cuttings (removal cuttings) is made. This may include the final cutting. In the case of oaks, about one-third of the crop is removed in the seeding cutting, leaving about 75 to 120 seed trees per ha, according to age and size, and there is a space of several meters between crowns. The stems are on average 10 m apart. The general objective is to create environmental conditions on the forest floor that are optimal for the regeneration and establishment of the desired species, and which do not favor competing species. All undergrowth and low cover should be removed. In France, seeding cuttings are generally made irrespective of mast years. When a good mast year occurs, the ground is thickly carpeted with seedlings and secondary cuttings follow rapidly. Generally speaking there are two secondary cuttings, including the final cutting, but under favorable conditions a single final cutting is done. In the case of beech, generally more than one seeding cutting is needed for complete regeneration. The seeding cutting is lighter than in oak, and the canopy is opened only to the extent that the crowns touch when swayed by the wind. In the beech forests of France, between 25 - 35% of the crop is removed, leaving about 170 stems per ha under average conditions. Any undergrowth and suppressed trees are removed. The secondary cuttings begin when the regenerating crop is about knee-high (6 to 8 years old) and are continuous and gradual. Under the most favorable conditions there are generally at least three secondary cuttings, including the final cutting.

It requires considerable knowledge and experience to determine the appropriate intensity of the seeding cutting (and secondary cutting). Seeding cutting affects the growth of seedlings by improving illumination and available water (Madsen and Larsen, 1997; Löf et al., 1998). However, the relationship between these factors and the growth of the seedlings of the desired species and competing vegetation is complex. If cutting is too heavy, competing light-demanding vegetation will grow well and suppress the seedlings of the crop species, but if it is too light, there may not be sufficient improvement in light conditions or available water. Thus, the optimum intensity must be determined for each stand composition and site condition on the basis of much information and experience. In spite of this, the shelterwood method is easier to apply in Europe, because of the relatively low number of plant species and vegetation cover on the forest floor compared to many other areas in the world.

Applying the shelterwood method in regions with a high number of plant species and well-developed understories is not straightforward and requires modification of the classical method. One area where a modified shelterwood method has been applied is the southern bottomland hardwood forests of Virginia to east Texas in the United States of America (McKnight and Johnson, 1980; cited in Meadows and Stanturf, 1997). These forests occur over about 13 million hectares, in river bottoms, minor stream bottoms and swamps (Figure 8-20). The shelterwood method is suitable for the heavy-seeded species such as oaks and hickories, but also promotes excellent seed dispersal and establishment of light-seeded species. The most valuable species in the southern bottomland hardwood forests for the production of timber are the oak species. The shelterwood method has been used to successfully regenerate oak in the southern Appalachian

Mountains in the United States of America (Loftis, 1990), but the success of this method has been variable for southern bottomland oak species. This could be attributed to the climatic conditions and vegetation structure of the southern Appalachian Mountains, which are more similar to that of Europe than to that of the southern bottomland hardwood forest zone.

One of the keys to successful use of the shelterwood method to regenerate oak in southern bottomland hardwood forests is the intensity of the seeding cutting (establishment cutting). Hodges (1989; cited in Meadows and Stanturf, 1997) concluded that heavy establishment cuts favor the development of fast-growing, shade-intolerant species rather than oaks, whereas light cuts encourage the development of less-desirable, shade tolerant species commonly present in the midstorey and understorey of mature bottomland hardwood stands. Designing the intensity of the seeding cutting to favor oaks rather than either of the other two groups of species is a difficult task. More research is needed to adequately define the optimum residual density necessary to successfully regenerate bottomland oak species through the shelterwood method.

Several variations and modifications of the classical shelterwood method have been attempted in southern bottomland hardwood stands, with mixed success. One essential modification is to control the midstorey and understorey at the time when the overstorey is partially removed (Hodges and Janzen, 1987; Janzen and Hodges, 1987, cited in Meadows and Stanturf, 1997). Most southern bottomland hardwood stands have dense, well-developed midstories and understories of shade-tolerant species, and cutting just the overstorey is insufficient to provide enough sunlight to the forest floor to promote to development of an adequate crop of advanced regeneration oak prior to final harvest.

The natural condition of the southern bottomland hardwood forests in the United States of America is similar to that of hardwood forests in Japan. In the Japanese forests there is also an abundance of plant species and a dense understorey of non-crop species in stands at the mature stage (understorey reinitiation stage) or whose canopy has been partially opened by thinning or regeneration cutting. The shelterwood method was introduced to Japan from Europe in the early part of the 20th century, but was not successful because the climate and resultant vegetation structure is very different from that of Europe. Following much research (Kondo, 1951; Abe, 1963; Imada, 1972; Kataoka, 1982, 1989, 1991a, 1991b; Nakashizuka, 1991; Hongo and Kataoka, 1987; Maeda, 1988; Tanimoto, 1990; Fujimori, 1991a; Sakurai, 1994), a modified shelterwood method has been recently developed for oak (*Quercus crispula*, mizunara) and beech (*Fagus crenata*, buna).

As both oak and beech are decurrent species (Section 2.3.2), a high stand density must be maintained during the young stage to develop a single, clear trunk. At the same time, promising trees must have sufficient growing space to promote their growth. To balance these requirements, the stand should be thinned when the lower branches of the dominant trees are dead up to a specified height, usually about 5-6 m (Yokoi, 1997). This will allow at least two standard length logs (2.1 m) to be harvested from the trunk beneath the crown. The time taken until the base of the crown reaches 5-6 m depends on the species, soil conditions, and stand density. Generally, it is around 30 years after regeneration. Before that, improvement cutting may be required if unwanted species are affecting the desired species, but the intensity of cutting must be light enough to maintain a sufficient density to control branch development.

Trees usually have a commercial value when their diameter (DBH) is over 30 cm, so the intensity of the thinning should be such that the retained trees will have sufficient growing space to reach 30 cm in diameter. The required growing space is determined by the crown diameter, and generally equates to about 200 stems per ha for beech (Fujimori, 1991a) and about 180 for oak (Sakurai, 1994). Retained trees should be distributed evenly, and can then be progressively harvested in thinnings, until the final cutting. Some trees may be retained until their diameter is 60 cm, and these should be selected in the same way. In beech, about 80 stems per ha can reach 60 cm DBH, and slightly fewer in oak. These estimates are based on the relationship between stem diameter to be harvested and crown diameter necessary for the trees to grow to that stem diameter. Data to develop this type of relationship should always be collected from stands where adequate thinning has been practiced.

If improvement cutting is required before thinning when the bottom of the crown reaches 5-6 m, it should be aimed at removing particularly poorly shaped but dominant trees. Both the early thinning and the one done when the crown bottom is at 5-6 m are precommercial thinnings, but they are essential for the production of high quality timber. At each thinning, appropriate space must be provided to each retained tree for it to continue to grow. A continued series of thinnings not only enables the stand to advance through its stages of development, but also provides appropriate light conditions for regeneration to develop.

Thinnings enable increased light to reach the forest floor, resulting in the appearance of abundant seedlings, usually in the spring following a mast year, even if no site preparation is conducted. Most of these seedlings will die by the following winter because of desiccation during summer as a result of their roots being restricted to the humus layer which can dry out in summer, or from shading by competing undergrowth. If regeneration by natural seeding is planned, the undergrowth must be removed and the ground scarified in or prior to a mast year. On steep slopes, however, scarification should be done carefully because of the risk of surface soil erosion and the loss of seeds in the runoff. If the stand is in the mature stage and has been adequately thinned, such site preparation avoids the need for either preparatory cuttings or seeding cutting. This method is termed the one-cut shelterwood method (Ford-Robertson, 1971) or the method of preregeneration by land preparation prior to clearcutting (Kataoka, 1982). Although preparatory and seeding cuttings are not necessary, the control of undergrowth that competes with the seedlings is critical to regeneration. Removal of suppressed trees and the midstorey is also required to enhance the growth of the seedlings.

Most thinnings are from above, and suppressed and intermediate trees are left as trainers for the crop trees to prevent them producing epicormic shoots. In regeneration cuttings, however, the trainers can be removed. Oak tends to produce epicormic shoots, but if the crowns of the selected trees are well developed, epicormic shoots should not be produced, even when the trainers are removed.

The final cut of the retained trees should be timed for when the regenerating seedlings are ready to be released. This is difficult to judge, as it is related to the density of the seedlings, the size of the competing plants, and the light conditions controlling the growth of the seedlings. The appropriate size for the release of seedlings differs between species; for example, oak should be released when it reaches 20-30 cm (Sakurai, 1994), beech at 70 cm (Kataoka, 1982) or 1.3 m (Tanimoto, 1990) in Japan.

As with all regeneration methods, successful implementation of the shelterwood method can be enhanced by carefully planned manipulations in the stand prior to the regeneration stage. Thinning or other partial cuttings can be designed to not only favor residual trees, but also to create and maintain conditions on the forest floor that are favorable for the germination, establishment and continued development of the desired species and which do not favor unwanted species. Thinnings can also be designed to control species composition in such a way that seed sources of less desirable species are reduced. In this way, thinnings performed late in the rotation can be used to prepare a stand for regeneration and can make a separate preparatory cutting unnecessary (Meadows and Stanturf, 1997).

Regeneration by planting

It has been persistently believed that the best regeneration method for hardwood high forests such as oak and beech is natural seeding. However, if regeneration is not successful, planting is necessary. Regeneration by planting has the advantage that it is assured and rapid, weeding and browsing damage can be reduced and the regeneration period shortened. In Japan, these advantages have been obtained by using large planting stock, as high as 1.5 m, as proposed by Kataoka (1991b).

b) Coniferous stand

Regeneration by natural seeding

In Europe, *Pinus sylvestris* (Scots pine), *Picea abies* (Norway spruce), and *Abies alba* (European silver fir) are often regenerated using the shelterwood uniform method (Matthews, 1989). *Pinus sylvestris* requires strong light for regeneration and has a winged seed that is dispersed in quantity by the wind to a distance equivalent to twice the parent tree's height. *Pinus sylvestris* is well adapted to the uniform method, provided regular thinnings are conducted at intervals of not more than 5 years, so that the crowns and roots of retained trees are well developed. Without regular thinnings, trees retained following the seeding cutting are prone to windthrow. Application of the uniform method is simple. At the seeding cutting, seed trees are retained at a wide spacing, and the final cutting should follow within a few years, when the young crop is not more than 30 cm high, presumably because it is a light demanding species. Pictures of this method (e.g., Matthews, 1989) suggest that the retained trees are so sparse that this method could be considered a seed tree method. Regeneration is greatly stimulated if the layer of needles on the forest floor is removed and the mineral soil exposed.

Picea abies (Norway spruce) is moderately shade-tolerant, and has a light, winged seed that can be dispersed a considerable distance from the parent tree by the wind. It is a shallow rooting species, so the uniform method is unsuitable in localities subject to gales, because of its instability. Climatic conditions should therefore be considered before the uniform method is applied to *Picea abies*. The seeding cutting should be done in a good seed year and applied cautiously to avoid isolating trees and exposing them to wind damage. At the same time, sufficient cutting (about 25 - 30% removal) needs to be done to provide enough light to promote regeneration. The final cutting should be done within 4 to 5 years, with or without an intervening secondary cutting, and gaps should be filled by planting. The difficulties of applying the uniform method to *Picea abies* also apply to many other coniferous species such as spruce, *Tsuga* and *Cryptomeria*, because their rooting systems are also shallow and tree form generally thin. In these cases, a series of appropriate thinnings to enhance crown development is essential.

Abies alba (European silver fir) is strongly shade intolerant and has a heavy winged seed that is dispersed by the wind only as far as the parent tree's height. *Abies alba* is well adapted to the uniform method. There are often large numbers of seedlings on the forest floor before any seeding cutting is done and secondary cuttings can begin immediately. If a seeding cutting is conducted, any understorey should be removed. Secondary cuttings should be done cautiously and several times over a number of years to provide protection to the regenerating crop until it is well-established.

The shelterwood method based on natural seeding is not commonly applied to coniferous stands in Japan. Natural seeding generally requires sophisticated techniques and careful management, especially to control competing undergrowth. In Japan, planting is generally used because it is reliable and quick. Natural regeneration by seeding is more commonly applied to hardwood species to achieve the initial high densities required to produce straight stems with sufficiently high crowns. This is not required in coniferous stands, because most conifers have a straight growth habit, with a slender crown in a range of stand densities (Sections 2.1.1 and 2.3.2). Despite this, there are some examples of successful regeneration by natural seeding using a shelterwood method in *Chamaecyparis obtusa* (hinoki), such as in Dando National Forest (Figure 8-9) in central Japan and in the Besshi working area of Sumitomo Forestry Company in Shikoku (Akai, 1991). Natural regeneration of *Chamaecyparis obtusa* seems to be successful in situations where the soil is comparatively dry and not very fertile. In these conditions, *Chamaecyparis obtusa* grows better than many of the competing species. Most *Chamaecyparis obtusa* forests are plantations, but if it is likely that regeneration will be by natural seeding, a long rotation with appropriate commercial thinnings should be used to gradually create the light conditions required for regeneration. In this process, the last thinning is equivalent to a seeding cutting. Young *Chamaecyparis obtusa* seedlings grow best at a relative illumination of about 5-10% and their survival drops if the relative illumination exceeds 30% (Akai, 1991). Therefore, the last thinning should reduce the canopy to

Figure 8-9 Natural regeneration of *Chamaecyparis obtusa* (hinoki) using the uniform shelterwood method in Dando National Forest in Aichi Prefecture in central Japan.

a relative illumination immediately following thinning of about 10-25%, which will then decrease as the crowns of overstorey develops. This level of light could be obtained by removing about 30% of the stand stem volume in stands that have been adequately thinned.

Removal of the undergrowth and scarification just after the last thinning also improves the survival of the seedlings in the first year (Sato, 1971; Satoo, 1983; Ogata, 1971). However, scarification should not be done in stands where the surface soil is prone to erosion (Akai, 1991) or where slopes are steep, because the very small *Chamaecyparis obtusa* seeds are easily moved down slopes in the raindrops and surface flow if the surface of the soil is not covered by litter. Therefore, the suitability of scarification must be carefully considered.

Regeneration by planting

This method is effective for converting stands from shade-intolerant species to shade-tolerant species, such as from birch to spruce or fir. Multi-storied stands naturally composed of these species are commonly found, so this technique closely imitates natural processes. If the species such as spruce or fir does not naturally regenerate in the stand of interest, seedlings can be planted under the birch. This technique can also be applied to develop a combination of species that is not naturally found. The desired species can be planted in the shelter of another species, and this can reduce weeding and the risk of damage from climatic events or pests and diseases such as rust and weevil.

An example of this approach is the establishment of *Pinus strobus* (white pine), a moderately shade-tolerant species under hardwood secondary stands in the north-eastern United States of America (Smidt and Puettmann, 1998). Lancaster and Leak (1978; cited in Smidt and Peuttmann, 1998) indicated that removing all hardwoods in the understorey and removing between 40 and 60% of the canopy would facilitate *Pinus strobus* regeneration on less fertile hardwood sites. Smidt and Peuttmann (1998) argued that modified shelterwood uniform methods should be applied depending on site quality, overstorey species composition, understorey density, and their interaction.

Regeneration by planting can also be applied in stands where the same, or an ecologically similar, species forms both the overstorey and the understorey. For example, older *Cryptomeria japonica* (sugi) or *Chamaecyparis obtusa* (hinoki) trees can form an overstorey to *Cryptomeria japonica* or *Chamaecyparis obtusa* seedlings. This method is applied in Japan and is called the short-term two-storied forest method. Appropriate techniques for applying this method to *Cryptomeria japonica* and *Chamaecyparis obtusa* have been discussed by Ando (1985), Kawahara (1988), Fujimori (1990, 1992b), Fujimori et al. (1995), and the Forestry

Agency of Japan (1996).

This technique is appropriate for *Cryptomeria japonica* or *Chamaecyparis obtusa* plantations that are in the mature stage (a minimum age of 60 or 70 years) and which have had a well-practiced series of thinnings. In such stands, the relative illumination will gradually approach a level suitable for regeneration, and the final thinning could be regarded as a seeding cutting. At the final thinning (the intensity of which should be about 30% of stem volume), the relative illumination immediately after thinning should be about 40%, as this will enable a relative illumination of at least 20% to be maintained for 15 years following planting of the seedlings. In such light conditions, large (80-100 cm in *Cryptomeria japonica* and somewhat smaller in *Chamaecyparis obtusa*) planted seedlings will grow to about 6 m in *Cryptomeria japonica* and 5 m in *Chamaecyparis obtusa*. If the relative illumination is about 30% immediately following the final thinning, it will decrease to 10% after 15 years, and the seedlings will grow to about 4 m in *Cryptomeria japonica* and 3.5 m in *Chamaecyparis obtusa*. If the relative illumination falls below 10%, the growth of the seedlings will almost stop and tree form will deteriorate. If it exceeds 40%, light-demanding herbaceous species will surpass the planted seedlings. Thus, the optimal relative illumination after the final thinning is 30-40%, both for growth of the planted seedlings and to control the growth of herbaceous species. In stands older than 60-80 years, the rate of crown reclosure decreases and so the relative illumination just after the final thinning needs to be lower if the growth of herbaceous species is to be controlled. When seedlings reach at least 3 m, the stand should no longer require weeding, even if all the overstorey trees were harvested. This method requires that harvesting operations be conducted with a high level of skill to avoid damage to the planted trees. The increased cost of harvesting means that crops must be a high quality to make the operation economical. This method is discussed as a short-term two-storied forest method in Section 8.1.2.2.

Soon after the removal of the overstorey, the young generation begins to grow rapidly. In stands regenerated by planting, diameter growth is remarkably fast for about a decade, because each individual is provided with enough growing space. This is not desirable when producing high quality timber with uniform annual rings. Pruning at this stage to produce knot-free timber can also control the excessive growth of the individuals. The same pruning regime as described in Section 6.1.6 can be used. The thinning regime after this stage is the same as one described in the standard method for coniferous plantation (Section 8.1.1.1).

c) Mixed stands

Generally, most natural stands are more or less mixed stands. However, it has been common around the world that stands managed for the production of timber tend to have a simple structure. This is most extreme in plantations which are typically a pure stand of a single species, but even in stands managed by natural regeneration, methods that lead to a simple stand structure have been common. However, the implementation of sustainable forest management requires that biodiversity be maintained or enhanced, even in stands managed for wood production. It is likely, therefore, that mixed stands will become increasingly important and appropriate silvicultural methods for converting pure stands and maintaining mixed stands will be required. Shelterwood methods would seem to be very suitable for such applications.

If a mixture of species needs to be regenerated in specific proportions, intensive and careful treatment is required. Generally speaking, shade-tolerant species are regenerated first by creating slight openings in the canopy. The canopy is then further opened by removing the seed bearers of these species, and allowing more light-demanding species to regenerate. Depending on the number of species and their light requirements, the number (frequency) and intensity of regeneration cuttings must be adjusted and the method of thinning considered. If a species required at a specific proportion tends to be suppressed by other species, the ratio of the seed bearers of that species should be kept high during thinnings and regeneration cuttings, and the seeding cutting should be done in the mast year of that species. Any seedlings of species that are more dominant than desired should be removed, and any species that is under-represented should have additional seedlings planted.

Lüpke (1998) outlined a method of oak [*Quercus petraea* (sessile oak) and *Quercus robur* (pedunculate oak)] regeneration in a mixed stand of shade-tolerant species in the sub-Atlantic climatic region of Germany. The principle aim was to produce high quality knot-free oak timber on a site where beech tended to be more dominant than oak. As beech gradually surpasses oak if both species are regenerated at the same time, oak needs to be regenerated before beech. Oak is therefore regenerated beneath a closed canopy by direct seeding, planting, or well-timed natural seeding. Oaks can tolerate shade for one to two years following regeneration, but then become more light demanding. Therefore, the canopy needs to be opened to about 30 or 40% of crown projection area (equivalent to 60 - 30% of full light) within a couple of years of establishment. This reduction in the canopy could be regarded as the regeneration cutting (seeding cutting), following which beech and other hardwood species would regenerate naturally. The beech and other species would grow as assisting admixture species. They can act as trainers to control lower branch development and prevent the formation of epicormic branches in the oak. Later improvement cutting and thinning operations should remove any dominating beech. Other species that do not dominate the overstorey could be retained, and a proportion of beech could be retained in the overstorey to provide timber, although the price is lower than oak. Such a silvicultural system would enable a level of high quality oak timber to be produced that could not be achieved in a pure oak stand. This is a good example of the potential for concurrent biodiversity conservation and wood production.

Group-shelterwood and group selection methods can also be effectively used to convert pure stands to mixed stands with a specified composition.

8.1.2.1-2 Group-shelterwood method

In the group-shelterwood method, gaps in the canopy that have groups of advanced growth developing beneath are expanded gradually to enhance development of the advanced growth and encourage the establishment of more seedlings towards the outside. The original gaps are usually formed by thinning or natural disturbances such as wind or snow damage. However, if there are not enough gaps in the stand, further gaps must be created. Regeneration thus spreads radially and the groups of regeneration finally meet each other when the last seed bearers are removed. Under the group-shelterwood method, the maximum duration of the period for regeneration is similar to that of the uniform method, but the minimum duration is longer (Matthews, 1989). The group-shelterwood method produces a more uneven-aged structure than the uniform method, and it tends to have a wavy profile. If a long rotation is used, however, the irregularities disappear and it is usually regarded as an even-aged method.

Under the group-shelterwood method, damage to young growth during cutting in the early stage can be avoided by cutting trees outside the gaps. However in later stages, harvesting becomes difficult because the extent of regrowth expands. One disadvantage of the group-shelterwood method is that the margins of gaps are prone to wind damage. An advantage, however, is that the mixture of species can be easily regulated by adjusting the initial size and rate of enlargement of the gap to suit the light requirements and hardiness of the regenerating or introduced species (Matthews, 1989). If shade-tolerant species such as beech are favored, the initial gaps must be small and only gradually enlarged. If relatively light-demanding species such as oak are preferred, the initial gaps should be larger and the enlargement more rapid. When the regeneration is not adequate, partial planting may be required after the final cutting.

This approach can also be used to regulate the species mixture in a uniform method. In mixed forests, shade tolerant species are regenerated first by making a slight opening in the canopy and others are regenerated progressively according to the light regime induced by later cuttings. Light demanding seed-bearers are left until the final cutting, or even until all other species have been removed, to regenerate the exposed site (Smith, 1986).

In Europe and the United States of America, the group-shelterwood method is no longer often used in its original form, having been replaced almost everywhere by the strip and group-shelterwood method which is more resilient to damage by wind and the extraction of timber (Matthews, 1989). In Japan, however, the group-shelterwood method may be useful because the stand structure is generally complicated as a result of the complex relief.

8.1.2.1-3 Strip-shelterwood method

In the strip-shelterwood method, successive strips are cut across a stand. A series of several strips is called a cutting section. Within each strip, several regeneration cuttings are done progressively; usually as seeding, secondary, and final cuttings. One of the greatest advantages of the strip-shelterwood method is that it provides protection from wind and sun damage along the sides of the strip, especially if the strip is aligned perpendicular to the prevailing wind. This kind of protection is more effective than overhead cover in areas subject to frost (Matthews, 1989).

Regeneration within each cutting section starts in the strips on the lee side. When sufficient regeneration is achieved within a strip, a secondary cutting is made on it and a seeding cutting is done on the next strip on the windward side. A few years later, the final cutting is made in the first strip, and a second cutting is done in the second strip. This series of cutting and regeneration activities moves progressively strip by strip, across the cutting section (Figure 8-10).

The width of each strip is generally half the height of the adjacent trees (Smith, 1986: Matthews, 1989) and the strips are straight if the stand is on a uniform site. However, as the trees in each strips develop, the strips often become irregular because the regeneration does not always develop evenly throughout the strip. Complicated topography may require modified strip shapes. As the topography of forested land in Japan is generally complex, most strips are irregular.

The advantages of the strip-shelterwood method include the protection it provides against wind and sun, and its greater effectiveness in frost protection compared with the uniform method or group method. The strip-shelterwood method also limits the damage to regenerated young trees during felling and extraction because trees are felled in the adjacent strip of old trees and can be extracted through it (Matthews, 1989). However, as the series of regeneration cutting advances, the damage tends to increase in strips where regeneration has started.

The wedge method is also a modification of the strip-shelterwood method, in which cuttings begin as narrow strips in the center of the cutting section, which are then extended into wedge shapes with their apices oriented towards the prevailing wind. These are then successively enlarged and advanced (Ford-Robertson, 1971). The strip and group-shelterwood method is another modification which combines the advantages of both the strip method and the group method (Matthews, 1989).

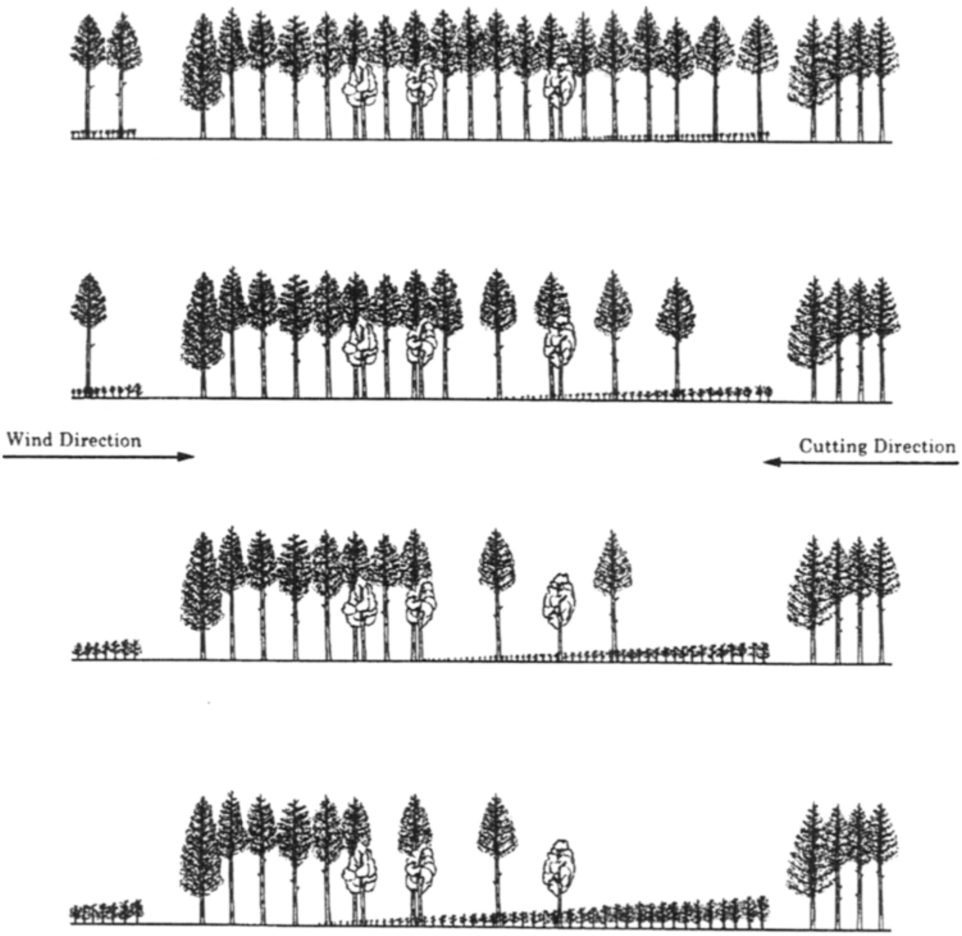

Figure 8-10 Strip-shelterwood method showing progress of cutting through a cutting section. (Matthews, 1989)

8.1.2.1-4 Strip and group-shelterwood method

The strip and group-shelterwood method was developed in Bavaria in Germany by H. von Huber, chief of the Bavarian Forest Service. It is widely used in central Europe (Matthews, 1989). Figure 8-11 shows the process of cuttings under the strip and group-shelterwood method. Dispersed, small group cuttings are made in the first strip and gradually expanded in size, then strips are gradually added side by side. The strip and group-shelterwood method is well adapted for regulating species mixtures. Shade-tolerant species may be introduced artificially in small gaps ahead of the strip cuttings and light-demanding species are generally

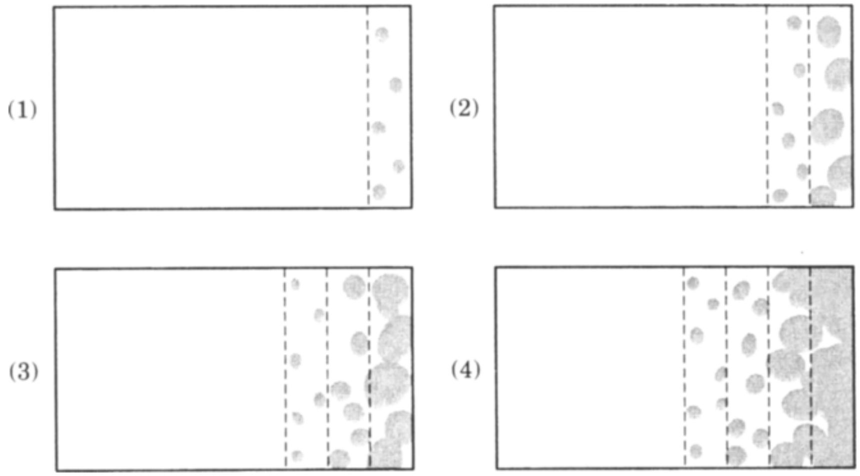

Figure 8-11 Strip and group method showing progress of cutting from (1) to (4). Regenerated areas are indicated by the shading. (Matthews, 1989)

retained in the strips until the final cutting. Beech is frequently introduced ahead of strip cuttings in a conifer forest, and the conifers are later regenerated naturally following the strip cuttings. Shade intolerant species may be introduced artificially following strip cutting.

The advantages of the strip and group-shelterwood method include the ability to regulate species mixtures relatively easily and rapid regeneration through the ready establishment of ample groups of advanced growth ahead of the strip cuttings. The main disadvantage of the method is the risk of damage to groups of advance growth when extracting logs, particularly on steep slopes (Matthews, 1989).

8.1.2.1-5 Irregular-shelterwood method

The irregular-shelterwood method is defined as a method in which the regeneration period is too long for the new stand to be regarded as even-aged. The irregular-shelterwood method differs from the selection method in that the stand has less than three layers. In the irregular-shelterwood method, the regenerated young trees are uneven-aged and irregular (Ford-Robertson, 1971; Matthews, 1989). Smith (1986) defines irregular-shelterwood methods as ones that result in two age classes for long periods and sometimes even for the whole rotation. The term "irregular" can be used either to describe either the age or height distribution (typically bimodal) of the new stand.

The upper layer in this method comprises old, selected trees and the lower layer comprises younger trees that are tended and thinned to produce high quality timber. The irregular-shelterwood method includes various elements of the uniform, group, and strip methods. There are many variations of the irregular-shelterwood method which can be used according to the site condition.

8.1.2.2 Two-storied (high) forest methods

In Europe, a two-storied high forest is a type of accessory method that can arise from a variety of silvicultural methods and is not dependent on any particular form of regeneration. Two-storied high forests are composed of an upper and lower storey of trees of seedling origin, growing in an intimate mixture on the same site. Trees of the understorey may arise through natural regeneration or planting. When an even-aged stand approaches middle age, heavy thinning takes place and seedlings of shade-tolerant species establish beneath the retained canopy. The lower storey can be established by planting, natural regeneration before or soon after the heavy thinning is done, or by direct seeding into the thinned stand. Both stories are allowed to grow and subsequent thinnings are done in the lower storey. The two stories may be cut together, or the upper storey may be removed in one or a series of cuttings to leave the lower storey as an even-aged maturing crop. Two-storied high forests are frequently only managed over one rotation because of the difficulty of forming a second understorey under the previous shade-tolerant storey (Matthews, 1989).

Two-storied high forests are most commonly used in Europe, to achieve diameter increment on selected upper storey trees whilst protecting the soil with the lower storey. It is most often used with *Pinus sylvestris* (Scots pine) underplanted or undersown with *Abies alba* (Europian silver fir), or *Pinus sylvestris* and oak underplanted with beech. Site improvement has been reported from the Sausen district of Germany where *Pinus sylvestris* was underplanted with beech and locust (Flöhr, 1969; cited in Matthews, 1989).

Hiley (1959; cited in Matthews, 1989), experimented with the two-storied high forest method on the Dartington estate southwest England. He wished to grow *Larix kaempferi* (Japanese larch, karamatsu) to large diameters but noted that in well stocked stands current annual diameter increment culminated quite early. To maintain rapid growth in diameter the trees need large crowns and this required virtual isolation at an early age. Hiley (1959) hypothesised that underplanting with a shade-tolerant species would make more complete use of the site whilst allowing rapid growth of *Larix kaempferi*. Site protection and weed suppression would be achieved if the lower storey was a shade-tolerant species which could be tended as an even-aged crop. In 1955, a compartment of *Larix kaempferi* was heavily thinned and underplanted with *Tsuga heterophylla* (western hemlock), *Thuja plicata* (western red cedar), and *Pseudotsuga menziesii* (Douglas-fir). The larch was 25 years old and had received four previous thinnings, the last having the specific object of improving root development and stability to wind. Howell et al. (1983) summarized the results of this trial. The larch was clearcut at 48 years, by which time the crowns had all but closed, the mean DBH was 47 cm on a fertile soil and one-third of the timber was suitable for boat building. The *Pseudotsuga menziesii* in the lower storey had been suppressed, but *Tsuga heterophylla* and *Thuja plicata* had thrived.

The term two-storied forest method has been commonly used in Japan. However, there are differences with the European two-storied high forest method. In Japan, several methods are referred to as two-storied forest methods. The shelterwood method is regarded as one type and is referred to as the short term two-storied forest method. Another method, the long term two-storied forest method is more similar to the European method, but differs because both stories are seldom cut together. The two-storied forest method is recognized as one of the non-clearcutting methods (multi-storied forest methods) as described in Section 7.1.2.

The typical two-storied forest method in Japan entails planting shade-tolerant species beneath the canopy of a stand of a light-demanding species (Figure 8-12). Usually, *Cryptomeria japonica* (sugi) or *Cahamecyparis*

Figure 8-12 Two-storied forest of *Larix kaempferi* (karamatsu) and *Chamaecyparis obtusa* (hinoki) in Nagano Prefecture in central Japan. (Photograph by T. Kawahara)

obtusa (hinoki) is planted under *Pinus densiflora* (akamatsu), or *Chamaecyparis obtusa*, *Cryptomeria japonica*, or *Picea jezoensis* (ezomatsu) are planted in a *Larix kaempferi* (Japanese larch, karamatsu). The Sanbu forestry area in Chiba Prefecture is renown for using the two-storied forest method with a combination of *Pinus densiflora* and *Cryptomeria japonica*. The original purpose of establishing two-storied forests in Sanbu was to protect the *Cryptomeria japonica* seedlings from frost damage, but it has developed into a long term two-storied forest method because it effectively utilizes the growing space under the canopy of overstorey trees. However, the virulent pine wilt disease (Section 15.3.2.2) has reduced the extent of the two-storied forest method in this area. In many places in the cool-temperate zone in Japan, species such as *Chamaecyparis obtusa*, *Cryptomeria japonica*, and *Abieas sachalinensis* (todomatsu) are planted under *Larix kaempferi*. The main objective of this is to protect the *Cryptomeria japonica* and *Chamaecyparis obtusa* from frost damage during the seedling and sapling stages. It also allows stands of less commercial species to be converted to more valuable species, and the growing space in the stand to be more effectively used. Relatively shade-tolerant coniferous species such as *Chamaecyparis obtusa*, *Cryptomeria japonica*, and *Abies sachalinensis* are often planted in deciduous hardwood stands to convert the species and to regenerate the conifers at a relatively low weeding cost.

The maintenance of two-storied forests composed of light-demanding and shade-tolerant species is relatively easy, but maintaining a combination of species with similar light requirements is more difficult. It is possible, however, to use the short term two-storied forest method for species with similar tolerances. In the intensive management of *Cryptomeria japonica* and *Chamaecyparis obtusa* which are both relatively shade-tolerant, the short term two-storied forest method using a combination of *Cryptomeria japonica-Chamecyparis obtusa* or *Cryptomeria japonica-Cryptomeria japonica* can be adopted. However, regeneration of planted *Chamaecyparis obtusa* beneath a *Chamaecyparis obtusa* stand is often unsuccessful (Fujimori et al., 1995).

Following final thinning in the mature stage of a single-storied stand of the desired species with a lower storey comprising naturally invaded, non-commercial hardwood species, the understorey is cut and the desired species planted. When the planted trees are large enough not to require weeding, the remaining overstorey trees are cut. The understorey trees at this stage are generally 3 to 6 m tall and the cut occurs 10 to 15 years after planting. In terms of wood production, a two-storied forest is generally defined as a stand in which the desired species form two canopy layers, but the natural understorey formed in the mature stage plays an important ecological role, so forests which have a single storey of commercially desirable species in the mature stage and a well developed non-commercial understorey are sometimes called ecological multi-storied forests in Japan (Fujimori, 1991a).

Generally the two-storied forest method is regarded as one of the non-clearcutting methods, but sometimes, it can be created by clearcutting. For example, a *Pinus densiflora* (akamatsu)-*Chamaecyparis obtusa* (hinoki) two-storied forest can form if *Pinus densiflora* regenerates naturally soon after planting *Chamaecyparis obtusa* on a clearcut site (Kawahara and Yamamoto, 1982). Various other two-storied forests such as *Betula maximowiczii* (udaikanba)-*Chamaecyparis obtusa* (Hara et al., 1995; Figure 5-4) and *Betula maximowiczii-Cryptomeria japonica* (sugi) forests (Sakaue, 1984) are formed in the same way. These combinations of species coexist well and the merits of the structure and function of these forests can be demonstrated to forest managers. These advantages include the suppression of light-demanding weeds by naturally regenerated desired species, which reduces weeding costs and contributes to protecting planted trees from frost damage (Hara et al., 1995). The mixture of species also improves soil structure and enhances biodiversity. A disadvantage of the use of this method for *Cryptomeria japonica* is that when it is in the understorey, *Cryptomeria japonica* is susceptible to crown snow damage (Ochiai et al., 1987; Waguchi et al., 1992).

8.1.2.3 Selection methods

In selection methods, trees in the oldest class are removed, individually or in small groups, annually or periodically, from throughout the stand. Regeneration occurs in and around the gaps created by each selection cutting, and an uneven-aged stand (selection forest) is created or maintained. Selection methods differ from all other silviculutural methods in that the age-class composition of the forest is maintained by constant partial harvesting and regeneration. The volume removed at each cutting should be about equal to the increment (increased volume) during the cutting interval. Therefore, the standing volume of a selection forest remains approximately constant over many years (Smith, 1986; Matthews, 1989). In Japan, the method in which a multi-storied structure is always maintained in a stand is called the perpetual multi-storied forest method. The perpetual multi-storied forest method is a typical selection method.

Selection methods are appropriate for sustainable production from specific stands where harvesting at short intervals is an option. The quality of wood produced in these methods is usually high because the knots produced in young stage are smaller and the width of annual rings do not decrease much as the trees grow larger, so the width of annual rings is uniform from the center to the outside of the stem. The forests are also comparatively stable ecosystems. However, selection methods tended to be misused around the world to harvest valuable trees or species without regenerating them, resulting in degraded stands. Other disadvantages of selection methods include the need for skilled cutting and extraction to avoid damaging young trees and this requirement for careful operations increases costs. Therefore, selection methods need to be carefully applied and the objectives always considered. Development of a high density forest road network is an essential condition for the implementation of selection methods.

It is often believed that selection forests resemble unmanaged natural forests which are in the old-growth stage or the climax stage. In fact, although boreal natural forests often have an uneven-aged and reversed J-shaped size structure (Lähde et al., 1999), they are not always composed of all age classes. Old-growth forests are characterized by an uneven age-class distribution and the presence of comparatively large size declining trees, snags, and fallen logs. Despite these differences, the selection method is regarded as a silvicultural method that is closer to natural systems than methods such as even-aged clearcutting or similar methods. For these reasons, there is great interest in using selection methods as a part of sustainable forest management systems such as those referred to as nature-oriented (Lähde, 1992), diversity-oriented (Lähde et al., 1999), or near-natural (Benecke, 1996).

8.1.2.3-1 Single-tree selection method

In the single-tree selection method, gaps are created by harvesting individual mature trees in a stand and regeneration occurs in each gap. As the size of gap is limited, this method can only be applied to shade-tolerant or relatively shade-tolerant species.

The modern selection method emerged during the period between 1880 and 1920. The Swiss forester Biolley developed the methods that the French forester Gurnaud had devised for estimating increment and controlling cuttings, and put them into practice during almost 50 years of work in the forest of Couvet and other forest of the Val de Travers (Matthews, 1989). The method used in Couvet, Switzerland, is described by Benecke (1996). This method has been applied in the Couvet Forest since last century, and steady production from within a continuous forest structure of multi-storied stands with a natural species mixture has been maintained (Favre, 1994; cited in Benecke, 1996). All size classes continue to be represented within a compartment area, and production over the whole area is almost continuous, i.e., cutting cycles occur over a short time interval (six-eight years), with the allowable cut determined from inventory of the whole compartment.

The Couvet forest has productive fir-beech-spruce (*Abies-Fagus-Picea*) stands with that meet many of the criteria for ecological sustainability. Trees emerging from the canopy are healthy, about 50 m tall and have a large diameter that shows no decline in wood increment (Figure 8-13).

Figure 8-13 A multiple-layered stand of fir-beech-spruce well managed by selection method with 6-8 year cutting cycle in Couvet Forest, Switzerland. (Photograph by H. Soyer)

Detailed records from between 1890 and 1992 of 16 complete inventories of all trees over 17.5 cm DBH demonstrate the benefits of the selection method compared with clearcutting. For stands on northern slopes, the overall current natural increment increased from 6 m^3/ha to 9 m^3/ha over the hundred-year period (Figure 8-14). Importantly, most of this increased increment occurred in large-dimension stems of high sawlog quality, so that the proportion of the standing volume that occurred in diameter classes above 52.5 cm DBH was 55% in 1992 compared to 27% in 1890. This has been achieved by using a sustained selective harvesting regime cutting around 10 m^3/ha/yr (i.e., the equivalent of about 60 m^3/ha per six-year cutting cycle), and was accompanied by a deliberate reduction in the permanent standing volume from 392 m^3/ha in 1890 to the current 365 m^3/ha.

The aim of management of this forest is to produce the maximum quantity of top quality sawlogs by maintaining only as much standing volume as allows maximum sustainable increment. Modest standing volumes keep the main crop trees growing steadily and lead to very even growth rings. Excessive standing volume results in production of less valuable timber and increases the susceptibility of the stand to wind damage.

The key to successful stand management in Couvet is a good road and extraction-track network and skilled workers. This is essential condition for implementation of selection method.

The yield of timber from the Couvet forest has been regulated by the

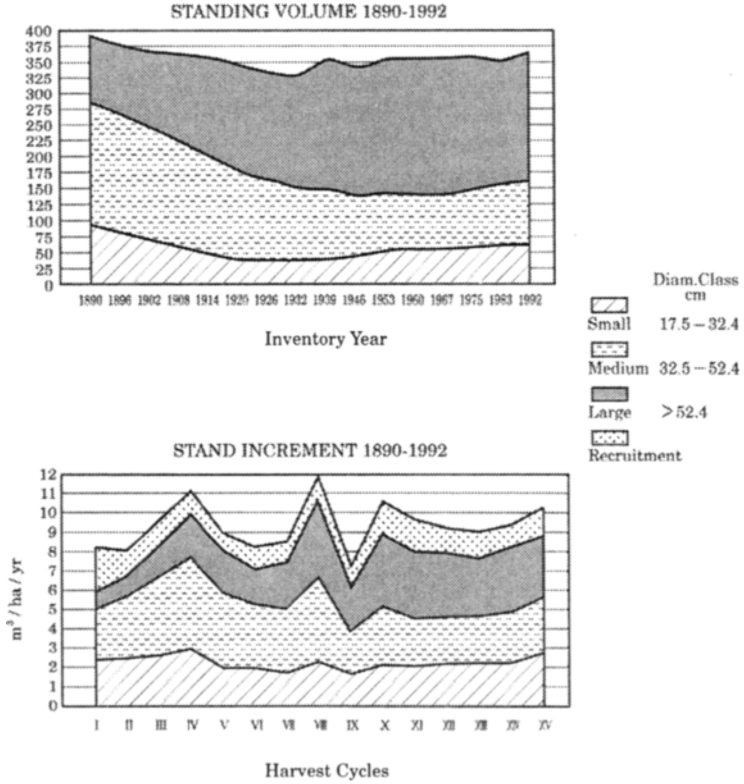

Figure 8-14 Effect of conversion from clearcutting to selection methods over 102 years in the fir-beach-spruce stands of Couvet Forest, Switzerland. During this period, the large sawlog volume increase from 27 to 55% and increment increased from 6 to 9 m³/ha. (Benecke, 1996, after Favre, 1994)

check method devised by Biolley (1920; cited in Matthews, 1989). The principle of this method is to gain the maximum possible increment from the least possible growing stock, and it relies on a defined distribution of size classes that equates to a normal forest and ensures sustained yields. Biolley divided the forest into compartments and made recurrent inventories of the growing stock in three size classes (large, medium, and small) at intervals of a few years (usually 6 to 10 years) to determine the relation between increment and growing stock, fix the yield for the next period, and plan harvests such that a normal distribution of size classes developed (Matthews, 1989).

In mixed conifer-hardwood forests in Tokyo University Forest in

Hokkaido, Japan (Figure 8-15), the single tree selection method has been applied successfully. The development of the management system was described by Watanabe and Sasaki (1994). The goal of management was to create an uneven-aged and multi-storied forest, and to increase timber production whilst maintaining higher residual volumes in standing crop trees. An additional objective was to allow periodic harvesting of high-quality timber by regulating the levels of residual stand volume, based upon site and stand conditions.

Management of this forest has the following characteristics: 1) the check method is used to determine silvicultural operations (Biolley, 1920), i.e., a target stand volume is maintained; 2) single-tree selection is used to modify and control stand composition, with a specified target composition; 3) effective and accurate inventory of each compartment is conducted; 4) individual high quality hardwood trees are marked to promote development of the most valuable species; 5) the cutting cycle is 8-10 years, and 13-17% of stand volume is harvested each cycle; 6) regeneration is generally natural, with ground scarification treatments, but planting of desired species is used for difficult sites; and 7) a permanent high density forest road network is constructed and maintained to ensure efficiency of

Figure 8-15 Mixed stand of coniferous and hardwood species in Tokyo University Forest, Hokkaido, Japan.

the silvicultural operations.

Individual crop trees are selected on the basis of crown condition, because it reflects their overall net photosynthetic potential. The two most important features are: 1) a crown that is not damaged by insects, disease, or wind; and 2) a well-developed crown that can maintain a high rate of net photosynthesis. If both conditions are met, rapid tree growth is possible under this management system, and crop trees will increase in volume and value. Individual trees that do not satisfy both conditions are harvested, but harvesting levels are limited to 13-17% of stand volume.

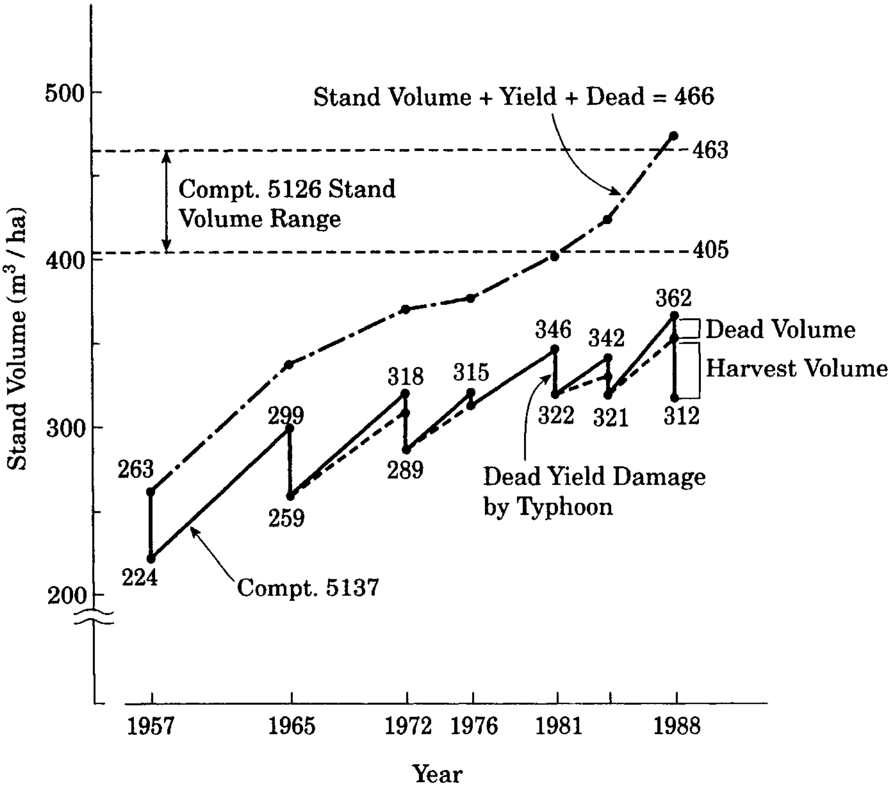

Figure 8-16 Changes in stand volume from 1957 to 1988 in an experiment conducted in Tokyo University Forest, Hokkaido, comparing single selection method (Compartment 5137) with an untreated old-growth stand (Compartment 5126). The total stand volume of Compartment 5137 in 1988 was 312 m^3/ha, and the net production was 8 m^3/ha/yr. The volume harvested between 1957 and 1988 was 148 m^3/ha, plus 31 m^3/ha in dead trees and 24 m^3/ha in trees salvaged following typhoon damage in 1981, giving a total volume of 203 m^3/ha in addition to standing volume. (Watanabe and Sasaki, 1994)

The total timber yield from the 20,000 ha forest over the past 90 years is 5.84×10^6 m^3. Many stands have been effectively converted into the ideal stand structure and composition, and growth rates and standing volume have increased following each cutting cycle. The 31-year results from the management are summarized in Figure 8-16 for compartment 5137, and compared with those for a 1 ha untreated old-growth control site, compartment 5126. The total area of the old-growth forest block is 61 ha, and this area had an average stocking level of 450 m^3/ha. The stand volume of compartment 5137 in 1957 was 263 m^3/ha, following exploitation and over-harvesting for more than 50 years. Selection cutting has been applied since 1958, with six low volume cuttings and a salvage cutting following a typhoon in 1981. By 1988, the residual standing volume was 312 m^3/ha. The cumulative volume produced from compartment 5137 over this period exceeded the standing volume of the old-growth control stand, demonstrating that maintenance of 70-80% of standing volume by periodic cuttings in a natural climax forest increased the total harvest volume without harming the productive capacity and health of the forest.

Individual tree selection requires a highly skilled and expert forester capable of assessing the ecological characteristics of the major species (particularly light tolerance and longevity), wood quality (market price) and past damage by wind, insects, and disease. There is a considerable variation in market prices in Hokkaido, depending on tree species, wood quality, and DBH. For example, good quality wood from single trees of at least 60 cm DBH of oak (*Quercus crispula*, mizunara), birch (*Betula maximowicziana*, udaikanba), or *Kolopanax pictus* (harigiri) was priced at more than 1×10^6 yen/m^3 (US\$10,000/m^3) around 1990. By contrast, softwood trees and deciduous pulpwood trees were worth only 1/100 of this. Fir (*Abies sachalinensis*, todomatsu), a shade-tolerant species, is the most dominant species in the area and has an average longevity of about 130 years, which is the shortest of all the main species in the area. Oak is a moderately shade-tolerant species and is one of the longest lived species in the area, with an average longevity of about 250 years. The fir trees suppress oak, so are generally targeted for cutting, unless they are acting as trainers controlling the lower branches of a high quality hardwood tree (Section 6.2.4.2).

The single-tree selection method has a long history in *Cryptomeria japonica* and *Chamaecyparis obtusa* plantations in Japan (Figure 8-17). *Cryptomeria japonica* and *Chamaecyparis obtusa* are only moderately shade-tolerant species, so require intensive management to be maintained in a selection forest. In the small, private forests of the Imasu forestry area in Gifu Prefecture, a typical single-tree selection method has been used since at least the 19th century. In each gap created by harvesting a mature tree, several seedlings are planted. The trees are pruned to over 10 m to improve wood quality and increase light for the seedlings. In a typical mixed stand of *Cryptomeria japonica* and *Chamaecyparis obtusa* on a

Figure 8-17 Selection forest of *Cryptomeria japonica* (sugi) and *Chamaecyparis obtusa* (hinoki) in Imasu in Gifu Prefecture, Japan.

fertile site in this area, the standing volume is about 332 m^3/ha and the mean annual increment is 12 m^3/yr. The cutting cycle is about 5 years and the volume corresponding to the increment is harvested. The mean relative illumination on the stand floor is maintained at about 19% and the frequency distribution of tree age or tree size is typically a reversed J (L) shape. (Fujimori et al., 1983). As trees grow older, their growing space increases as surrounding trees are harvested, which ensures that the width of the growth rings is uniform and a high volume of knot-free timber is produced. The timber from this region is highly regarded. Single-tree selection methods can only be used if the crop has a high value. Without high returns, the intensive management cannot be justified.

Plantations can be converted from single-storied pure forests to multiple-storied mixed forests and managed using selection methods. An example of the process of conversion from a coniferous single-storied pure stand to a multi-storied conifer and hardwood mixed stand in Japan is shown in Figure 8-18. In the mature stage, individual mature trees are selectively harvested and seedlings of *Cryptomeria japonica* or *Chamaecyparis obtusa* which are moderately shade-tolerant are planted in the gaps. Naturally regenerated hardwood can be tended as well as the

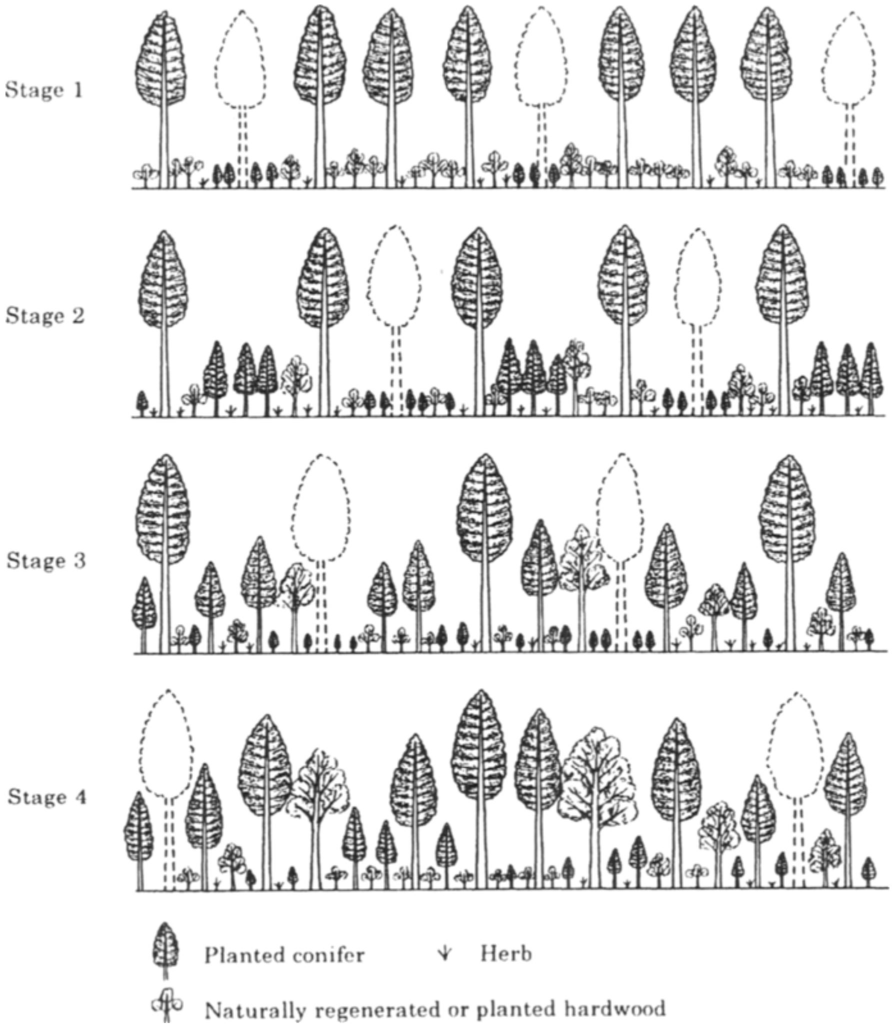

Figure 8-18 A hypothetical process for converting a single-stored forest of *Cryptomeria japonica* (sugi) to a multi-storied mixed forest of *Cryptomeria japonica* and hardwoods using the selection method. Stage 1 is a mature stand (understorey reinitiation stage) that has had a series of thinnings practiced and which has abundant undergrowth. Following thinning, the undergrowth in the gaps that does not have the crop species is removed and seedlings of *Cryptomeria japonica* or *Chamaecyparis obtusa* (hinoki) are planted. If natural regeneration of hardwood crop species has not occurred, hardwood seedlings are also planted. This is repeated from stages 2 to 4 each time the overstorey is selectively cut. Overstorey trees are managed to maintain a crown length to tree height raitio of at least 50%. Brush and herb species that are not suppressing regeneration are retained for conservation of biodiversity and soil and water resources.

planted coniferous seedlings. As this selection harvesting and regeneration operation is repeated, the stand gradually develops into a selection mixed forest, which can then be maintained. If natural regeneration of the hardwood crop species is not successful, seedlings can be planted. This single selection method can be expanded to group-selection method according to the shade-tolerance of the species targeted for regeneration.

One of the advantages of the single-tree selection method is that the composition of stand can be controlled effectively. Further advantages can include a more even distribution of work through the seasons and improved working conditions. Single-tree selection typically reduces the need for weeding, but any weeding that is required can be done in the shade. The period of planting can also be extended in the single-tree selection method to include all seasons except mid-winter and summer. The balance between these and other advantages and the higher cost of extraction must be considered before implementing a single-tree selection method.

8.1.2.3-2 Group-selection method

In this method, trees are removed in small groups. One advantage of this method is that it provides a better opportunity to regenerate species with different light tolerance characteristics. It also allows more efficient extraction than the single-tree selection method, but increases the need for weeding.

Well-developed natural forests are often composed of a mosaic of even-aged groups or patches. The group-selection method imitates this structure and can therefore be used to manage natural forests. The size of the gap can be controlled to ensure regeneration of most species, including light-demanding species. Ecologically, a space in which the environment (microclimate) is influenced directly by the surrounding trees can be called a gap or opening. Smith (1986) regarded the maximum size of a gap to be about twice as wide as the height of the surrounding mature trees, from an ecological standpoint, although it may be not based on enough data. In Japan, the critical size of a group (patch) is regarded as one to two times of the surrounding high trees in its diameter or one length in terms of the microclimate, although there has been little scientific evaluation of this (Fujimori, 1991a; Fujimori, 1996). One reason that the gap size in Japan is smaller than elsewhere is that the general size of stands in Japan is small due to the complex topography; if the size of a stand is small, then the critical size of a gap, as a unit within a selection forest, will tend to be smaller. The critical size of a gap may differ between sites and it is therefore necessary to obtain much more information about the relationship between gap size and the microclimate of the gap surrounded by the residual trees

Under the group-selection method, various species can be regenerated and this is therefore a useful technique for managing mixed stands. Typically, the climax forests in the lowland areas of Hokkaido are mixed stands of coniferous and hardwood species, including conifers such as *Abies sachalinensis* (todomatsu), *Picea jezoensis* (ezomatsu), and *Picea glehnii* (akaezomatsu), and more than 20 hardwood tree species including *Quercus crispula* (mizunara), *Tilia japonica* (shinanoki), *Tilia maximowicziana* (obabodaiju) and *Acer mono* (itayakaede). The distribution of these species generally forms a micro-mosaic or macro-mosaic pattern (Ishizuka, 1980, 1981). The group-selection method can be used to maintain a similar structure as the original stand, or a combination of the group-selection and single-tree selection method may be used.

An analysis of the mixed forests in Hokkaido by Ishizuka (1994) found that the gaps created by natural disturbances occur at intervals of about 10-30 years and the average area disturbed is 31-62 m^2/ha annually. If it is assumed that the stand is naturally disturbed at intervals of 20 years on average, the average gap size opened by a disturbance is between 620-1240 m^2/ha. This is equivalent to 8-17% of the total canopy area and 8-15% of stand volume. These values can be used to determine the interval between successive cuttings and the intensity of the group-selection or single-tree selection method.

In the mixed natural forests of Tokyo University Forest in Hokkaido, the group selection method has been used with intervals of 10 years between successive cuttings and a removal ratio of 15%. This has allowed previously degraded forests to recover and the management has now stabilized (Takahashi, N., 1971; Ishizuka, 1994).

In Shimokita Peninsular in Aomori Prefecture, Japan, the group-selection method was adopted to manage *Thujopsis dolabrata* var. Hondai Makino (hiba) in the late 17th century. However, valuable trees tended to be removed and the quality of the forests declined. Natural regeneration of *Thujopsis dolabrata* was not always successful and mixed stands of *Thujopsis dolabrata* and broad-leaved deciduous trees developed (Yamada, 1975). Matsukawa (1935) implemented a selection method using a structural unit (group) within each stand which had a combination of mature and young trees. In each unit, a moderate single-tree selection cutting of seedlings smaller than 60 cm in height was conducted. Larger openings were made for taller seedlings or saplings, and as the young trees grew, much larger openings were made. This combined single-tree selection and group-selection cutting method has also been used in the National Forest in northern Japan.

On Teisenberg (Inzell, Upper Bavaria) in Germany a group-selection method has been used to convert forests to a more natural uneven structure containing a mixture of species (Benecke, 1996) (Figure 8-19). The forest comprises spruce (*Picea excelsa*) and silver fir (*Abies alba*) trees

Figure 8-19 Group selection forestry in mixed conifer-hardwood forest yielding high quality sawlogs in Teisenberg, FA Siegsdorf, Upper Bavaria, Germany. (Photograph by U. Benecke)

of up to 75 cm DBH and 40 m top height with long clean boles, are interspersed with beech (*Fagus sylvatica,* European beech) that is mostly in the subcanopy. In this area, beech is climatically outside its optimum range and the production of high quality timber cannot be expected, but it is recognized as an important natural component of the stand that enhances stand stability and the ecological sustainability of the forest. Cutting of small groups (<0.1 ha) is conducted on a 10-year cutting cycle under the classical "Dauerwald" (continuous-cover forestry) regime of tending for "quality and dimension." In this system, the poorest competing stems are removed and the best retained, but enough large high-quality stems are harvested to maintain economic viability.

Conversion of nearby even-aged compartments of tall spruce to near-natural, uneven-structured stands of mixed species managed as group-selection stands has entailed the phasing out of the previous practice of strip-cutting in 2-3 ha blocks and the progressive thinning of stands over a 100-year transition period. Clearcutting in 20 ha coupes was stopped more than 100 years ago because of problems with serious windthrow and slope erosion. The aim now is to manage for maximum stability. However, the risk of windthrow persists in even-aged stands where thinning is late and the tree height to diameter ratio (H/D) exceeds 80. By comparison, emergent trees in stands managed using selection methods commonly have an H/D of around 60, and the crowns are long and healthy, occupying up to 60% of tree height. Such emergents are more stable than trees with higher H/D ratios (Burschel and Huss, 1987; cited in Benecke, 1996).

In the southern bottomland hardwood forests (Figure 8-20) which extend from Virginia to east Texas in the United States of America, the most valuable species for timber production are oak species which are moderately to very shade-intolerant. If single-tree selection methods are applied repeatedly in stands containing commercially valuable shade-intolerant species, such as most bottomland oaks, the stand composition will gradually shift to less valuable, more shade-tolerant species, such as sugarberry (*Celtis laevigata*), elms, maples and hickories (Johnson and Krinard, 1989; cited in Meadows and Stanturf, 1997). Therefore, the group-selection method is more effective. The maximum unit area of a group-selection cutting is regarded as twice the height of overstorey of the surrounding trees (Smith, 1986; Meadows and Stanturf, 1997). This is the equivalent of a gap with a diameter of about 70-75 m or an area of about

Figure 8-20 Typical bottomland hardwood stand of the Lower Mississippi Alluvial Valley in the floodplain of the Mississippi River in the United States of America. The stand is about 70-80 years old, the average diameter of the larger trees is about 60 cm, and species are primarily *Quercus nigra* (water oak), *Quercus nuttallii* (nuttal oak), and *Liquidambar styraciflua* (sweetgum). (Photograph by J. S. Meadows)

0.40-0.55 ha in most mature southern bottomland hardwood forests. Application of the group-selection method according to these rules would create relatively small openings that would fail to allow sufficient light to reach the forest floor across the entire gap for satisfactory establishment and development of shade-intolerant species such as the bottomland oaks (Clatterbuck and Meadows, 1993). In openings of this size, light conditions in the center of the opening would enable successful establishment of most shade-intolerant species, but away from the center, light conditions would be inadequate, with the consequence that regeneration of shade-intolerant species is limited to a small area at or near the center of the gap. The resulting stands would then be dominated by low-value, shade-tolerant species.

Patch cutting, a combination of uneven-aged (group selection) and even-aged (clearcutting) silviculture, is a method that enables larger openings of up to 1-2 ha to be created. It has been successfully used by many forest managers to produce an uneven-aged stand that consists of many small, irregularly shaped, even-aged groups (Marquis, 1989). Patch cutting allows for small even-aged groups to develop within an uneven-aged forest. It combines the biological advantages of clearcutting, by creating larger openings, with the aesthetic, wildlife and market advantages of group selection, by always retaining a substantial number of large trees in the stand. Consequently, patch cutting, though difficult to implement, is becoming increasingly common in bottomland hardwood forests across the south of the United States of America because it produces the biological conditions necessary for the successful establishment and development of bottomland oak production (Clatterbuck and Meadows, 1993; Meadows and Stanturf, 1997).

The key to the successful use of patch cutting is to match the size of the opening to the regeneration requirements of the desired species, and then to cut all stems within the selected opening. The opening should be large enough to allow adequate sunlight to the forest floor to nurture the development of desired seedlings and to provide sufficient sunlight to promote the eventual development of those seedlings into overstorey trees. Use of patch cutting for *Quercus nuttallii* regeneration would require the creation of openings of at least 100 m in diameter (Johnson and Krinard, 1989; cited in Meadows and Stuntruf, 1997), or 1-2 ha for light demanding species (Marquis, 1989; Meadows and Stantruf, 1997). Smaller openings would not provide enough sunlight to allow this species to develop into overstorey trees, and the patch would eventually become dominated by more shade-tolerant species. If the top height of *Quercus nuttallii* is assumed to be about 30 m, the recommended cut area is the equivalent of an opening with a diameter of about 3-5 times tree height. Although such an opening could be regarded as a small clearcut, it is close to group-selection cutting. The distinction between patch cutting and small clearcutting would depend on stand size, topography, and shade tolerance of the species. Patch cutting is a complicated and intensive approach to forest management, but, if applied properly, can be used to successfully establish bottomland oak (Clatterbuck and Meadows, 1993) and probably many other shade-intolerant species.

The group-selection method can be used to convert hardwood secondary stands to mixed managed stands of hardwoods and softwoods, as shown in Figure 8-21, by planting seedlings of commercial softwoods amongst the secondary hardwoods. This method could be useful for sustainable forest management. The stand established by this method for the conservation of soil and biodiversity can be compared with the monoculture stand established following clearcutting (seen behind the mixed stand in Figure 8-21). The mixed stand also has aesthetic value.

Recently, the widespread use of monoculture plantations, especially coniferous plantations, has been questioned from the perspective of conservation of biodiversity and conservation of soil (Benecke, 1996; Fujimori, 1997a, 1997b; Schabel and Palmer, 1999; Piussi and Farrell, 2000). Group-selection methods can be used to convert a monoculture plantation to a mixed stand by natural regeneration or planting (Fujimori, 2000). The size of the cutting area for such a conversion could range from

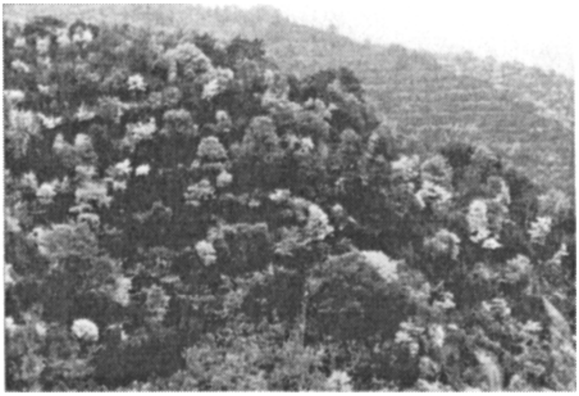

Figure 8-21 A mixed stand of hardwood and commercial softwoods in private forest, Gifu Prefecture, Japan. This stand has been developed to produce *Cryptomeria japonica* (sugi) commwecially, but giving consideration to the conservation of soil and biodiversity. It is managed using the group selection method.

single-tree selection to small clearcutting, depending on the regenerating species and the local natural and/or social conditions.

In general, single-tree selection is applicable to very shade-tolerant to tolerant species, group-selection cutting is applicable to moderately shade-tolerant to moderately shade-intolerant species, and patch cutting is applicable to shade-intolerant to very shade-intolerant species (Figure 8-22). The appropriate cutting size should be decided according to the shade-tolerance of the desired species. If a mixed stand of shade-tolerant and intolerant species is being established, a combination of group-selection and small patch cutting could be applicable, with actual sizes and combinations of the openings dependent on the desired mixture of species. Frost damage is sometimes greater in small openings because of cold air accumulation, and such areas are called frost holes or frost pockets. In areas where frost holes are anticipated, methods such as single-tree selection or strip-selection are preferable.

A patch mosaic stand that has developed from group-selection or patch cuttings would have enhanced biodiversity. The mosaic of many different age classes that is created would provide a wide range of niches for various animal species. The boundaries between patches of old trees and young trees or grasses provides food, protective cover, and nests for many animals (Yui and Ishii, 1994). However, some species of wildlife and plants with strong interior-forest microclimatic preferences (i.e., a requirement for large areas of mature or old-growth stands) may have special

Size of cutting area	← Small		Large →
	Single selection cutting	Group selection cutting	Small clearcutting (Patch cutting)
Shade tolerance	Very tolerant	Moderately tolerant	Intolerant
	Tolerant	Moderately intolerant	Very intolerant

Figure 8-22 The relationship between shade-tolerance of species and the appropriate size of a cutting area to ensure regeneration. The boundary between the group selection cutting and small clearcutting (patch cutting) is when the diameter of the cut area is about twice the height of the surrounding trees. The boundary between small clearcutting (patch cutting) and large clearcutting is when the diameter of the cut area is about three to five times the height of the surrounding trees.

conservation requirements (Chen et al., 1992). In the Pacific Northwest of the United States of America (west side of Oregon and Washington), a cutting method (aggregated clearcutting) which gradually enlarges the patch made in the first cutting has been proposed (Swanson and Franklin, 1992). This method could be an option for the regeneration of very to moderately shade-intolerant species in many parts of the world, or a mixture of patch cutting and aggregated clearcutting might be appropriate to particular site and social conditions.

8.1.2.3-3 Strip-selection method

In the strip-selection method, long and narrow strips, each composed of a different age class are created. These strips generally line up in order of age class. Successive cuttings are made within each strip, usually against the direction of the prevailing winds. However, in mountainous areas with relatively steep slopes, strips cannot always be arranged against the prevailing wind.

This method has enables efficient extraction, but if the strips are arranged vertically along the steep slopes, there can be problems with soil erosion. It is better for soil conservation to arrange the strips horizontally down the slopes, but this is less efficient for extraction. Therefore, a compromise of the two techniques can be achieved by a herring-bone pattern which was discussed in Section 6.2.4.5 and shown in Figure 6-24. Figure 8-23 shows a plantation stand of *Chamaecyparis obtusa* in which

Figure 8-23 A stand of *Chamaecyparis obtusa* (hinoki) in Ibaraki Prefecture, Japan, in which the herring-bone selecction method has been applies. The overstorey was cut 20 and 1 years previously when stand was 77 and 96 years old, and the understorey planted with seedlings following cutting.

the herring-bone selection method was used. The trees in the understorey were planted 10 and 1 years ago when the overstorey trees were 88 and 97 years old, respectively.

8.2 Coppice Methods (Production of small logs mainly for fuelwood, pulpwood, and other biomass uses)

Regeneration methods can be classified as either seed based (regeneration from seeds or planted nursery stock) or vegetative (regeneration from sprouts or layered branches) (Section 2.4.3.1). Forests developed from seed or planted nursery stock are traditionally called high forests and ones developed from sprouts or layered branches called low forests. The term coppice is used to describe stands which arise primarily from sprouts and the means of regenerating such forests is called the coppice method (Smith, 1986).

The coppice method has been used throughout the world since ancient times to produce fuelwood (Figure 8-24). Although the demand for fuelwood has declined in advanced countries, the significance of the coppice method for energy production remains because it is important in developing countries and is being re-evaluated in advanced countries. The coppice method has also become important in many countries for the production of pulpwood.

However, in advanced countries, a high proportion of coppice stands have been left unmanaged since the fuel revolution, and their ongoing

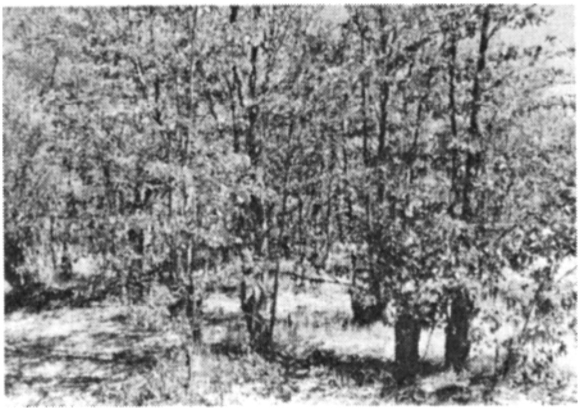

Figure 8-24 Coppice stand of *Colophospermum mopane* (mopane) in Zimbabwe.

treatment is an important issue (Matthews, 1989; Fujimori, 1997b, 2000; Piussi and Farrell, 2000). Re-evaluation of coppice systems for the production of biomass energy (Sections 12.3.2, 14.3.3) may be one option, or conversion to mature or old-growth forest for the production of sawn timber, recreation, conservation of biodiversity or other benefits are other options.

In Mediterranean countries, coppice stands are managed not only for the production of fuelwood but also for products such as acorns, chestnuts, cork, and grazing. However, owing to social changes, the management of coppice stands has been abandoned and the incidence of fire has increased. This is because changing farming practices have meant that farmers no longer collect dead wood and litter, which accumulates, and together with the development of low scrub in former fallow land between the stands of trees, increases flammability and facilitates the transmission of fire from the ground to the tree crowns (Piussi and Farrell, 2000). Such problems can only be solved if the associated socio-economic issues are dealt with concurrently with the forest management issues.

In Japan, coppice methods are used to produce mushroom bed logs. Many coppice forests which used to produce fuelwood have been converted to mushroom bed log production. Mushroom bed logs are produced from stems that have a DBH of 10-14 cm. There is also interest in converting coppice forests formerly used to produce fuelwood to the production of sawn timber, or unmanaged natural forests.

The main types of asexual vegetative reproduction that are important in regeneration in coppice forests are shown in Figure 8-25. Sprouts which arise from the side of a stump almost invariably develop from dormant buds (Smith, 1986) (A1 and A2). This type of sprout is the most common and can appear at any height on the stump. The sprouts which arise at, or very close to, ground level (A1) can form independent roots and develop into stable trees, and those which arise further above the ground (A2) are generally not firm and tend to develop into crooked trees or are prone to breaking. Therefore, it is recommended that coppice stumps are cut close to the ground.

The sprouts which arise between the bark and wood on the surface of the stump (B) in Figure 8-25 develop from adventitious buds (Kamitani, 1986a). Adventitious sprouts are less common than dormant buds and tend not to be firm and are prone to breakage by snow or wind. Adventitious sprouts are limited to a few species, including oak (*Quercus crispula*, mizunara) (Kamitani, 1986a).

Some species produce root-suckers (C) which develop from adventitious buds in the root cambium. Root-suckers arise at even spacings and are not clustered, so they tend to develop into straight trees. They are therefore a preferable form of regeneration because they produce a desirable stand

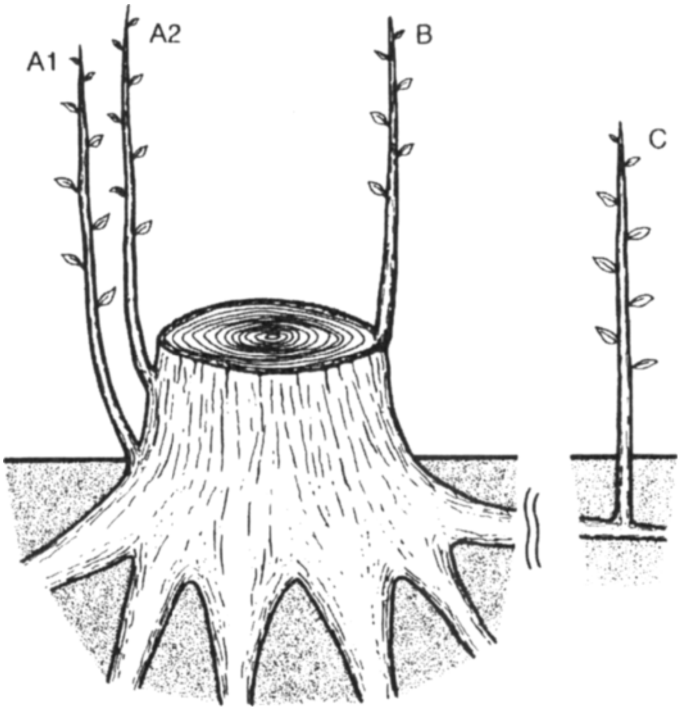

Figure 8-25 Forms of vegetative sprout. A1: Sprout from a dormant bud at ground level. A2: sprout from a dormant bud at a higher position. B: Sprout from an adventitious bud. C: Root sucker.

structure. The ability to produce sprouts and root-suckers is generally limited to hardwood species, with the exception of some coniferous species such as *Sequoia sempervirens* (coastal redwood) in the United States of America, *Torreya nucifera* (kaya) and local races of *Cryptomeria japonica* (sugi) such as kuma-sugi in Japan. Of the main species in Japan used to produce wood from coppice, *Populus shieboldii* (yamanarashi) is a species which typically regenerates by root suckers. Other species such as *Quercus serrata* (konara) sometimes produce root suckers in addition to sprouts from the side of the stump. If regenerated sprouts are thinned, preferential retention of root-suckers is desirable.

Layering is another form of vegetative reproduction in which low-hanging branches that have been partially buried in the soil form roots. Layering is found in *Cryptomeria japonica* (sugi) in natural forests in areas of heavy snow in Japan. In a private forest in Sawauchi Village in Akita Prefecture, a selection method reliant on layering has been adopted (Figure 8-26). A similar form of regeneration is found in *Cryptomeria*

Figure 8-26 Regeneration of *Cryptomeria japonica* (sugi) from stumps following selective harvesting of stumps. At pruning, branches at the base of the stem are left and when the stem is harvested, one or two branches at the base grow into stems of the next generation.

japonica in Kitayama forestry area in Kyoto Prefecture (Figure 8-26). At pruning, low branches are retained, and at harvesting, the stem is cut just above these small branches. The branches then grow up straight and develop into stems. In each new stem, the lowest small branches are left for future regeneration. In *Cryptomeria japonica*, branches near the ground remain small despite the growth of the tree. The harvested poles are used for ornamental pillars or similar applications in traditional Japanese houses.

8.2.1 Simple coppice method

The simple coppice method is based on regeneration by sprouts or root suckers and is generally used in hardwood forests. Typically, the coppice is cut on a short rotation for the production of fuelwood, pulpwood, or other biomass uses. This method has similarities to agricultural methods, i.e., the rotation is relatively short, regeneration, tending, and harvesting methods are simple, and the forest ecosystem is always immature. The advantages and disadvantages of this method are therefore similar to those of agriculture. Coppice methods are most appropriately applied on flat areas or on gentle slopes, because if it is used on slopes in mountainous areas, soil erosion can be induced and site depletion can follow. In snowy areas, coppice methods can increase the chance of avalanches, which further exacerbates soil erosion. In many snowy areas of Japan, low productivity, dwarf broad-leaved deciduous stands are often found on steep slopes. The presence of many of these stands has been attributed to the intensive use of simple coppice methods in the past.

Method of cutting

Stems should be cut close to the ground so that the sprouts can arise from ground level and form their own roots. The stump should be cut on a slant with a smooth surface to prevent water settling and avoid rot.

Season of cutting

Cutting should be done during the dormant season, because the productivity of the sprouts will be greatest if they can utilise the stored photosynthates produced during the previous growing season (Satoo and Takegoshi, 1952). If cutting is deferred until after the new leaves have developed in spring, the sprouts will be less productive (Akenaga, 1929; Asakawa, 1939) and the bark will tend to strip easily, which may cause rot. If cutting is delayed until summer, the sprouts will be susceptible to freezing damage in the following late autumn, because the sprouts continue growing longer than usual and the development of frost hardiness is delayed.

Rotation

There are several types of relationship between stump age and the ability to produce sprouts. In some species, the ability to produce sprouts does not change with age; in other species, the ability to produce sprouts increases with stump age up to about 50 years of age; and in other species sprouts can only be produced from juvenile stumps. In many hardwood species, sprouting ability peaks at about 30 years of age (Kamitani, 1986a). The rotation period for forests managed under coppice should therefore be less than 30 years. Smith (1986) considered that the longest coppice rotation likely to produce satisfactory results is between 30 and 40 years and Matthews (1989) specified that a coppice rotation should not be more than 40 years. Some eucalypt species lose their ability to sprout very early, i.e., can only sprout when they are juvenile.

Thinning of sprouts

For the production of fuelwood or pulpwood, sprouts do not usually need to be thinned. However, thinning is required to produce mushroom bed logs because a specific log size is required. Thinning should not be done within the first two or three years after cutting, because young sprouts are susceptible to snow and wind damage, and enough sprouts must be retained to maintain stocking in case of damage.

Application of the simple coppice method

Simple coppice method is regarded as the oldest silvicultural method known in most of the countries in the world. It has been traced back to Neolithic times in Britain and was used throughout the Bronze Age and during the Roman and Saxon periods. In France and Germany coppice was practiced during the middle ages mainly under short rotations for the production of fuel. Coppice was widespread by the year 1250 in Britain, even in large woodland areas such as the Forest of Dean (Matthews, 1989).

During the 17th and 18th centuries throughout Europe, coppice forests continued to supply domestic firewood, building material, fencing, and increasing quantities of fuel for industry and oak bark for tanning. By the middle of the 19th century in many parts of Europe, coal began to supplement wood as a fuel and many of the traditional products of coppice were being superseded. In Britain, the decline in coppice management accelerated after the World War I as rural electrification spread, and declined further after the World War II as oil and gas became readily available. By the 1950s regular coppicing had become rare and conversion of coppice to high forest was under way (Matthews, 1989). Similar historical trends of coppicing are also found in other advanced countries outside of Europe.

Recently, the use of short rotation forestry for energy production and to mitigate CO_2 concentration in the atmosphere has been re-evaluated, especially in European countries. Short rotation forestry can be used as an alternative crop on low productivity farmland to produce an annual yield of wood for farmers (Hofmann-Schielle et al., 1999; Liesebach et al., 1999; Lindroth and Båth, 1999). Short rotation management usually involves intensive coppice management of fast growing species from the genera *Populus*, *Salix*, or *Alnus*. These species are planted at a high density and harvested at short rotations using the simple coppice method.

Short rotation forestry is close to agricultural systems and techniques in that high yield clones, hybrids, and genotypes are selected, fertilization is usually required to maintain or improve site productivity, and basic pest and disease management is required (Sasaki, 1992; Gruppe et al., 1999; Mitchell et al., 1999; Ramstedt, 1999). Under this type of management, *Populus*, *Alnus*, and *Salix* in temperate and boreal zones can have a productivity of between 2-25 t/ha/yr (above-ground dry matter) under rotations of between 1 and 15 years (Sasaki, 1992; Ceulemans and Deraedt, 1999; Hofmann-Schielle et al., 1999; Liesebach et al., 1999;

Linddroth and Båth, 1999; Mitchell et al., 1999).

The most common coppice method now used in Japan is for the production of mushroom bed logs from *Quercus acutissima* (kunugi) and *Quercus serrata* (konara). *Quercus acutissima* and *Quercus serrata* were commonly managed using the simple coppice method for the production of fuelwood, and now they have been converted to produce mushroom bed logs. *Quercus acutissima* and *Quercus serrata* produce sprouts easily and commence seed production within decades. These characteristics have enabled these species to survive and dominate over a long history of coppice management. The rotation period to produce trees with a 10-14 cm DBH is about 15-20 years for *Quercus acutissima* and somewhat longer for *Quercus serrata*. The rotations to produce fuelwood or pulpwood may be more variable, as the size of the logs can be more variable. The best season for the inoculation of shiitake mushrooms (*Lentinus edodes*) grown on the bed logs is from October to December, so logs should be cut in this season. If mushroom bed logs are not being produced, the stems should be cut in the early spring before the buds begin to swell, to avoid the risk of the stumps being damaged by winter cold through separation of the cortex from the wood (Matthews, 1989).

As the sprouts of *Quercus serrata* can coexist for a long time, thinning should be done three or four years after cutting, leaving the best single sprout except where the density of stumps is low, in which case two sprouts should be left. The sprouts of *Quercus acutissima* will thin naturally as the stand grows, but production is increased if the sprouts are thinned. If the density of stumps of *Quercus acutissima* or *Quercus serrata* is low, naturally regenerated seedlings or additional planted stock are raised between the stumps. The standard number of trees in a coppice forest is about 4000 per ha (Sasaki, 1986).

If repeated clearcutting occurs in broad-leaved evergreen stands in the warm-temperate zone of Japan, the dominant species tend to shift from broad-leaved evergreen species to broad-leaved deciduous species. This is attributed to the change in microclimate following clearcutting which does not allow regeneration by natural seeding of shade-tolerant broad-leaved evergreen species. Although most of broad-leaved evergreen species can produce sprouts, this ability declines over time and with repeated cutting, and so broad-leaved deciduous species become prevalent. As a consequence, coppice forests of broad-leaved evergreen species are now only common in the southern part of Kyushu and the Nansei Islands.

Castanopis cuspidata (kojii) is the species most commonly managed using coppice methods in the southern Kyushu. The productivity of *Castanopis cuspidata* is high, so efficient production of pulpwood or mushroom bed logs using the simple coppice method is possible. Other species, such as *Quercus salicina* (urajirogashi), *Quercus acuta* (akagashi), and *Quercus glauca* (arakashi), can also be managed under coppice methods.

8.2.2 Coppice selection method

The coppice selection method is usually used for shade tolerant species. In *Cryptomeria japonica*, a coppice selection method based on layering can be used in snowy areas, and such a method is applied in Sawauchi Village, Akita Prefecture, Japan. The low-hanging branches of young trees touch or are buried in the litter layer of the soil and develop roots, forming new individuals. Every five years or so, harvesting of single trees is conducted, selecting the biggest trees with a DBH in excess of 50 cm to improve the light condition in the lower strata.

In Kitayama forestry area in Kyoto Prefecture, Japan, *Cryptomeria japonica* is regenerated from small branches retained near the ground. Three to five stems of different ages are left on each stump and stems with a diameter (about 6-7 cm at the base) suitable for ornamental logs are harvested selectively (Figure 8-26). When a stem is harvested, it is cut just above the small branches near the ground which then develop into stems, of which the best one is retained. The history of this method is not clear but it seems to have been in use since about 400 years ago.

The wood of *Castanopis cuspidata* (kojii) has been evaluated recently for sawn timber in Japan. Logs older than 50 years are prone to rot, so a method to produce logs of about 20-30 cm DBH from a rotation of 30-35 years is being developed (Agriculture, Forestry, and Fishery Division of Kagoshima Prefecture, 1990; Taoda, 1990, 1994; Fujimori, 1991a). In this method, thinning is repeatedly conducted to produce logs of the required size. This method will develop into a coppice selection method. *Castanopis cuspidata* is a shade tolerant species, so selection methods can be used. Sustainable coppice management of *Castanopis cuspidata* or other broad-leaved evergreen species is possible by adopting the selection method. The operational methods for cutting are the same as those for the simple coppice method.

8.2.3 Coppice-with-standards methods

The coppice-with-standards method combines production of fuelwood with sawn timber from larger trees. In general, this method is done by reserving a few of the better trees, called standards, at the time each crop of coppice material is cut. The standards comprise several cohorts whose age differences correspond to the coppice rotation (Smith, 1986; Matthews, 1989).

In Europe, the coppice-with-standards methods was historically popular, but has diminished as demand for fuelwood has declined (Matthews, 1989). The coppice-with-standards method was not common in Japan, although a combination of broad-leaved species as coppice with

Pinus densiflora (akamatsu) as a standard was used in the past. A typical version of this combination of species had three rotations of coppice for each cohort of *Pinus densiflora* (Inoue, 1960). When *Pinus densiflora* and the coppice were harvested, the *Pinus densiflora* was planted sparsely, the coppice harvested 25 and 50 years after planting, and then both the *Pinus densiflora* and coppice are harvested when the *Pinus densiflora* is 75 years old. The operational methods for cutting in this method are same as those used in the simple coppice method.

8.2.4 Coppice method research requirements

Research is required to clarify the relationships between coppice management and the conservation of soil and water resources and conservation of biodiversity. For the conservation of soil and water resources, the relationship between coppice management and the angle of the slope on which coppice management is undertaken must be analyzed. Specific questions include the appropriate density within and between stools (stumps), competition between species, stump longevity, dynamics of the root systems, vegetation propagation, and regeneration by seed (Piussi and Farrell, 2000).

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Part IV

Silvicultural Strategies for Sustainable Forest Management

As described in the Preface, the paradigm of forest management has shifted across the world from maintaining a sustainable yield of forest products to sustained forest ecosystem management. Sustainable forest management is synonymous with sustained forest ecosystem management. Sustainable forest management aims to maintain and enhance the various functions of the forest ecosystem. This Part examines what defines sustainable forest management (Chapter 9) and some appropriate silvicultural methods that fulfil various functions of forests and achieve different objectives of forest management (Chapters 10-15), based on in Parts I to III.

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Chapter 9

Sustained Forest Ecosystem Management

9.1 Significance of sustainable forest management

Sustainable forest management was emphasized in the Statement of Forest Principles and Agenda 21 adopted at the United Nations Conference on Environment and Development (UNCED), held in Rio de Janeiro in June 1992. The Helsinki Process and Montreal Process* were initiated to develop a definition of sustainable forest management that would enable evaluation of forest management on the basis of a framework of criteria and indicators. These developments have shifted the paradigm of forest management from management for the sustained yield of forest products to sustained forest ecosystem management (e.g., Schlaepfer et al., 1993). According to the definitions developed in the Montreal Process, the criteria are a set of overall objectives or conditions by which sustainable forest management may be assessed. Each criterion comprises a set of related indicators which can be monitored to assess change. The main criteria for sustainable forest management are related to the ecological functions of the forests, such as maintenance of biodiversity, maintenance of productive capacity, soil and water conservation, and carbon sequestration, but a criterion for multiple socio-economic benefits is also included.

Sustainable forest management can be defined as management that

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*** Helsinki Process and Montreal Process**

Following UNCED in Rio de Janeiro, countries in temperate and boreal zones submitted criteria and indicators for conservation and sustainable forest management to the Commission for Sustainable Development (CSD) of the United Nations by April, 1995. European countries (Helsinki Process) and other countries in temperate and boreal forest zones (Montreal Process) made submissions. Other criteria and indicators were also developed, both before and since UNCED, and under other initiatives, including the ITTO (International Tropical Timber Organization) initiative and four others as of 2000. The criteria of Helsinki Process and Montreal Process are shown in Tables 9-1 and 9-2. Each criterion is composed of several indicators.

Table 9-1 Criteria and number of indicators of the Helsinki Process.

Criteria	Number of indicators
1. Maintenance and appropriate enhancement of forest resources and their contribution to global carbon cycles	5
2. Maintenance of forest ecosystem health and vitality	7
3. Maintenance and encouragement of productive function of forests (Wood and non-wood)	3
4. Maintenance, conservation and appropriate enhancemaent of biodiversity in forest ecosystems	7
5. Maintenance and appropriate enhancement of protective functions in forest management	2
6. Maintenance of other socio-economic functions and conditions	3

Table 9-2 Criteria and number of indicators of the Montreal Process.

Criteria	Number of indicators
1. Conservation of biodiversity	9
2. Maintenance of productive capacity of forest ecosystems	5
3. Maintenance of forest ecosystem health and vitality	3
4. Coservation and maintenance of soil and water resources	8
5. Maintenance of forest contribution to global carbon cycles	3
6. Maintenance and enchancement of long term multiple socio-economic benefits to meet the needs of society	19
7. Existence of a legal, policy and institutional framework that facilitate sustainable forest management	20

In the Montreal Process, five of the criteria are related to ecological functions of forests and the sixth criterion is related to the economic and cultural functions. A total of 67 indicators were developed for the seven criteria. The indicators for the second criterion are closely related to forest products. The seventh criterion does not relate to the functions of forest but to the legal, institutional and economic frameworks required to achieve criteria 1-6. This framework is helpful for discussing and defining sustainable forest management.

meets present needs for various forest functions by maintaining the forest ecosystem's health and vitality, without compromising the ability of the forest to fulfil the needs of future generations. The forest functions considered as objectives of forest management in this book are conservation of biodiversity, conservation of soil and water resources, enhancement of forest products, enhancement of cultural and recreational functions, and maintenance of forest contribution to global carbon cycle. The relationships between these functions are discussed in Section 9.3.

The trend of sustained forest ecosystem management began in the late 1970s. In the 1980s, the notion of New Forestry, which emphasized the ecosystem as the basis for forest management, arose in the Northwest of the United States of America (e.g., Franklin, 1989). These ideas were further developed into the concept of Ecosystem Management (e.g., Franklin, 1997) and spread from the United States of America to many other countries in the world during the 1990s. Ecosystem Management satisfies society's varied needs from forests, is developed using scientific knowledge of the ecosystem, and has an ethical basis, and can be regarded as a form of sustainable forest management. It is sustainable because it satisfies the needs of the present generation, without losing the ability to satisfy the needs of future generations.

In Europe, trends such as nature-oriented silviculture (Lähde, 1992, 1993), ecological silviculture (Benecke, 1996), and diversity-oriented silviculture (Lähde et al., 1999) for enhancement of sustainable forest management have appeared in the past decade. In Japan, interest in diversity-oriented forest management including long rotation and non-clearcutting methods arose in the late 1980s to combine environmental and economic benefits (Fujimori, 1991a, 1997).

Although the emphasis on enhancing environmental functions of forests has increased, there has also been an increasing recognition of the potential role of forest products in mitigating CO_2 concentration in the atmosphere.

9.2 Integrating sustainability criteria into new silvicultural systems

The framework of the criteria of the Montreal Process can be illustrated as shown in Figure 9-1. The criteria shown vertically (Criteria 1, 2, 4, and 5) are those immediately related to functions of forest ecosystems. These functions can be enhanced and/or maintained by means of forest management. Maintenance of forest ecosystem health and vitality (Criterion 3), shown horizontally at the base of the Figure, is a fundamental condition for enhancing and/or maintaining the four criteria (functions) above. Criterion 6 (multiple socio-economic benefits) which are

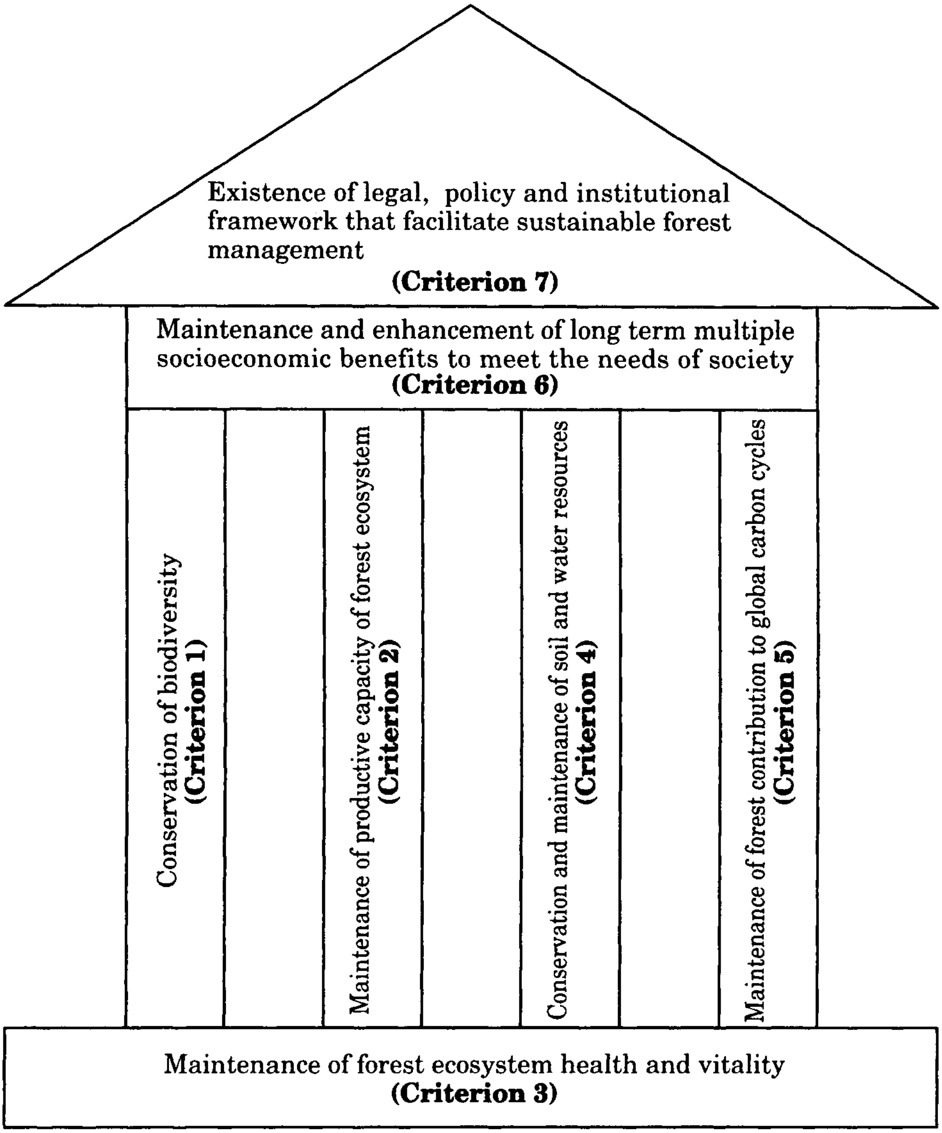

Figure 9-1 The framework of the criteria of the Montreal Process (based on a figure presented by J. Maini at a workshop in Kochi, Japan, 1997).

a result of enhancing the ecological functions of forest (Criteria 1, 2, 4, and 5) is shown horizontally above those four criteria. Criterion 7 (legal, institutional, and economic frameworks) which supports the enhancement and/or maintenance of Criteria 1 to 6 is placed above those criteria. In an indicator in Criterion 7, importance of developing monitoring systems is emphasized. A similar figure could be drawn for the criteria of the Helsinki Process, although the legal and institutional criterion is not in the Helsinki Process.

In the criteria of the Montreal Process, ecological Criteria 1, 2 4, and 5 are closely related to the generally recognized forest functions. The cultural and recreational function recognised in Criteria 6 of both the Montreal and Helsinki Processes (Tables 9-1, 9-2) is also generally recognized as a forest function and an objective of forest management.

Criteria, such as those specified by the Montreal and Helsinki Processes, help to define the components of sustainable forest management. Although criteria are not objectives of forest management themselves, they can form the basis of management practices that will meet the objective of sustainable forest management. In recognition of the Montreal and Helsinki Processes, the following criteria will form the basis of the discussion of ecological and silvicultural strategies for sustainable forest management.

1. Conservation of biodiversity
2. Conservation and maintenance of soil and water resources
3. Maintenance of productive capacity for forest products
4. Maintenance and enhancement of cultural and recreational functions
5. Maintenance of forest contribution to global carbon cycle
6. Maintenance of the forest ecosystem's health and vitality

These criteria correspond to Chapters 10 to 15. Although the sixth criterion is not a specific forest function, as recognised above, it is an important condition for achieving criteria 1-5.

Management systems that maintain, conserve or enhance these functions need to be considered at both a stand and landscape level. Ecological and silvicultural strategies that can be applied to meeting these criteria are discussed in the following Chapters.

9.3 The relationship between forest ecosystems and human requirements from the forest

Forest functions have usually been regarded as having equal importance, but Suzuki (1994) argued that these functions should be stratified, and Fujimori (1999) developed this concept as shown in Figure 9-2. The functions of the forest are stratified vertically and horizontally, with the horizontal length of the uppermost line representing their relative importance in meeting the needs of human society. The horizontal length of each function varies depending on the social conditions of the area. The relative importance of each function as a fundamental component of the forest ecosystem is represented by its vertical depth and area.

Soil conservation is the most basic component of sustainable forest management, because productivity (forest production), water yield (soil

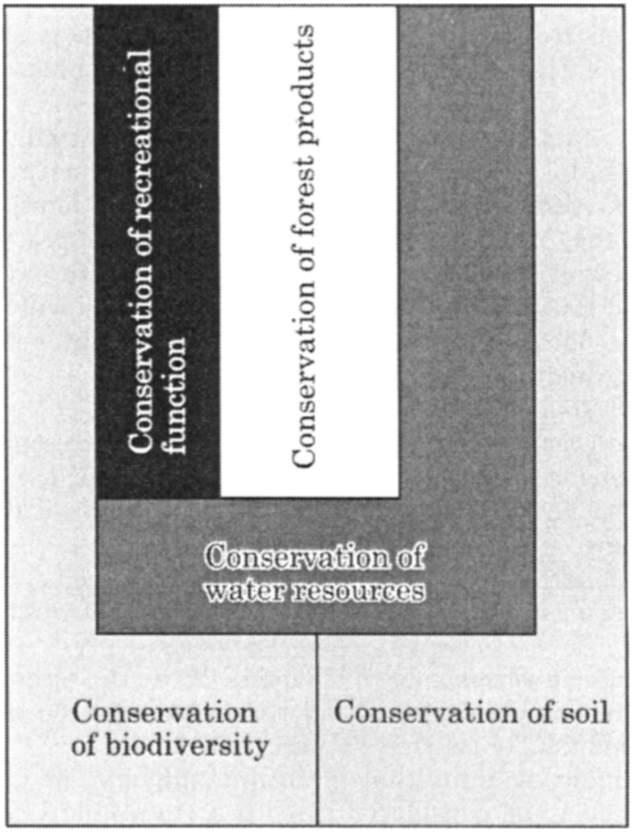

Figure 9-2 Stratification of the functions of forests. The vertical length and area of each function indicates its importance as a functional component in the forest ecosystem. The horizontal length of the uppermost line indicates its importance as a provider of social benefits. The social benefits vary depending on natural and social conditions. (Fujimori, 1999)

water holding capacity), and biodiversity all depend on the soil. However, biodiversity is also a fundamental component of sustainable forest management, because elements of the forest ecosystem, including the soil, depend on interactions between a wide range of species. Conservation of soil and biodiversity, therefore, forms the basis of an ecosystem and allows conservation of water, and provision of forest products and recreational resources to be achieved.

A high proportion of our immediate demands in daily life are dependent on the functioning of the forest; e.g., provision of forest products, water, and recreational opportunities. These three functions therefore have been represented with a greater horizontal length of the uppermost line in Figure 9-2. Although our demand for soil and biodiversity is less immediate, the fundamental importance of these functions should be recognized. Thus, all functions need to be considered together.

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Chapter 10

Conservation of Biodiversity

10.1 Significance of biodiversity

The conservation of biodiversity (biological diversity) has been recognized as one of the most important duties of human beings that should be undertaken as part of our social and economic activities. The importance of conserving biodiversity is discussed by many authors, including McNeeley et al. (1990) and Washitani and Yahara (1996), and the reasons for biodiversity conservation can be summarized by the following four points.

- **Maintenance of resources for present and future generations**

  There are species which are not currently used, or which do not have currently recognized value, but which may have some future value as a resource. The maintenance of the genes and genetic diversity of such species is important, because it may enhance future human welfare.

- **Maintenance of ecosystems which provide the environment and resources for present and future generations**

  Human beings coexist with a community of other species within the natural environment. It is difficult to predict how ecosystems will change if some species become extinct. However, a decrease or extinction of common species usually means that the environment has been degraded. Monitoring biodiversity can provide an indicator of the condition of the environment. Maintaining ecosystems will also directly maintain the supply of resources.

- **Value as a source of culture**
  The natural environment has played an important role in the development of human sensitivity and intelligence, and the range of human cultures reflects the natural environment and its biodiversity. Therefore, losing biodiversity means losing the basis and origin of our cultures.

- **Intrinsic value of the existence**
  This is an ethical position that recognizes that all species have value because they have evolved over a long period and are adapted to specific ecological conditions.

The first three reasons for valuing biodiversity are inextricably linked with the welfare of human society, but the fourth reason is not linked to human welfare and is, instead, an ethical reason which has no advantage or disadvantage for human society. The third and fourth reasons could be regarded as a cultural reasons for valuing biodiversity, and the first and second reasons value biodiversity for its resource or environmental value.

Given that biodiversity is valuable for this range of reasons, its maintenance should always be included as an objective of forest management. In terrestrial ecosystems, forests are the largest reservoirs of biodiversity (Roxburgh and Noble, 2001), and this further emphasizes the importance of including it as a goal of forest management.

10.2 Ecological principles of biodiversity

Biodiversity has arisen as a result of adaptive evolution through the processes of natural selection and biological interaction (Washitani and Yahara, 1996), and such biological interaction will continue to be a source of biodiversity. Therefore, it is essential that maintenance of the capacity for biological interaction always be considered in strategies aimed at conserving and maintaining biodiversity.

The presence of a diversity of plant species results in a greater diversity of plant-dependent organisms. In a forest, plants are usually distributed unevenly and vertical stratification develops. A number of different plant species can coexist on a given area with a particular microclimate. The growth of these plants creates a microenvironment suitable for other species. Depending on the intensity and frequency of disturbance on the site, various other species may be able to exist on the same site. Thus, a diversity of niches exist in forest communities, which enables a high level of biodiversity to develop (Perry, 1994).

The different life histories of plants, and their various requirements for environmental resources, has arisen as a result of evolution, and enhances continuing evolution of organisms through the selection pressures that arise from competition, stress, and disturbance (Grime, 1977). Evolution of some plants with particular life-histories has enhanced the development of other species that are directly dependent on coexistence with other plants, animals or fungi. These dependencies mean that if the extinction rate of plants increases, there will be increased extinction of species of animals and fungi, and vice versa.

There are four levels of diversity to be considered in conservation strategies: genetic diversity; species diversity; ecosystem diversity; and landscape diversity (Noss, 1990). These levels of diversity interact, and these interactions must be well understood if biodiversity is to be maintained. The extinction of a species, for example, may be caused by degradation of genetic diversity or by destruction of ecosystem diversity at a landscape level.

Maintenance of biodiversity will sometimes conflict with management for the efficient production of wood, but it may help prevent the outbreak of abnormal pests and diseases through complex species interactions and the food web. Thus, the maintenance of biodiversity is fundamental to protecting the forest from biological injury over a long period and broad area.

10.3 Forest conditions that enhance biodiversity

10.3.1 Significance of the forest ecosystem to biodiversity

Forest stands usually develop into large, complicated structures, which contain abundant habitats and niches for various organisms. Different types of forests can develop depending on site characteristics. As forests age, they pass through different stand development or successional stages (Figure 2-22). Each stand development stage and forest type has different range of habitats and niches and supports different organisms. An old-growth forest (Figure 10-1) is usually composed of trees of various ages and sizes, snags and fallen logs, herbs, and soils with high level of organic matter. Landscapes which comprise forests of a range of stand development stages will have an abundance of habitats and niches, and will therefore favour high biodiversity.

10.3.2 Stand development stage and biodiversity

Understanding the relationship between successional or stand development stage and biodiversity is important for the management of forests. In natural forests, the diversity of both plants and animal species

Figure 10-1 Old-growth forest of mixed broad-leaved evergreen species in southern Kyushu, Japan.

is likely to be highest in the herb/brush stage (stand initiation stage), lowest in the young stage (stem exclusion stage), recovers to a higher level in the mature stage (understorey reinitiation stage), and is maintained at a high level in the old-growth stage (Figure 2-22). Figure 10-2 is an example of the relationship between stand development stage of natural forests and species diversity of mammals in the Pacific Northwest of the United States of America (Harris, 1984; Franklin and Spies, 1991; Oliver, 1992). The high diversity of plant species in the herb/brush stage is a result of the survival of forest species and the addition of weedy generalist species (Halpern, 1988; Schoonmaker and McKee, 1988). Species diversity is lowest in the young stage when a limited number of dominant tree species close the overstorey and thereby exclude most other plant species which in turn reduces the diversity of consumers and decomposers. In the mature stage, an understorey develops, increasing the number of plant species and the habitat for animals. In the old-growth stage, there is the greatest number of stand layers, composed of various cohorts of individual trees of various ages and sizes. In addition, there are large numbers of snags and fallen logs which form important structural components of the old-growth stage. As a result, there is a great variety of niches in the old-growth stage, which enables the survival of the many species that are usually associated with old-growth forests (Franklin and Spies, 1991).

The relationship between stand development stage and biodiversity in plantations is similar to that of natural forests, although the diversity of

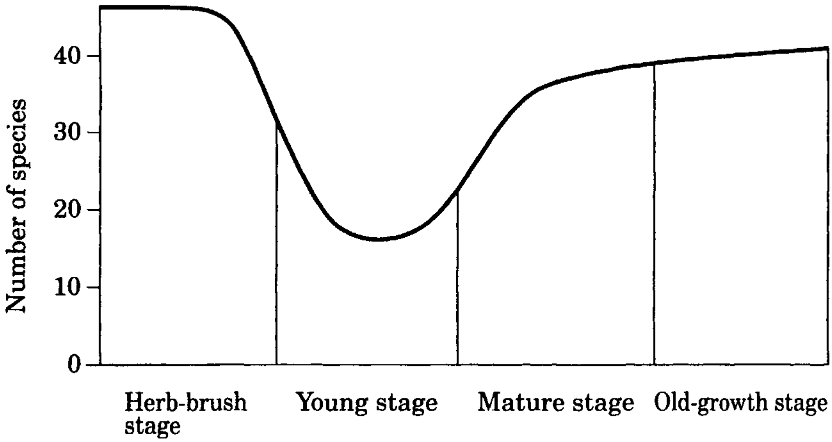


Figure 10-2 The relationship between stand development stage and mammal diversity in *Pseudotsuga menziesii* (Douglas-fir) forests (Franklin and Spies, 1991).

plantations is generally lower at each stage (Yoshida, 1983). The diversity of species in the herb/brush stage in a plantation is lower than that of a natural forest, because in plantations, there are fewer snags, logs, and debris to provide habitats for various species. The structure of the young stage of a plantation is very simple, and the canopy is generally a single species which closes evenly, reducing the diversity of species compared with natural forest at a similar stage. The diversity of species can increase to quite a high level in the mature stage of a plantation, as a variety of plant species can develop in the understorey.

10.3.3 Relationship between niches (habitats) and forest types

The ability of different species to occupy different niches is a fundamental factor underlying species diversity (Perry, 1994). As a forest stand develops into different stages, its structure develops and the number of niches increases. The actual structure and associated number of niches will depend on the site conditions and disturbance history. This is best demonstrated by the patterns of occurrence of particular plants or animals, and such patterns can be seen in Japanese forests.

The number of species of fungi in a forest varies according to the dynamics of the forest and is highest in mature and old-growth forests (Doi, 1977). The diversity of insects also increases as the structure of forest develops (Toda, 1987). Many bird species living in forests are predators at higher levels of the food chain, and because their presence reflects stand structure and the presence of prey, they can be regarded as an indicator of biodiversity. The diversity and density of birds increases with developing stand structure, and if there is large continuous forest cover, or a mosaic of forests across the landscape (Yui, 1994; Yui and Ishii, 1994). Figure 10-3 shows the relationship between bird density, number of species in the bird community, and forest type. It shows that both bird density and number of species are higher in the cool-temperate zone than in the warm-temperate zone; and in each zone, the density and number of species are lower in young coniferous plantations, but higher in mature coniferous plantations. It is notable that the diversity of birds is highest in a mature plantation in the cool-temperate zone which is partially mixed with hardwood species that invaded after planting. Species diversity in this forest was the same as in oak (*Quercus crispula*, mizunara) natural forest and higher than beech (*Fagus crenata*, buna) natural forest. The plantation in which hardwood species invaded probably developed as a result of insufficient tending or a poor choice of planting site. However, Figure 10-3 implies that introducing broad-leaved species to coniferous plantations can enhance species diversity.

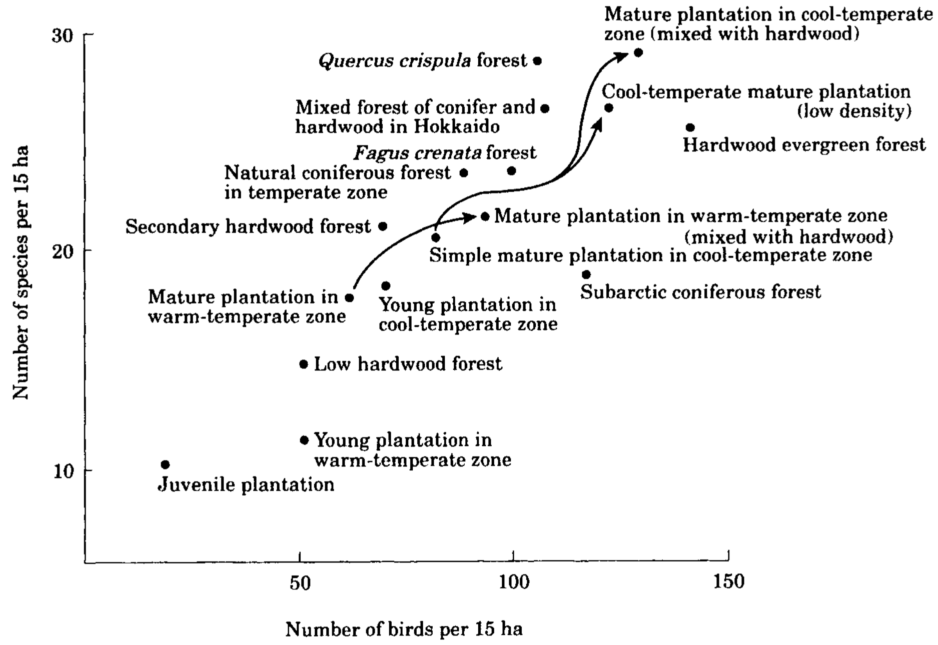


Figure 10-3 Relationship between population density and number of species of birds by forest type. The arrows indicate the change from a simple coniferous stand to a mixed stand containing hardwoods. Plantations are coniferous. (Yui and Ishii, 1994)

The home ranges of predatory birds, such as the golden eagle (*Aquila chrusaetos*, inuwashi) and mountain hawk-eagle (*Spizaetus nipalensi*, kumataka), are several thousand hectares, and they require mostly natural forest throughout their range (Yui, 1994; Yui and Ishii, 1994). As the area of natural forests has declined, they have become endangered species. To conserve these species, the area of natural forest must be increased and natural elements in the landscape recovered as much as possible. Other species are dependent on particular structural components of forests. For example, species such as owls and woodpeckers, nest in the cavities of large old trees and the decline in old-growth forests has led to many of these species becoming rare, vulnerable, or endangered.

Large animal species such as bears and wild boar (*Sus scrofa*, inoshishi) contribute to the regeneration of natural forests by scarifying the forest floor and, grazing dwarf bamboos which prevent regeneration of the trees. However, as the population of large mammals has decreased, the regeneration of natural forests has declined in many areas of Japan (Watanabe, 1994). These examples illustrate the importance of a comprehensive strategy for conserving the total ecosystem in natural forests.

10.4 Forest management for the conservation of biodiversity

10.4.1 Conservation of target species

It is difficult to maintain all populations of all species in all regions because of the effect of human activity. One way of maintaining all species is to establish an area for the preservation of the target species. This approach has been recognized and is gradually being implemented in many countries, although as yet only limited areas have been established. The target species is that species which is representative of the community in the area and whose preservation leads to the preservation of all other species. (Wilcox, 1984). Target species may be either keystone species or umbrella species. Umbrella species are species occupying a habitat shared by most other species in the area, and are usually at the top of the food chain (Washitani and Yahara, 1996). Keystone species are species which are essential to the community interactions and dynamics. If these species are lost, the community and ecosystem would change (Washitani and Yahara, 1996).

In order to maintain a viable genetic diversity of each target species, the minimum area required (MAR) as habitat for a minimum viable population (MVP) must be managed as a preserved area (Wilcox, 1984, Yui, 1994). Typical target species in Japan include the golden eagle, the mountain hawk-eagle, the brown bear (*Ursus arctos*, higuma), the Japanese black bear (*Ursus thibetanus*, tsukinowaguma). The MVP and

MAR for each target species must be derived from sound scientific data. The biodiversity of plant species can be maintained in a similar way if target species are identified.

10.4.2 Landscape

If the necessary habitat for a target species is to be provided, then the most appropriate stand structure must be recognised and ways of maintaining a dynamic balance of stands of different structures across the landscape must be considered. It is desirable to preserve large tracts of natural forest, but as this is difficult in most areas of the world, we must consider how to distribute managed forests as well as preserved areas to maintain biodiversity.

Ecosystem conservation areas need to be distributed according to their ecological significance, and there should be as many as possible throughout a country. The minimum area for a conservation area should be the minimum area required to maintain a viable population of the target species. Schnitzer and Borlea (1998) assumed that at least 5000 ha would be sufficient for the preservation of most forest processes and species, except for large mammals. Zoning of the land in each conservation area could depend on the present land use (including forest types such as managed forest, unmanaged forest, natural forest, and plantation) and future planned uses. Conservation areas are generally divided into three zones (Yui, 1994).

Preservation zone;	zones which preserve the ecosystem in a natural condition;
Conservation zone;	zones which allow the utilization of resources (forests) if it is compatible with maintenance of biodiversity; or
Multi-use zone;	zones which allow resource use and other multiple purpose uses.

Preservation zones are often divided into a zone for strict preservation (core zone) and a buffer zone where limited activities such as research and nature observation are allowed, and where paths, lodges, and other structures associated with these activities are permitted on the condition that a healthy ecosystem and biodiversity levels are maintained.

In conservation zones, silvicultural methods which fully consider biodiversity and ecosystem health must be applied. In these zones it is important to consider the distribution of stands or patches of unmanaged forests in which there are declining trees, snags, and fallen logs. The presence of these natural elements is essential for the conservation of biodiversity (Franklin, 1989, 1997; Franklin et al., 1997). Even if each stand or patch is small, unmanaged parts should be distributed as evenly as possible. Aggregated retention (Franklin, 1997; Franklin et al., 1997) can be regarded as a strategy to provide unmanaged stands or patches. In managed forests, long rotation, non-clearcutting, or minimum size clearcutting methods should be applied. Even in managed forests, it is desirable to increase the proportion of forests which have the potential to regenerate naturally.

Multi-use zones include farmlands and residential areas. If there are ecologically significant areas in conservation or multi-use zones, they should be protected as important environmental preservation zones. Preservation zones and important environmental preservation zones should be connected by corridors which are also protected. A landscape model of these zones and corridors is shown in Figure 10-4.

Figure 10-5 shows a landscape managed by a private owner in Gifu Prefecture, Japan. This demonstrates landscape-scale management applying conservation zones and/or multi-use zones in which forest management for timber production considers biodiversity conservation as

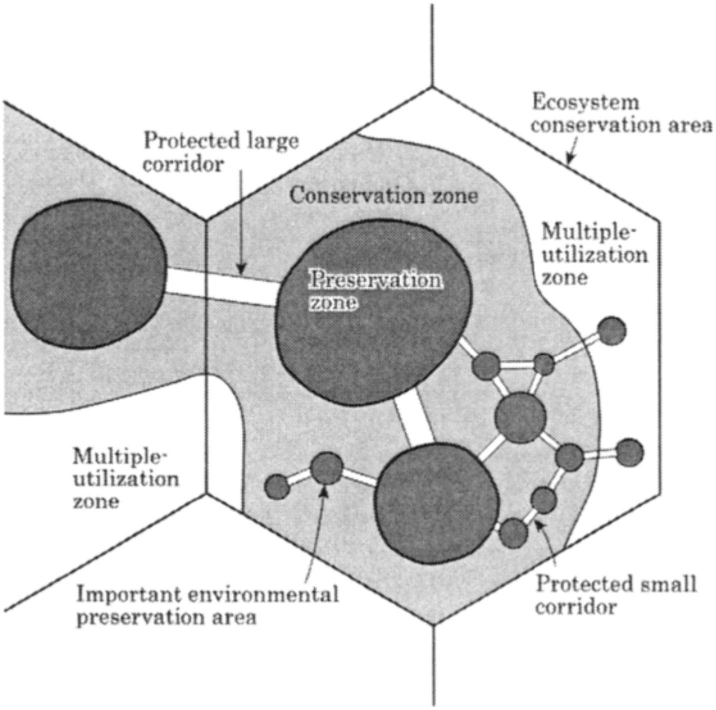


Figure 10-4 A landscape model for conservation of wildlife communities. (Japan Wildlife Research Center, 1991)

Figure 10-5 Forests owned by Ishihara Company in Gifu Prefecture, Japan. that are managed at a landscape level for timber production, biodiversity, and other forest functions.

well as other forest functions. The forests in the foreground are managed for mainly timber production, and there is a distribution of various types or stages of stands managed using non-clearcutting methods. In the background, natural forests are interspersed amongst plantations. This provides aesthetic benefits.

Harris (1984) proposed a basic scheme for maintaining biodiversity and resource use functions in a forested landscape, which he called a Multiple Use Model (MUM). A MUM consists of four land classes, i.e., (1) a core reserve area, which is surrounded and buffered by (2) an area of "light-touch" management (first-order buffers), which is surrounded and buffered by (3) an area permitting moderately intensive management (second-order buffers). The fourth category consists of lands outside of these three classes that are highly altered by humans (Perry, 1994). These zones (modules) are similar to the ones proposed by Yui (1994).

In regional landscapes, the Multiple Use Model can be applied in several ways, depending on the local land-use constraints. A landscape can be regarded as regional when three areas are defined: a) the core protected areas, including different forest types and different representatives of each type along with their buffers; b) the protected corridors; and c) lands devoted to intensive human use. Such a form of combination is called Multiple Use Landscape (MUL) (Perry, 1994).

Figure 10-6 illustrates a number of models of MULs which vary

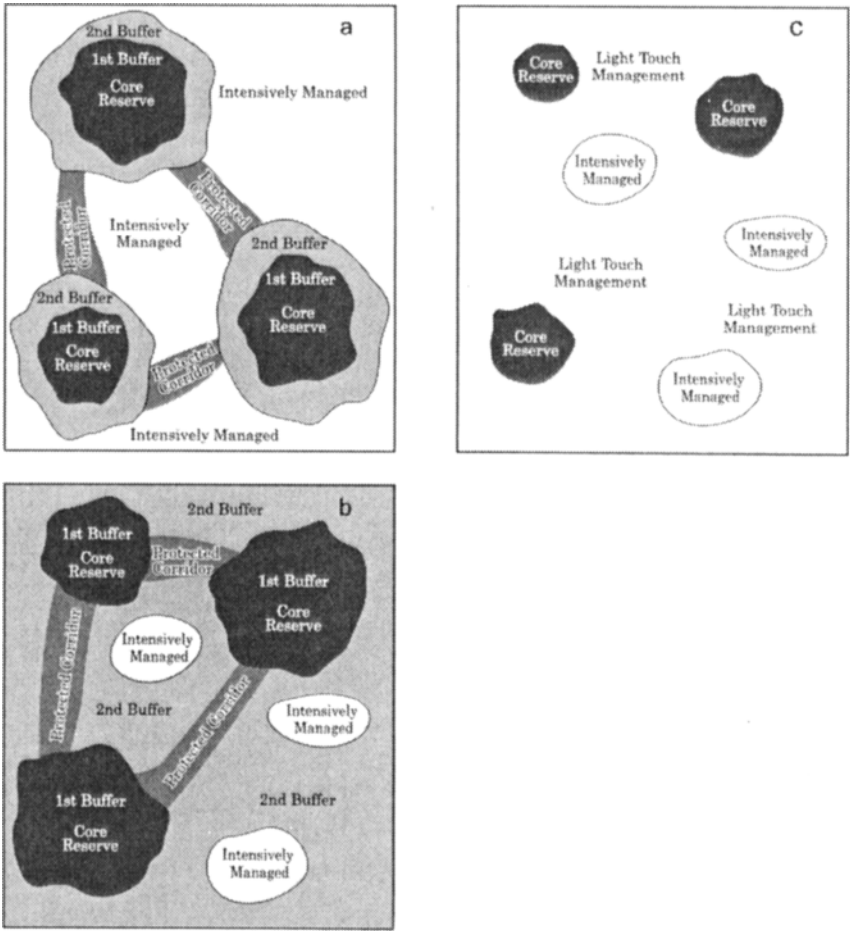


Figure 10-6 Multiple-use landscape showing various levels of intensity of management. (Perry, 1994)

according to the intensity of land use. Figure 10-6a represents an area with intensive land use and Figure 10-6b represents an area with less intensive land use. In Figure 10-6b, the core reserves, protected corridors, and intensively managed areas exist as islands within a sea of moderately intensive forestry (the 2nd buffer). In Figure 10-6c, land-use is least intensive, and the reserves and intensively managed areas exist as islands in sea of "light-touch" management (Perry, 1994). Appropriate landscape suitable to the local conditions can be created using the systems shown in Figures 10-4 and 10-6.

Even outside ecosystem conservation areas, an excessive concentration of plantations should be avoided, and some retained or regenerated natural forests should be adequately distributed in the landscape. In areas where plantations have been concentrated, some should be converted to mixed forests and/or regenerated with local species after harvesting the planted trees.

10.4.3 Population control

If the population of some animal species, either within or outside a conservation area, increases so much that it excessively affects the ecosystem, the population must be controlled (Watanabe, 1994; Yui, 1994; Miura and Horino, 1996). The population of the target species and other species which influence the ecosystem should be maintained at a level suitable for their survival. If overpopulation occurs, population control will be required to limit destruction of the ecosystem or to prevent severe damage to forestry and agriculture. The acceptable or appropriate level or degree of damage by animals is an important but difficult issue. If there is no allowance for a certain level of damage, it will be difficult to maintain or recover biodiversity. Therefore, a new system for identifying and considering stakeholder interests is urgently required.

Population control is necessary not only in conservation areas but also in other areas where overpopulation causes excessive damage to forestry and agriculture or unusually affects an ecosystem.

10.5 Silvicultural practices

10.5.1 Stand structure and regeneration method

As discussed in Chapter 7, traditional silvicultural approaches such as those described by Smith (1986) and Matthews (1989) cannot ensure maintenance of biodiversity, because under these systems, there are generally no large declining trees, snags, or fallen logs, so the functions of the forest ecosystems are restricted (Franklin, 1997). Long rotations using non-clearcutting methods, including selection methods, can assist in the conservation of biodiversity, but structural elements such as declining trees, snags and fallen logs are absent, and normal biodiversity cannot be preserved.

At harvest, declining trees and snags can be maintained by dispersed retention, aggregated retention, or a combination of these techniques (Figures 8-7, 10-7). Various prescriptions for retention at harvest are recognized for their advantages of 1) "lifeboating" species and processes immediately after logging and before forest cover is reestablished, 2) "enriching" reestablished forest stands with structural features that would otherwise be absent, and 3) "enhancing connectivity" in managed landscapes (Franklin et al., 1997). Lifeboating has the primary objective of

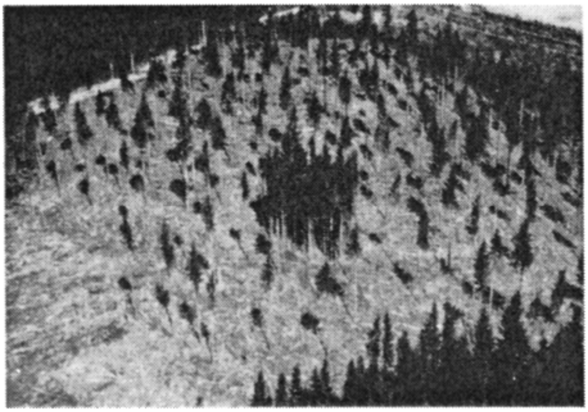


Figure 10-7 Mix of scattered retention and aggregated retention of *Pseudotsuga menziesii* (Douglas-fir) in Washington States, the United States of America (Photograph by J. F. Franklin).

providing refugia for components of biodiversity that might otherwise be lost from the harvest area. Lifeboating is achieved in one of at least three ways: 1) providing structural elements that fulfil habitat requirements for various organisms, 2) ameliorating harsh microclimatic conditions that would be encountered under clearcuttting, and 3) providing energetic substances to maintain non-autotrophic organisms. Structural enrichment enables the structural complexity of managed forest stands to be reestablished much earlier in the rotation than would otherwise be possible. It also enhances the movement of organisms within a managed landscape. Connectivity assists the dispersion and migration of organisms, and conditions in the matrix or dominant patch type are the most important factor controlling connectivity in the landscape (Franklin, 1993; Franklin et al., 1997).

Franklin (1997) proposed a gradient of variable retention for forest harvest systems (Section 12.2.3, Figure 12-1) that is based on the need to maintain much of the biodiversity already on a harvested site to preserve productive capacity. Elements that should be maintained include components of the below-ground community, such as a diversity of fungi capable of forming mycorrhizae. Such diversity can be critical for optimal, as well as long-term, productivity of the site. Retaining features such as live green trees and fallen logs is necessary to achieve the desired *in situ* survival of affected organisms and processes.

Aggregated retention is a way to distribute unmanaged patches or stands of varied sizes and shapes which include, or have potential for developing, declining trees and snags. In northwestern North America, the typical size of aggregates is 0.5 to 1.0 ha (Franklin et al., 1997). Scattered retention also facilitates the maintenance of biodiversity, but is not as effective as aggregated retention in providing the stand structural elements, microclimatic conditions or preferred habitats for other organisms. In forests managed for the production of timber, undertaking silvicultural operations in stands where there are declining trees and snags is ineffective and often dangerous for workers. Therefore, there are added advantages in managing these stands as aggregated unmanaged stands or patches distributed as a mosaic through the landscape.

The suitable distribution of unmanaged stands or patches must be accompanied by appropriate management of the surrounding forest. Suitable silvicultural techniques may include long rotation methods with minimum sized clearcutting areas or non-clearcutting, including individual and group selection, methods. Non-clearcutting methods, especially the single-selection method or group selection method, are usually regarded as the best techniques for maintaining biodiversity and other functions, because the disturbance of the ecosystem by selective cutting is the least of any harvesting method. However, these advantages must be balanced against the likelihood that shade-intolerant species will decrease and there may be a corresponding decrease in biodiversity. Clearcutting, therefore, may also be necessary to maintain the presence of shade intolerant species (Figure 8-22 in group-selection method in Section 8.1.2.3-2).

In the Pacific Northwest of the United States of America, a dispersed pattern of clearcutting has been used. However, it has been pointed out recently that this creates a landscape composed of dispersed small forest patches and young plantations with a high proportion of forest edges with altered microclimates. The environment of the remaining small patches is influenced for a distance equivalent to up to two or three tree heights from their edges (Chen et al., 1992), and this may eliminate some species of wildlife and plants with strong interior-forest microclimatic requirements. To overcome this, it has been proposed that an aggregated pattern of clearcutting can be used. In this method, new cuts are placed adjacent to earlier cuts, rather than in the middle of uncut blocks of forest, so that relatively large blocks of continuous interior-forest habitat can be retained until later in the clearcutting cycle (Franklin, 1989; Hemstrom, 1990; Swanson and Franklin, 1992).

Similar patterns have been observed in bird populations. Yui (1994) showed that a mosaic landscape is conducive to enhancing species diversity in birds, but if the forest (stand) edge is increased too much, the populations of species with interior-forest habitat requirements decrease, and species which favor the forest edge increase. This may also be true of other animals and some plants. Therefore, the patch size and distribution that is optimal for each species and area must be identified.

The idea of aggregated retention could be extended such that small preserved natural stands are distributed throughout a forestry area. This would ensure the continuing presence of large-sized snags and fallen logs. This would be particularly important in areas where plantations or intensively managed forests are concentrated. The size of these small preserved stands would vary depending on natural (physiognomy and microclimate) and social conditions, but is essential for the implementation of sustainable forest management. There may be barriers that need to be overcome before such a system could be implemented, such as complex forest tenure and differing levels of understanding amongst owners.

10.5.2 Rotation

If the rotation is extended, a stand becomes stratified and the biodiversity increases (Franklin, 1989, 1997; Franklin et al., 1997; Kiyono, 1990; Oliver, 1992; Swanson and Franklin, 1992; Yui and Ishii, 1994). The simple structure of plantations could be improved by extending rotations (Figure 10-8) and developing a range of stands of different age classes.

A long rotation is essential for the production of timber for construction

Figure 10-8 *Cryptomeria japonica* (sugi) stand managed under a long rotation in Northern Honshu, Japan. This stand is 190 years old and managed by a private owner using selective cutting. The mean tree height is 44 m and the stem volume per ha is about 1500m^3. An understorey of broad-leaved trees is developing, improving biodiversity.

or furniture. Over a long rotation, trees of various sizes can be harvested by thinning at different times, with minimal damage to the forest ecosystem. To increase the ratio of mature forests in the landscape, a rotation of at least 100 years would be required in many parts of the world. This would enable high quality timber that is knot-free and has uniform annual rings to be produced from large trees at rotation. Scheduled thinning and pruning would also allow high quality timber to be produced from smaller trees and the highest quality timber to be produced from large trees (Section 8.1.2). Thinnings and prunings during the young stage improve the stand structure if undergrowth is poor. Pruning should be done until the beginning of the young stage and intensive thinning should be undertaken during the young stage to develop solid, high quality trees resistant to strong winds. Thinning during the mature stage allows the stand to develop a similar structure to that of an old-growth stand, except for the presence of declining trees, snags, and fallen logs.

For the production of pulp or wood used for biomass purposes, short rotations are required and the coppice method is often used (Section 8.2.1). Each rotation is generally less than 20 years long. These systems can be regarded as a kind of combination of forestry and agriculture managed on flat areas or on gentle slopes. For these systems to be efficient, clearcutting over a reasonably large area is usually necessary. To balance this with biodiversity conservation, the distribution and size of cut areas of short rotation forests within a landscape must be carefully considered.

10.5.3 Improving the structure of simple plantations

In many of forestry areas in the world, large areas of monospecific plantations have been established. These plantations are often concentrated in discrete areas. Generally, the number of species and genetic diversity of the ecosystems in these areas is relatively low. Although the productivity of simple plantations is often high, it cannot be assumed that extending such management throughout a landscape is sustainable. Therefore, one of the most important issues in forest management is how to rectify this situation and improve the structure of plantations.

Figure 10-9 shows the relationship between stand structure and diversity index in boreal forests in Finland. The diversity index (LLNS diversity index) accounts for stem size distribution, the number of tree species, level of undergrowth, presence of decaying standing and fallen trees, charred woody materials, and any special trees such as those used for nesting by rare bird species. Using this index, the diversity of even-sized stands is lowest and the diversity of regularly all-sized stands is the highest. Other forms of uneven sized stands were also relatively high. The smaller index values in 1985 compared to 1951 may have been caused by differences in assessment techniques. The current annual volume

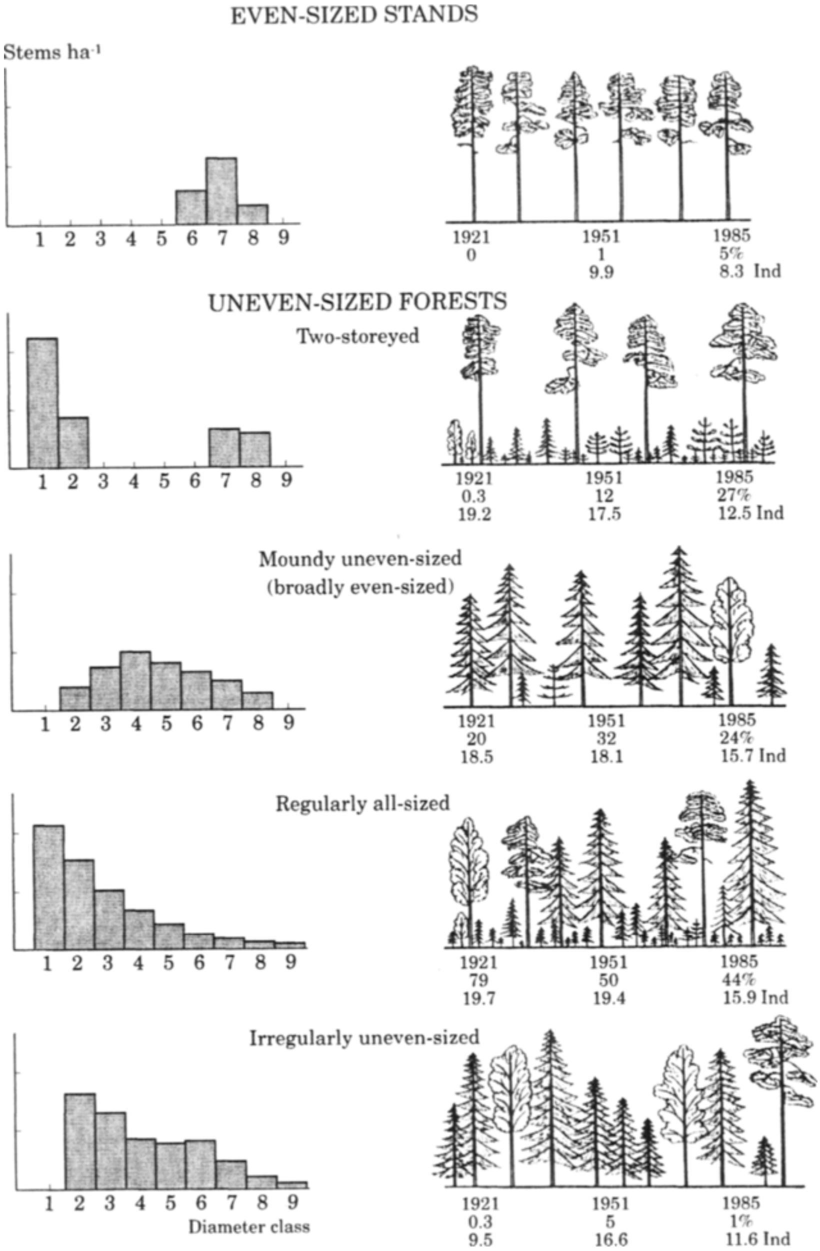


Figure 10-9 Stand structure types in Finland in 1921, 1951, and 1985, showing, for each forest type, their diameter class distribution, the stand's typical vertical structure, the proportion (%) of the total forest area occupied by each forest type, and LLNS diversity index (Ind). The diameter classes are: 1=2-6 cm, 2=6-10 cm...., 9 >34 cm. (Lähde et al., 1999).

increment was highest in the regularly all-size stands and moundy uneven-sized stands (Lähde et al., 1999). This analysis suggests that regularly all-sized stand (stand with a size class distribution that is a reversed J-shape) should be the target structure for most forests.

The structure of monospecific plantations can be improved by thinning and pruning in the young stage, which allows undergrowth to develop (Fujimori, 1991a). This allows continued production of high quality timber and also enables a concurrent increase in biodiversity.

In Japan, some plantations are now a mix of conifers and hardwoods because insufficient tending or poor site selection has allowed hardwoods to invade. A proportion of these plantations should now be converted to mixed forests (Figure 10-10), and some should be allowed to revert to natural forests. Reversion could occur either after harvesting the planted trees or by thinning to remove conifers in dense stands dominated by conifers (Fujimori, 1997a). When plantations are regenerated following clearcutting, several methods should be considered: (i) traditional establishment of a pure stand; (ii) retention of some invaded hardwoods supplemented with planted conifer species; or (iii) mixed planting of conifers and hardwoods.

If the first method is used, the plantation should be intensively managed to maximize the yield of the planted species as described in Section 8.1.1.1. This results in the maximum proportion of biological productivity being concentrated into forestry yield, with the consequence

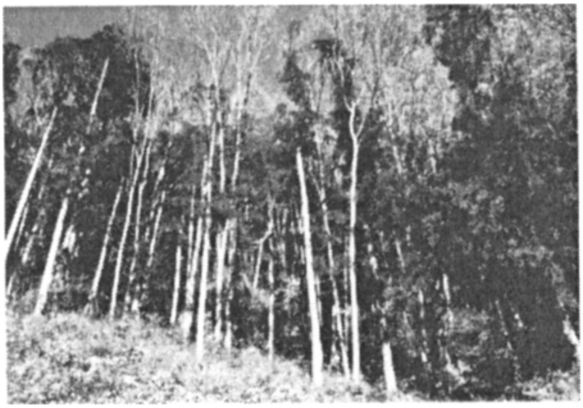


Figure 10-10 Mixed stand formed by oaks invading a *Cryptomeria japonica* (sugi) plantation in Ibaraki Prefecture, Japan. (Photograph by M. Ishizuka)

that pressure on natural forests can be lessened and their degradation and loss reduced. If the second method is used, biodiversity can be increased in each plantation, which enhances soil conservation and reduces the labor requirement for weeding and improvement cutting. If the third method is used, more complex techniques are required, but techniques such as group planting are likely to succeed. This approach would be required in areas where high hardwood species have been eradicated from areas where they would naturally occur.

10.5.4 Treatment of secondary forests

A secondary forest is defined as a forest in the secondary successional stage; i.e., a forest that has regenerated naturally after a large natural or anthropogenic disturbance, excluding plantations. Secondary forests have great potential to meet various forest functions and the questions of how they should be distributed and managed are important for conserving biodiversity. Some should be converted to unmanaged natural forests and some should be maintained as managed secondary forests. A proportion of the managed secondary forests could be used to produce hardwood sawn timber over long rotations and the balance could be used to produce biomass over a short rotation. An adequate distribution of these forests will enhance biodiversity. The secondary forests of Japan provide a good example of the management options that may be adopted.

The secondary deciduous hardwood forests of the Kanto district in Japan have a greater species diversity than old-growth (climax) forests if the area surveyed is small, but the species diversity of the climax forest is greater if the area surveyed is large (Figure 10-11). This reflects the

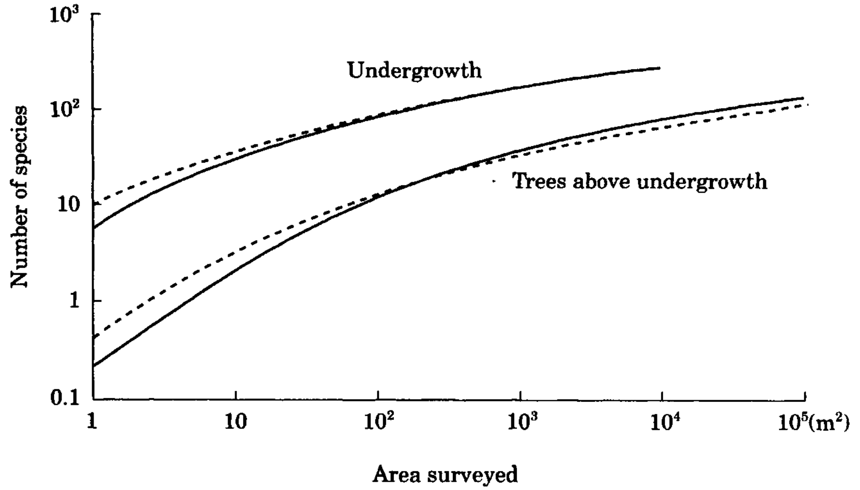


Figure 10-11 Species-area curve for vascular plants in virgin (solid-line) and secondary (dotted line) forests. (Nakashizuka and Iida, 1996)

increased number of recordings of plant species that occur at a low frequency as the area surveyed increases. Such relationships can be used to define the area of forest required for the conservation of species.

A high percentage of the secondary forests in Japan used to be managed as coppice on a short rotation for production of fuelwood, but have been left untreated for about 40 years. When managed for fuelwood production, these forests used to have their litter and undergrowth removed, but since they have been left untreated, the structure and composition of these forests has changed. Herbaceous species which used to be common on the floor of the fuelwood forests, such as katakuri (*Erythronium japonicum*) and ichirinso (*Anemone nikoensis*), have become very limited, because they cannot survive in the presence of either a dense understorey of shrubs or a closed overstorey. These forests will continue to develop into advanced successional stages and reach their climax if large disturbances do not occur. Such forests should be classified to identify those forests which should retained as unmanaged natural forests and identified forests zoned accordingly. There needs to be an adequate distribution of unmanaged natural forests in lowland areas because there is such a small area of natural forest remaining in these areas.

A proportion of the secondary forests should be managed over long rotations for the production of hardwood sawn timber. The proportion of hardwood species valuable for sawn timber can be increased by enhancing regeneration or improvement cutting. Some secondary forests on flat and gentle slopes can also be used to produce wood for biomass uses such as energy and pulp, using the coppice method over a short rotation.

Some of these secondary forests should be managed to maintain the structure that they traditionally had when managed for fuelwood, in order to maintain the species composition and biodiversity characteristic of the traditional forests. This could be achieved by reverting to management for using fuelwood (bioenergy) and litter (for fertilizer). This can be realized when social systems and lifestyles change from those evaluated only on the basis of the costs and efficiency of the economy to an evaluation that includes environmental and cultural aspects. This issue is further discussed in Sections 14.3.3 and 15.3.2.1-1.

Chapter 11

Conservation and Maintenance of Soil and Water Resources

As discussed in Section 9.2, the conservation of forest soil is fundamental to the conservation of forest ecosystems, and the conservation of water yield is directly related to the conservation of soil within a catchment. As populations and exploitation in catchments increase, especially in urban areas, the demand for maintaining and enhancing water holding capacity and erosion control increases. In mountainous forest areas with steep slopes, conservation of soil and water resources requires particularly careful management.

11.1 Water yield as a function of forests

11.1.1 Quantity of water

The presence of a forest decreases the total amount of water supplied to streams compared to areas where forests have been removed (Bosch and Hewlett, 1982; Swank et al., 1987). This is a result of the large volume of water that is transpired by the forest. However, forests better regulate streamflow, by limiting the rapid increases in streamflow which follow rainfall events and maintaining streamflow for longer periods. This is achieved as a result of their capacity for interception and soil water storage. Rain water is stored in the regolith and soil and groundwater gradually supply water to streams via baseflow. Comparisons of direct runoff from a forested catchment with that of a catchment where quarrying was taking place showed that the direct runoff from the quarried catchment was greater than that of the forested catchment (Fujieda et al., 1988). Increases in direct runoff and peak flow occur after forested catchments have been clearcut (Nakano, H., 1971).

The runoff characteristics of a catchment can be described by a storm hydrograph (Figure 11-1) and flow-duration curve (Figure 11-2). The models presented in Figures 11-1 and 11-2 are based on Japanese data. The hydrograph shows changes in streamflow at a point on a river. Figure 11-1 shows that runoff increases during a storm and decreases quickly when the rain ceases (part A in Figure 11-1). The runoff continues to decrease gradually (part B) before becoming almost constant at a low level (part C). If undisturbed and disturbed forest catchments are compared, the peak flow is lower and the time taken to reach peak flow is longer in the undisturbed forest catchment than in the disturbed catchment, except in unusually heavy storms. The decline in runoff (from peak flow to the end of B) is also slower in the undisturbed catchment than the disturbed forest catchment, but the base flow (C) of both catchments is similar.

A flow-duration curve (Figure 11-2) shows the daily runoff, in order

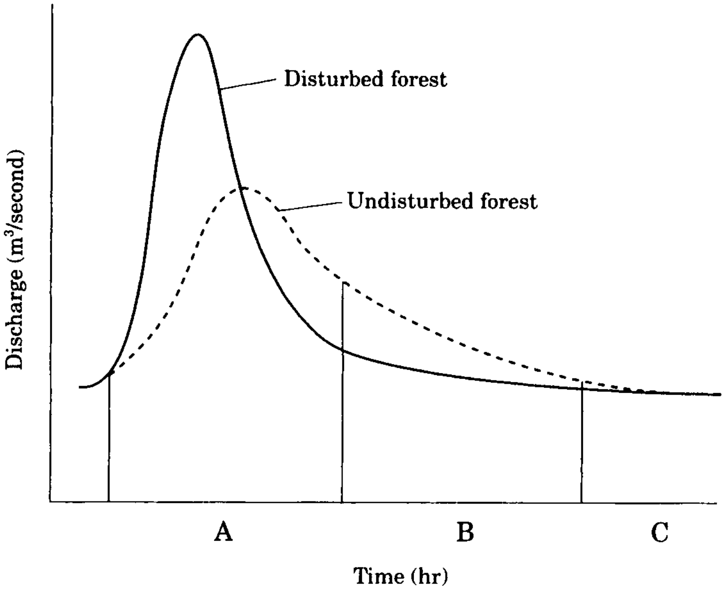


Figure 11-1 Storm hydrographs for disturbed and undisturbed forest catchment. Part A on the time axis represents the period when discharge increases and decreases rapidly. B when it decreases gradually, and C when it stabilizes. (Study Group on Forests and Water in Forestry Agency of Japan, 1996)

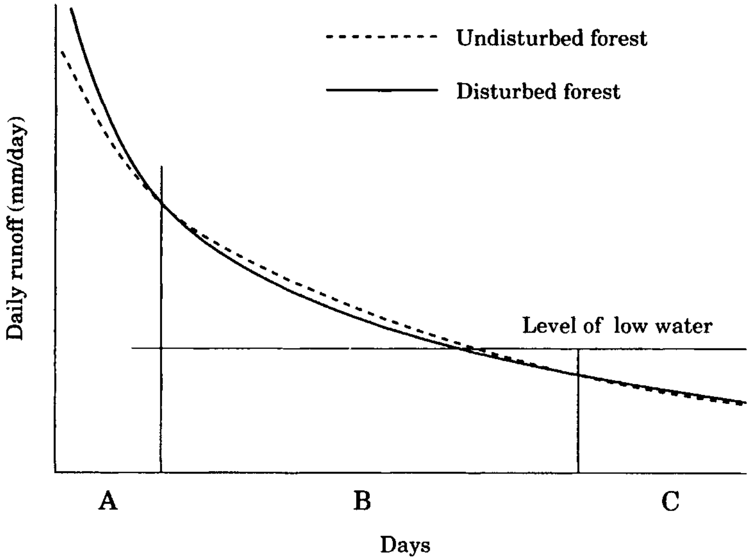


Figure 11-2 Flow-duration curve for disturbed and undisturbed forested catchments. Part A on the time axis represents the range of mainly rainy days, B the range between rainy days and the level of low water, and C the range of days at low water. (Study Group on Forests and Water in Forestry Agency of Japan, 1996)

from maximum to minimum, throughout a year. The ranges A, B, and C in Figure 11-2 correspond to the number of days of high water (approximates the number of rainy days); the number of days between high water and low water; and the number of days of low water, respectively. The level of low water (shown as a horizontal line in Figure 11-2) is defined by the demand for water within the region. Comparisons of undisturbed and disturbed forested catchments show that the level of runoff in the undisturbed forest catchment is lower in A, higher in B, and approximately the same in C. This is another illustration of the regulation of streamflow by forests.

It is important for forest managers to know the relationship between stand age or stand development stage and water yield. Kuczera (1987) developed a model for yield-age relationship for *Eucalyptus regnans* (mountain ash) forests in Australia by mathematically analyzing data from long-term monitoring. Figure 11-3 shows the curve he developed, known as the "Kuczera curve". Watson et al. (1999) explained the form of this curve on the basis of the relationship between evapotranspiration [estimated from leaf area index (LAI)] and stand age. LAI is leaf area over a defined area (Section 3.2). In Figure 11-3, starting from 2 years after age zero, water

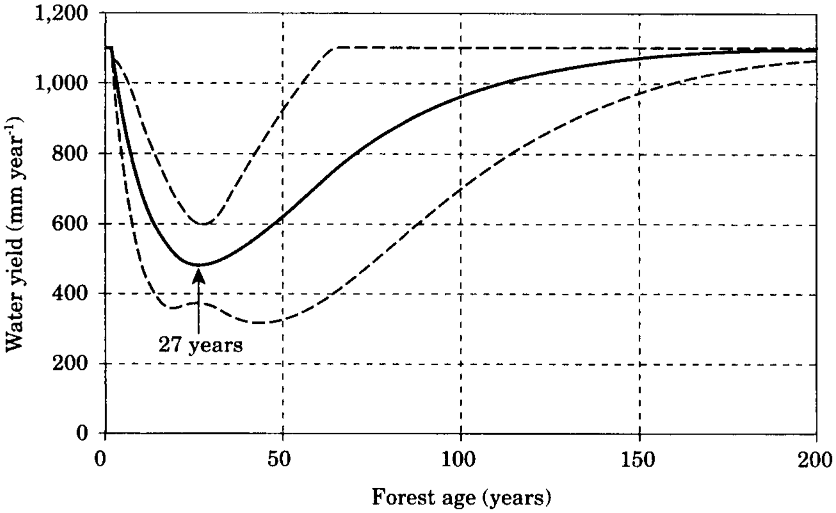


Figure 11-3 Relationship between forest age and water yield in *Eucaliputus regnans* (mountain ash) forests near Melbourne, Australia. Dotted lines represent 90% confidence limits of the Kuczera curve. (Watson et al., 1999)

yield rapidly declines to age 27, and then gradually rises back to equilibrium levels by about age 200. Water yield is low in the young stage (stem exclusion stage) when forest growth rates are high, increases as the stand develops through the mature stage (understorey reinitiation stage) and equilibrates in the old-growth stage.

11.1.2 Quality of water

Dust, particulates and pollutants that arrive in a forest in the rain or by dry deposition are filtered by a combination of physical, chemical, and biological processes in the forest soil. As a result, streamflow from forests is generally clean and clear. The water is purified by the following processes within the forests: (i) nutrient absorption by plants; (ii) decomposition of organic matter and mineralization or nitrification of nitrogen by microorganisms; and (iii) absorption of ions by buffering in the soil (Hotta, 1991). Water quality is also protected because erosion of the surface soil is prevented by the canopy, undergrowth and litter.

When a forest is clearcut, the rate of decomposition of organic matter in the soil generally increases (Barns et al., 1998). The concentration of soil nitrogen particularly in the form of nitrate, increases (Arimitsu et al., 1973; Osumi et al., 1973). Nitrate is easily dissolved in water and will runoff into streams. Other cations, such as calcium, magnesium, and potassium also increase following clearcutting (Likens et al., 1978; Hotta et al., 1991), but the concentration of these elements in the runoff is not always serious (Tsutsumi, 1989; Hotta, 1991; Shimizu et al., 1994). Most water pollution caused by clearcutting or destruction of forests is due to an increase in suspended sediments (Shimizu et al., 1986; Shimizu et al., 1994). If water quality in forested catchments is to be conserved, the conservation of the soil is essential, and this is achieved by the same measures which conserve water quantity.

11.1.3 Factors related to the quantity and quality of water

Water resource conservation has several components, including reducing peak flow, reducing periods of low-water, and conserving water quality. Each component requires that the soil has high infiltration rates and water holding capacity. This requires coarse pores in the soil and a thick soil layer. The surface soil should also be covered by enough litter to absorb rain water before slowly penetrating the surface soil (Arimitsu, 1987). If the undergrowth is poor in broad-leaved deciduous stands, the leaf litter tends to be blown out by the wind. In *Chamaecyparis* stands with poor undergrowth, the leaf litter tends to move with surface flow on slopes. Undergrowth thus plays an important role in accumulating leaf litter on the floor of these types of stands.

The water holding capacity of soil is governed by extent of coarse pores in the soil. Coarse pores generally increase as stand age increases although it is often delayed in the young stage if undergrowth is scarce (Takeshita and Takagi, 1977). Coarse pores are formed by the development of root systems and the activities of soil fauna. Small roots repeatedly grow and die, forming humus which has a high water-holding capacity. Soil fauna create coarse pores and their excrement helps the soil to develop an aggregated structure, which increases its infiltration and water holding capacity (Arimitsu, 1987). The abundance of soil fauna increases as the number of plant species increases, litter supply improves, and the microclimate is stabilized.

Clearcutting disturbs the soil structure (Kobayashi, 1982; Arimitsu, 1987). In *Chamaecyparis obtusa* (hinoki) plantations, the number of coarse pores in the soil and the depth of the organic layer was lower in areas regenerated following clearcutting than in areas regenerated after using non-clearcutting harvesting methods (Araki et al., 1987a, 1987b, 1988; Araki and Miyagawa, 1990; Miyagawa et al., 1987; Miyagawa and Araki, 1988, 1990). Soil disturbance was less after final cutting of the overstorey in the short term two-storied forest method, than in clearcut stands (Araki et al., 1987a; Araki and Miyagawa, 1990; Miyagawa et al., 1987; Miyagawa and Araki, 1990). The better soil structure resulting from non-clearcutting suggests that these methods are preferable for the conservation of water resources. The soil structure in a mixed two-storied stand with a sparse canopy of *Zelkova serrata* (keyaki) and a dense understorey of *Chamaecyparis obtusa* was better than that in a pure *Chamaecyparis obtusa* stand (Araki and Miyagawa, 1989; Miyagawa and Araki, 1989). This suggests that mixed stands of conifers and broad-leaved species are preferable to pure conifer stands for soil and water protection.

11.2 Sediment disaster control

Sediment disasters are events such as the shallow collapse or deep collapse of hill slopes. Forest cover influences the occurrence of shallow collapses (Ohta, 1991). As a forest develops, the soil structure develops and the depth of soil layer increases, which increases the potential for shallow collapse. However, the root system of a stand reinforces soil, increasing soil strength (Endo and Tsuruta, 1969; Kobashi, 1983; Abe, 1984, 1997; Kawaguchi, 1987; Tsukamoto, 1987, 1991). When the balance between soil strength and root reinforcement of the soil is affected by heavy rain, surface collapse occurs (Tsukamoto et al., 1984; Ohta, 1991).

Surface erosion in Japan is far more frequent and greater on bare slopes than on forested slopes. Depending on the geological structure, shallow collapse can occur at intervals of between 100 years to over 10,000 years (Ohta, 1991; Tsukamoto, 1991). Increased soil erosion reduces the risk of shallow collapse, but causes other damage and should be prevented. Slopes which are susceptible to shallow collapse at intervals of more than several hundred years do not merit special management. However, those slopes which are susceptible to relatively frequent shallow collapse, such as slopes with parent materials of granite or Tertiary strata (Tsukamoto, 1991), should be carefully managed. On these sites, plantations of shallow-rooted species, clearcutting, and management on short rotations should be avoided.

Reinforcement of soil by tree root systems is enhanced if the root systems are thick, strong, and widely spread (Ohta, 1986; Kawaguchi, 1987). Thick and deep roots bind the soil layer to the underlying rock, which is especially important in preventing shallow collapse (Kawaguchi, 1987).

Shallow collapse occurs more frequently in plantations less than 20 years old than in older plantations, and seems to occur most frequently in stands about 15 years old (Kitamura and Nanba, 1981; Tsukamoto, 1991). This is attributed to soil strength reaching a minimum as the resistance of the stumps with roots following clearcutting decreases, although the strength of the roots of the regenerating trees has not yet been increased. This relationship is likely to be different in stands managed under coppice, because regenerating stumps remain alive and are stronger than either dead stumps or young trees (Kawaguchi, 1987). Therefore, clearcutting on a short rotation is probably the most risky management option on slopes susceptible to shallow collapse.

11.3 Silvicultural practices for the conservation of soil and water resources

As discussed in Section 2.4.4, the structure of an old-growth forest is the most suitable for conserving soil and water resources. It is therefore desirable to maximize the extent of old-growth forests in each catchment. This will also serve to maximize biodiversity, but will not be optimal for wood production. Therefore, an optimal mix of forest structures needs to be determined.

In management for wood production, long rotations are necessary if water yield needs to be increased (Figure 11-3) or runoff stabilised. This suggests that to conserve soil and water, the mature stage should be retained as long as possible. In addition, silvicultural methods which improve the structure of the young stage of plantations for the conservation of soil and water resources must be developed. In the young stage, undergrowth is generally scarce due to the shortage of illumination on the forest floor (Section 2.4.4), and this is especially notable in plantations of species such as spruce and fir. Low undergrowth on the forest floor protects the surface soil from damage by splash impacts of rainfall, limits the movement of dropped leaves in the wind and prevents the movement of dropped leaves in surface flow. Therefore, thinning and/or pruning should be aggressively practiced during the young stage to increase illumination on the forest floor, improve the growth of an understorey and, concurrently, enhance the quality of the wood being produced.

The water yield from forests partially depends on the crown and canopy structure. A proportion of rainfall is intercepted by the crown or canopy, which decreases runoff. Stands which are too dense when young reduce water yield because of their high levels of transpiration and interception. Thinning and/or pruning is effective in reducing interception and transpiration, as well as increasing undergrowth. However, it can also increase evaporation from the soil. These trends were found following removal of 24% of the stem volume by thinning in a 31 year-old *Chamaecyparis obtusa* (hinoki) stand (Chikarashi et al., 1987; Morikawa et al., 1986). There have been few studies of the dynamic relationship between thinning or pruning and the amount of interception and transpiration. These relationships are complex, because thinning and/or pruning increases the transpiration by residual trees and undergrowth, and evaporation from the stand floor. Although water yield can be managed by controlling crown and canopy structure by thinning and pruning, the maintenance or development of the soil structure in the forest is more important for controlling the yield of water than manipulating the crown and canopy structure.

The structure of the forest affects the formation of snow piles and the rate of snowmelt and runoff. Forests can delay snowmelt, thereby reducing the period of low-water flow (Shimizu and Yoshino, 1997). The amount of snow on the forest floor can be partially controlled by manipulating the stand structure through silvicultural techniques such as forest type, rotation period, or thinning.

Bosch and Hewlett (1982) summarized the relationship between forest types, reduction in vegetation cover, and increased annual streamflow from hydrological experiments around the world (Figure 11-4). They showed that runoff increases in direct proportion to the reduction in vegetation cover, and the increase in runoff is greater in coniferous forests than hardwood forests. This is due to the general reduction in crown interception and transpiration caused by removing vegetation, and because the interception and transpiration of closed coniferous forests is greater than that of closed hardwood forests (Swank et al., 1987). Variations from the general trends shown in Figure 11-4 are common and large, because of

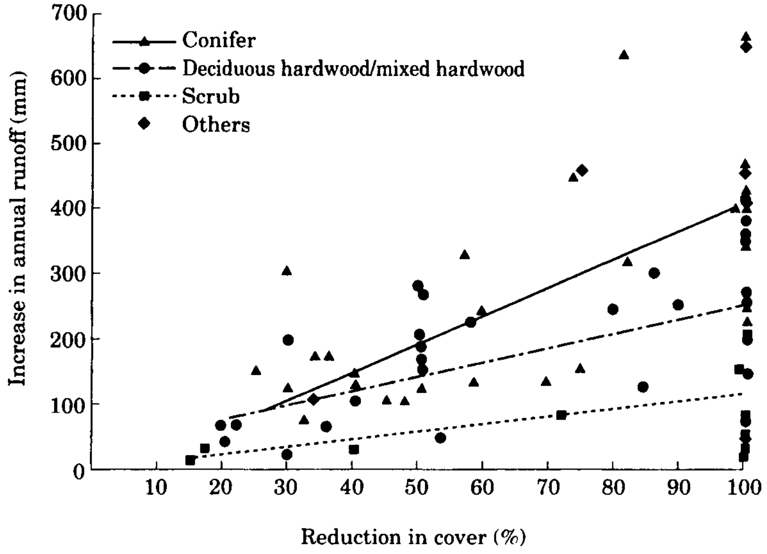


Figure 11-4 The relationship between vegetation cover and increased runoff. (Bosch and Hewlett, 1982)

different site conditions such as soil type and stand age. Given this finding, and that thinning increases runoff, silvicultural practices must be practiced carefully to ensure the soil structure is not disturbed.

Non-clearcutting methods are preferred for conservation of the soil, and the selection method is the best for the conservation of soil and water resources (Cornish, 1993; Bäumler and Zech, 1999). However, if light demanding species need to be regenerated, either group-selection or clearcutting the minimum area necessary for regeneration should be used. The stand structure which results from selection or group selection harvesting has similarities with old-growth stands, except for the absence of snags and fallen logs. It is desirable to establish mixed stands, because the soil under these stands is more chemically and physically diverse than under simple stands. Soil diversity is associated with diversity of soil animals and microorganisms, which enhance soil structure.

Chapter 12

Maintaining productivity for provision of forest products

In forest management for wood production, the main objective is to produce wood as efficiently as possible. This requires that the yield be maximized; i.e., that as high a percentage as possible of biological productivity be converted to the production of wood. A range of specific silvicultural techniques have been developed for this purpose, including genetic improvement, regeneration, tending, and harvesting, as reviewed and discussed in Part II. A range of silvicultural methods incorporating specific silvicultural techniques have also been developed, as reviewed and discussed in Part III. However, the specific focus of these techniques and methods on wood production has often conflicted with the conservation of biodiversity, soil and water resources, and provision of recreational functions. A sole focus on wood production can induce an unhealthy stand structure which may result in susceptibility to disease, pests, and damage from meteorological factors such as wind and snow (Chapter 15).

In Chapters 7 and 8, silvicultural methods for wood production were discussed in the context of traditional silvicultural systems, and various new aspects of silvicultural methods were introduced and discussed. In this Chapter, new silvicultural methods that consider other functions of forests are discussed outside the framework of the traditional silvicultural systems.

Non-wood forest products such as edible herbs, mushrooms, game, are included in most definitions of forest products. Although these are important, especially at a regional level, wood production is the main focus of this Chapter.

12.1 Significance of wood production

Throughout history, human beings have depended on wood products for energy (fuel), tools, construction, and many other uses. Over the last few centuries, however, wood has been replaced by a range of materials such as steel, cement, and plastic, and alternative sources of energy such as coal and petroleum. Recently, however, wood has been re-evaluated and recognised as a renewable, environmentally-friendly product that can play an important role in a future sustainable society.

As described in Section 2.1.1, the stems of trees grow as a result of the development of the xylem, and the wood of the stem can be used in various ways. Timber is a natural material produced using solar energy, water and carbon dioxide combined with nutrients such as nitrogen that are supplied from both within and outside the forest ecosystem. In forest ecosystems, plant biomass including timber is partially consumed by animals and fungi, and dead plants and animals are decomposed by microorganisms into inorganic matter which is utilized as nutrients by plants. Harvesting timber from forest ecosystems represents a variation of material and energy cycles of natural ecosystems, because it is eventually decomposed by rotting or burning during or after its use.

Within the global ecosystem, use of timber enables carbon to be pooled. For example, harvested timber can be used in construction and can be recycled, preventing its decomposition for long periods of time. Use of scrap wood for energy emits CO_2 into the atmosphere, but at least the same amount of CO_2 is absorbed by the regenerating forest stand on the site where the timber was harvested. Therefore, if the use of wood is increased, the level of CO_2 in the atmosphere will not increase, and should decrease, as long as the forests where the wood is sourced are managed sustainably. A further advantage of timber is that the energy required to produce wood from logs is far less than that required to process iron, aluminum, or other substitute materials. Further discussion on issues related to carbon and carbon balances is presented in Chapter 14. As wood products can be recycled and burnt with only low noxious emissions, wood products can assist in reducing various environmental impacts. In addition to their potential contribution to the global environment, use of woody materials enhances both our physical and mental health, and there is a strong link between utilization of wood and culture in areas with rich forest resources.

12.2 Conflicts between wood production and conservation of other forest functions

12.2.1 Species and genetic diversity

Plantations are generally established using a single species that has been selected as the most suitable for the production objectives and best adapted to the selected site. Within the selected species, the genetic diversity of the planting stock is often limited because superior phenotypes or genotypes have been selected to enhance the quality and quantity of crop trees (Section 4.1.2). This conflicts with objectives of conserving biodiversity on a site.

Options for overcoming this conflict in objectives include improving the species composition in each stand, or distributing different types of forests across the landscape. The species composition can be improved at a stand level by establishing and maintaining a mixed stand, using either intermingled plantings of species with different shade-tolerance traits or group-planting of species with similar shade-tolerance traits (Section 4.4.6).

If a shade-tolerant species is planted and light-demanding tree species invade the stand soon after the planting, a two-storied mixed stand can develop if the invaded trees are not removed or reduced by weeding, improvement cutting, or thinning (Hara et al., 1995; Figure 5-4). Fast growth of the light-demanding invading species can suppress any vegetation competing with the planted species, and the cost of weeding and improvement cutting can be reduced (Hara et al., 1995). Appropriate thinning and harvesting regimes for the fast-growing overstorey species will depend on its growing pattern and commercial value.

If a stand has been regenerated by natural seeding, in many regions of the world it will usually be composed of several tree species. In this case, a desirable species composition can be developed by improvement cutting and thinning as discussed in Section 8.1.2. For example, higher value oak can be effectively produced by manipulating mixed oak-beech stands on sites where beech dominates naturally (Lüpke, 1998; Section 8.1.2.1).

As described in Sections 2.4.4 and Chapter 10, biodiversity is generally lowest in the young stage of forest stand development, and this is most extreme in plantations. However, undergrowth begins to develop from the mature (understorey reinitiation) stage, so, even in plantations, biodiversity can be increased by extending the rotation period. This can be promoted by heavy thinning which improves the light conditions in the understorey. Long rotations have a number of advantages (Sections 7.1.4 and 8.1), including the ability to produce high-value sawn timber. Thinning is essential for rapid production of a high proportion of valuable timber and to improve stand resistance to damaging agents such as wind, disease and pests.

12.2.2 Diversity of tree size and vertical stratification

In plantations, especially conifer plantations managed under short rotations, the production objective (e.g., boxed-heart sawn timber) commonly relies on production of uniformly-sized individual trees through breeding, thinning, and pruning. This results in a pure, uniform stand that yields a high percentage of timber that meets product specifications. The structure of such stands is not desirable from either the viewpoint of biodiversity (Chapter 10) or because of their increased susceptibility to wind and snow damages (Chapter 15). One way to improve these shortcomings is to modify the production objective to larger logs from which any sized square timber or board can be produced at final harvest, with a thinning regime that yields commercial logs suitable for products such as boxed-heart square timber. By extending the rotation, an understorey will develop and biodiversity and soil development will improve. Further extension of the rotation and continued thinning improves conditions for regeneration of desired species, particularly if competing species in the understorey are controlled (Sections 8.1.1 and 8.1.2). Regeneration can be achieved either naturally or by planting, depending on the natural and social conditions.

Extension of plantation rotations can be followed by conversion to a shelterwood or selection method. Regeneration of the desired species by management of the stand floor at the time of the last thinning, and final cutting 10 or more years later, is a type of shelterwood method, called the short-term two-storied forest method in Japan (Section 7.1.2). If natural regeneration is to be used, the last thinning must coincide with the mast year of the crop. The stand structure developed following regeneration by this method is more complex than a stand established by planting on clearcut site.

Promotion of regeneration in gaps created following harvesting of individual trees or groups of trees is the selection method. Either natural regeneration or planting can be used in this method. The resulting stand has trees across a large range of size classes and the level of biodiversity tends to be high (Lähde et al., 1999). Use of this technique, together with a long rotation, appropriate thinning regimes and control of the undergrowth, will result in the development of multi-storied forests of crop trees.

The shortcomings of simple stand structures typical of plantations and other managed forests can also be overcome by careful planning of their distribution in the landscape. At a landscape level, it is desirable to intermingle simple stands with various forest types, including natural forests, and within tracts of simple stands, intermingle areas of different age-classes.

12.2.3 Existence of snags and fallen logs as an element of structural diversity

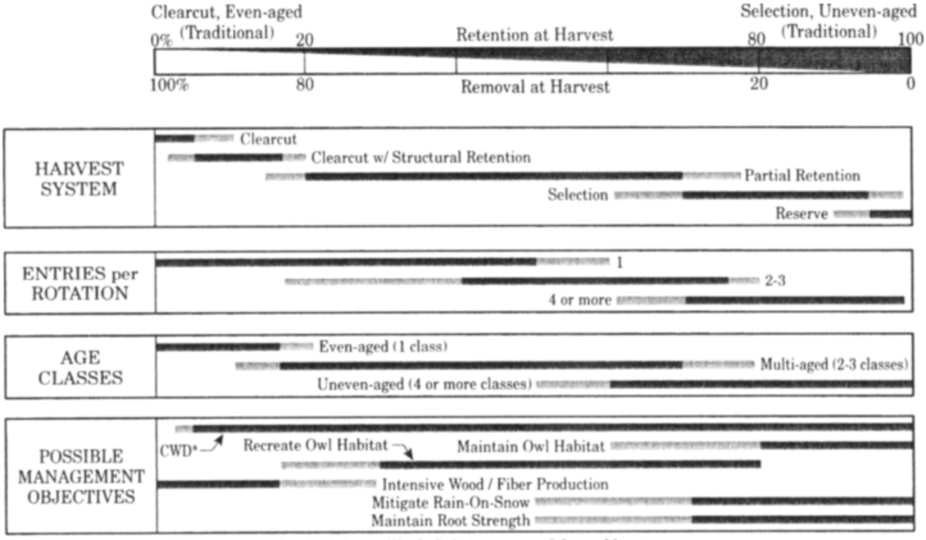
The significance of declining trees, snags, and fallen logs in forest ecosystems for biodiversity and soil and water conservation has been repeatedly described (Sections 2.4.1, 2.4.4, 10.5.1, and Chapter 11). These components provide essential food resources and habitats for various organisms and reduce the erosion of soil and forested streams. In plantations and managed forests, however, declining trees, snags, and fallen logs are not usually found, because the large trees are harvested before they begin to decline or die. It has been believed that it is desirable for plantations and managed forests to be composed of living healthy individuals. Therefore, how to retain, conserve, or preserve declining trees, snags and fallen logs in managed forests is an important issue for implementation of sustainable forest management.

The strategies for retaining declining trees, snags, and fallen logs were discussed in Sections 10.5.1 and 11.3. Possible methods include dispersed or aggregated retention (Franklin, 1997). Aggregated retention is preferred because it maintains more ecological elements. Use of dispersed retention in plantations or intensively managed forests dependent on natural regeneration is economically costly, because of the losses associated with producing selected valuable dominant individuals through tending operations until the stands reaches the mature stage and because of the difficulty of working beneath a canopy containing declining trees and snags.

In less intensively managed forests, dispersed retention is a viable option. In this method, a proportion of trees is retained at final harvest and left to decline and become snags in the future. Some of these trees may be harvested later, but the primary objective is to provide some structural diversity. Snags can also be created during thinning in the mature stage. If thinning from above or selection thinning is practiced in the mature stage, a certain proportion of dominant trees with less value that would have been removed can be killed by girdling and left standing.

Franklin et al. (1997) demonstrated a range of forest regeneration harvest systems according to the proportion of trees removed at harvest (Figure 12-1). Zero retention corresponds to clearcutting and high proportions of retention correspond to selection cutting. Franklin (1997) criticizes traditional silvicultural systems as being biased to extreme clearcutting (no retention) or, less often, to low levels of removal such as selection cutting. Various cutting methods such as group selection cutting and small clearcutting (patch cutting) can be adopted and used to retain declining trees and snags. Dispersed retention can be used in single-tree selection methods, and aggregated retention can be used in group-selection or small clearcuttting methods.

Although it is important to retain declining trees and snags, their



*CWD=minimum levels of Coarse Woody Debris (snags and downed logs)

Figure 12-1 Forest harvest and regeneration systems in relation to retention (or removal) rates at harvest and their links to forest structure and possible management objectives. (Franklin, 1997)

potential role as a source of serious pests and diseases must be considered. For example, if dead trees of *Pinus densiflora* (akamatsu) are retained, serious damage caused by the exotic pine wood nematode (*Bursaphelenchus xylophilus*) can occur (Chapter 15). In such cases, declining and dead trees should not be retained in or around infected areas, and if trees do die, they must be removed and sterilized or burned to kill the vectors and the virus. If damage by pests and diseases harboured in retained trees and snags does not reach abnormal levels, they should be retained as elements of a normal ecosystem.

The retention systems proposed by Franklin et al. (1997) for natural or managed forests have the primary goal of producing snags, but they must be managed in association with the surrounding areas that are managed for wood production. Effectively, aggregated retained patches must be regarded as part of a stand's rotation and the distribution of the patches or strips should be considered. These patches and strips, even if small (about 0.5-5 ha), can fulfil important functions such as conservation of biodiversity, provision of recreational opportunities and aesthetic benefits. The presence of these areas in the landscape could also contribute to the conservation of soil and water resources even though the effect may be marginal.

If possible, retention of strips of natural forests is desirable and a combination of retained strips and patches is ideal, as illustrated in Figure 12-2. This Figure illustrates a managed secondary forest in which unmanaged retained patches and strips are left in perpetuity to maintain elements such as declining trees, snags and fallen logs. This strategy can also be adopted in plantations. In this case, unmanaged natural patches and strips would have to be recovered or created, and this may take a long time to achieve. The strips in Figure 12-2 are not intended to be corridors for the movement of animals initially, but they could fulfil this function (Franklin et al., 1997), or at least would have the potential to become corridors if further developed. The ideal proportions of an area that should be retained in strips or patches, and the ideal size of each strip or patch is uncertain at this time, but would probably vary depending on the natural and social conditions of the area. The area of natural forest (upper right corner of Figure 12-2) might be several hundred hectares, but it is not a strict preservation area. Strict protection areas for the preservation of forest ecosystem need to be at least 5000 ha (Schnitser and Borlea, 1998).

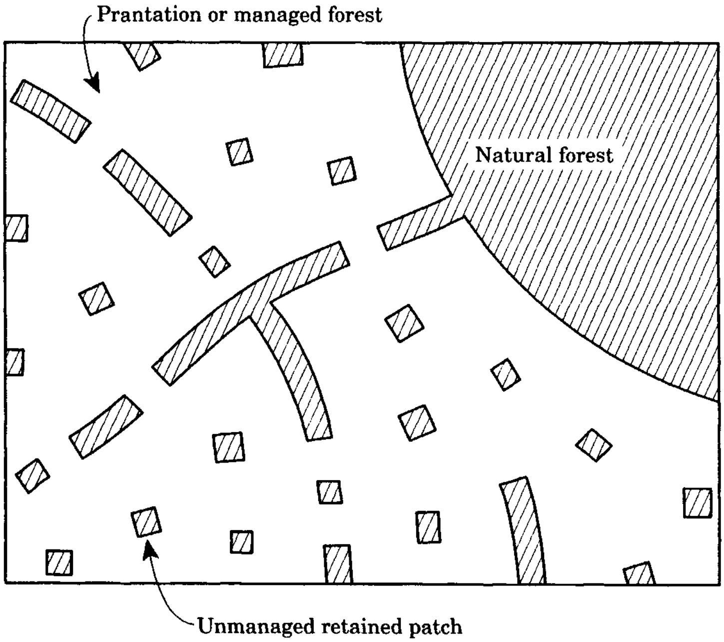


Figure 12-2 Diagrammatic representation of the possible distribution of unmanaged retained patches and strips amongst managed forests or plantations. The total area of the Figure is about 500 ha and each patch or strip is about 0.5 – 10 ha. The block of natural forest in the upper right corner is several hundred hectares, and blocks of natural forest of about this size should be distributed adequately in forested landscape.

12.2.4 Impacts on forest ecosystems by harvesting

Harvesting timber conflicts with maintenance of the original stand structure of a forest ecosystem because of the removal of trunks from the ecosystem and the disturbance to the soil. Generally invaluable tree species are removed from the overstorey of managed stands during improvement cutting and thinning operations, and large crop trees are harvested before they decline. As a result, such stands tend to develop a simple stand structure composed of a limited number of species (often a single species). As discussed in Chapter 11, this is not conducive to soil and water conservation or maintenance of productivity.

Following natural disturbances in forest stands, even after disastrous disturbances such as fire or typhoons, considerable structural legacies remain which provide important elements to the regenerating ecosystem. These legacies help protect the soils of the stand and may provide some advanced growth to the regenerating stand, commonly a mixed stand of shade-tolerant and intolerant species. The most notable difference between stands managed for timber production and unmanaged natural stands is usually the absence of large-sized declining trees, snags, and fallen logs which once dominated in the overstorey. As noted above, these features provide important niches for various animals, plants, and microorganisms, are important in nutrient cycling and contribute to the development and maintenance of the forest soils by limiting erosion and slowly decomposing. An important step in developing sustainable forest management systems, therefore, is to bridge the gap between enhancing wood production and maintaining soil and biodiversity within a forest ecosystem.

12.3 Silvicultural and ecological management methods to fulfil other forest functions

12.3.1 Production of wood for sawlogs

Plantations

In first-generation plantations established to reforest natural or secondary forest areas or for afforestation, fast growing species are often planted under a short rotation. This is usually to achieve commercial stability during the early stage of management, but it would be desirable to shift to long rotation management as rapidly as possible to achieve sustainable forest management as described in Figures 7-1 and 7.2. In flat areas, repeated short rotations of plantations comprising fast growing species can be commercially important, but even in this case, the distribution of the plantations through the landscape and variation amongst stands in terms of age classes and rotations is desirable for sustainable forest management.

The implementation of proper thinning and pruning regimes is an important step in converting plantations to management under a long rotation (e.g., Section 8.1). The quality of sawn timber is dependent on the existence and condition of knots. Specific techniques for production of timber with defined characteristics were described in Chapter 6. Desired log quality can be defined by dimensions, lengths that are knot-free and the width and distribution of growth rings. Knot-free timber to about 6-7 m for conifers is obtained by pruning while the trees are relatively small (for example, while DBH is less than about 15 cm) and/or by stand density control. Stand density control involves maintaining the young stand at a high density (about 3000-4000 stems/ha for conifers in Japan) until branches are adequately controlled, followed by frequent thinning to enhance the growth of promising trees. Thinning is required even if the stand is established at relatively low densities, although it may commence later.

Thinning enables growth to be concentrated on promising trees that have superior traits, by ensuring that these trees have access to the light, water and nutrient resources within the stand that are critical to growth. Once branch control has been achieved, thinning regimes should aim to develop the crowns of the most promising trees to maintain even growth of the stem, especially the highest value portion, and to enhance the resistance of the trees to wind or crown snow damage. Deterioration of the crown can lead to poor distribution of diameter growth up the stem (Figure 6-6) and trees may become susceptible to wind or crown snow damage. Suitable development of the crown is characterised by the lower branches of the crown declining and dying more slowly than the crown grows in height. Typically, crown length should be about 50-60% of total tree height in consideration with a report by Burschel and Huss (1987) cited in Benecke (1996). Horizontal crown development is also important, particularly in hardwoods, but clearing of branches must be done more carefully because of their decurrent growth habit and the risk of epicormic branch development.

Enhancing the growth of promising trees in the overstorey by expanding the available growing space is accompanied by increased illumination to the understorey, promoting the growth of the understorey as well. Development of the undergrowth is desirable for conservation of biodiversity and soil and water resources. Thinnings aimed at producing high quality timber can also improve conditions for regenerating the crop species, enabling non-clearcutting methods to be adopted (Section 8.1.2). Successful regeneration may require control of competing undergrowth in areas where it is dense.

There are various options available for harvesting and regenerating mature stands. If the same type of management, using the same species on the same rotation is desired, the stand can be clearcut. If the stand is mature and a repeated thinning has occurred, harvesting and regeneration options expand, and multi-storied forests of shade-tolerant and shade-intolerant species can be developed. Other options are briefly described in the following section.

Secondary forests

In stands with a high proportion of promising crop trees, a series of improvement cuttings and thinnings is necessary to effectively produce high quality timber. Appropriate tending regimes were discussed in Section 8.1, and are similar to those described for plantations. The general approach is to maintain high stand density until the early young stage to obtain straight trees with knot-free stems, followed by selection of promising crop trees and repeated thinning to provide these trees with sufficient growing space. This allows the crowns of the crop trees to develop well, maintain a high growth rate and develop resistance to wind and crown snow damage. Such methods also enhance the development of undergrowth and increased biodiversity. Thinnings also create conditions suitable for regeneration of the crop species and natural regeneration can be achieved, although it may sometimes be necessary to undertake some site preparation or removal of the undergrowth and middle-storey trees prior to regeneration (Fujimori, 1991a; Meadows and Stanturf, 1997).

As the biodiversity in secondary forests is generally high (Iida and Nakashizuka, 1995; Nakashizuka and Iida, 1996; Figure 10-11), it is important that silvicultural practices aimed at wood production also maintain biodiversity at as high a level as possible. Management for wood production tends to result in a higher proportion of desired species, and an accompanying decrease in species diversity, especially of high tree species. However, this can be partly overcome by maintaining a mixture of species in the stand that satisfy a number of objectives. For example, in some hardwood stands, selected crop trees benefit if surrounding intermediate trees are retained to limit the production of epicormic buds on the crop trees (Sections 6.2.4.2 and 8.1). The retained intermediate trees are called trainers and their retention adds to higher biodiversity in the stand. A number of harvesting and regeneration methods are available in these systems, including clearcutting, patch cutting, group-selection cutting, or single-selection cutting. The appropriate choice depends on the traits of the species to be regenerated, the mixture of species required, the costs, and environmental considerations.

In degraded secondary forests which have had valuable trees selectively harvested and regeneration has been unsuccessful, enrichment of the stand is necessary. If the desired species has been eliminated, seedlings of the same provenance should be planted. Trees within former coppice stands typically have poor form that is unsuitable for sawlogs. Such stands must be enriched by planting or natural seeding and only superior stems retained. This will mean that a high proportion of stems are harvested, and these can be used for pulp or energy. Retained stems should be limited to one per stump, and if all stems on a stump are inferior, all of them should be cut. After the enrichment has been achieved, tending and regeneration techniques can be implemented as described above.

If secondary forests and plantations can be sustainably managed for wood production, the pressure on natural forests and consequent degradation can be reduced and stopped.

12.3.2 Production of fuelwood

Fuelwood is commonly produced from native species managed under coppice regimes in many parts of the world, but it can also be produced by natural seeding in species such as pine and birch. Silvicultural techniques for coppice forests were described in Section 8.2. Coppice rotations are typically short, in the range of 15-25 years. If the rotation is too short, productivity decreases, and if the rotation is too long, the ability of the stumps to regenerate by sprouting generally decreases.

Recently, very short rotation management of fast growing species for the production of bioenergy has been applied in many countries to mitigate CO_2 concentration in the atmosphere. The species typically used are from genera such as *Populus, Salix* and *Alnus*, and selected high yielding clones and hybrids are commonly used. These species are planted at a high density and managed under a simple coppice method using a rotation of between 1 and 15 years (Ceulemans and Deraedt, 1999; Hofmann-Schielie et al., 1999; Liesebach et al., 1999). Fertilization is usually required to maintain or improve site productivity, as is pest and disease management (Gruppe et al., 1999; Mitchell et al., 1999; Ramstedt, 1999). Such highly intensive management is close to agriculture, so is most appropriate on flat areas or on very gentle slopes to avoid soil erosion. If fertilizer is used, the energy required for its production and application should be calculated and its utilisation balanced against the increased wood (bioenergy) production.

12.4 Overview of cutting methods, rotation length, and stand structure

Cutting methods, rotation length, and stand structure are closely related to silviculture, and the development of silvicultural practices should consider these factors. Over long rotations, harvesting techniques should be selected giving consideration to the returns at the time of harvest and the future structure of the stand. If continued harvesting is required, thinning should be adopted, and if regeneration needs to commence at the same time, selection or shelterwood methods should be adopted. Planting or natural seeding within or around a gap begins the shift to a selection method. If planting or natural seeding is undertaken throughout the stand at the time of a thinning, it begins the shift to a shelterwood method. If thinning has been conducted throughout a long rotation, specifically designed preparatory cutting and seeding cutting become less important (Section 8.1). If shade-intolerant species such as pines need to be regenerated, the seed tree or clearcutting method should be used. If a mixed stand of shade-tolerant and intolerant species is wanted, group selection cutting, patch cutting, or small clearcutting should be applied according to the desired species mix and their regeneration requirements (Section 8.1). As the rotation period extends, if it has been accompanied by a series of thinnings, the options combining harvesting and regeneration activities increase, but if a stand is managed on a short rotation, the options are limited and usually restricted to clearcutting.

12.5 Overview of the distribution of forest types and stand development stages

Successful implementation of sustainable forest management requires that conflicts between different functions of forests be overcome. The main conflicts are between wood production and other functions such as conservation of biodiversity and soil and water resources. These conflicts can be minimised at both a stand level and landscape level. At a stand level, this can be achieved by the techniques described above, that result in effects such as enhanced understorey development and maintenance of mixed stands. At a landscape level, various types of forests can be distributed across the landscape.

The distribution of natural stands containing (or with the potential to contain) declining trees, snags and fallen logs is an important component of the landscape strategy (Section 12.2.3, Figure 12-2). Strategies which include distribution of natural stands should be accompanied by the development of strategies for ecological control of pests, disease, and mammal damage in plantations.

Even though declining trees, snags and fallen logs are few, managed stands that have originated from natural seeding generally have more natural elements than plantations, but even the structure and function of plantation stands varies according to the stand development stage. Therefore, if long rotations are adopted in plantations, the variety of stand types increases and there will be an accompanying increase in biodiversity. The most appropriate distribution of stands and management systems depends on ecological knowledge, social and natural conditions, and its implementation depends on the willingness of landowners, local residents, local governments, and nations to participate. The distribution strategy is one of the important indicators of sustainable forest management. The structure of land ownership is an important factor determining an appropriate distribution strategy, and it will often be hindered if there is complicated ownership. Systems for achieving agreement amongst many owners on the distribution of stand types in an area is important, and processes and systems for reaching agreement will become an important issue in the future. Institutional supports such as tax subsidies may be necessary for effective implementation.

Chapter 13

Maintenance and Enrichment of Cultural and Recreational Functions

Forests are a cultural and recreational resource used by people to refresh themselves and enhance their spirit. People appreciate the scenic beauty of forests and enjoy activities in forests. Walking through forests provides experiences for people's senses of sight, smell, and hearing, as they are surrounded by natural beauty, pleasant aromas, and the delicate sounds of leaves moving in the wind and birds. People also enjoy gathering edible wild plants and mushrooms. These functions of forests have become increasingly appreciated as the area and quality of forests near urban areas has decreased.

In places of scenic beauty, forests should be managed primarily for their aesthetic function. Generally, natural old forests best achieve this, but artificial treatment may be required to develop and maintain an aesthetically pleasing stand structure. In places where recreational demand is high, but forest production is also required, management should be directed to achieving both functions at the same time.

13.1 Cultural and recreational functions

13.1.1 Scenic beauty

Natural forests are generally very scenic, because they often have a mix of species and the stands are well stratified. Simple plantations are not usually regarded as scenic, and although their uniformity may be appreciated their widespread distribution is monotonous, so natural forests or forests which include more natural elements should be intermingled with them.

It has often been assumed that citizens think that cutting forests destroys their scenic beauty. However, some people regard well managed forests and the landscapes containing them as having their own scenic beauty (Hori et al., 1997). In traditional forestry areas in Japan, there is a cultural acceptance of the scenic beauty of managed forests. Therefore, it is possible for forest managers to manage forests so that they satisfy both the local demand for forest production and scenic beauty.

Old stands containing big trees are usually appreciated, even if they are old plantation stands. Thus, the long rotation methods that can be used for wood production can also satisfy scenic and recreational demands of a forest. The presence of coppice stands in the landscape may also enhance scenic beauty, although coppice management has been declining in advanced countries due to social change (Piussi and Farrell, 2000). The beauty of forests is also enhanced if they are in scenic landscapes containing rivers, ponds or farmland. Places that provide scenic views should be identified and the structure of nearby stands managed to maintain and enhance the view (Hori et al., 1997).

13.1.2 Activities in forests

The characteristic refreshing aroma of forests arises from phytoncides, which mainly occur in the leaves or needles. The aroma has measurable physiological effects on humans, reducing the activity of the autonomic sympathetic nervous system and arousing the parasympathetic nervous system, which has a calming effect (Yatagai, 1995). This effect is enhanced if it is combined with the sights and sounds of the forest, and in Japan since the beginning of 1980s, this has been referred to as "shinrin-yoku", which can be translated as "green shower."

Walking, gathering of edible wild plants or mushrooms, and many other activities are also popular in forests. Gathering of edible wild plants has historically been popular in many countries in the world. If the supply of edible wild plants is to be sustained, the forests that support these plants need to be recovered or maintained. The plants of interest occur in a variety of forest types and stand structures. Some occur in the interior of mature or old-growth stands, and others occur at stand edges or in disturbed stands. Therefore, a mixture of stands at various development stages and of different sizes will need to be maintained.

The gathering of edible mushrooms is popular in Japan. One of the most popular mushrooms is the matsutake (*Tricholoma matsutake*) which occurs on the floor of the picturesque *Pinus densiflora* (akamatsu) forests. The occurrence of this mushroom has decreased since the fertilizer and fuel revolutions, because changes in management have resulted in the enriching of the soils of these forests. If matsutake production is to continue, the undergrowth and litter of the stand should be removed periodically. Many other kinds of edible mushrooms occur in Japan, particularly in the broad-leaved deciduous forests. Many of these occur on the stems of dead and dying trees or fallen logs, requiring a mixture of mature and old-growth stands.

Bird watching is popular in many countries in the world. Bird watching is best in natural forests, because the biodiversity of these forests is generally higher than in plantations (Yui and Ishii, 1994). Stands with well developed layers and a variety of species generally have the most number of bird species. Such structures develop as stands age, and are best developed in mature and old-growth stands. However, some birds occur at particular developmental stages, so there needs to be a mixture of stands at various developmental stages.

Fishing is also popular in many countries in the world. Fish are dependent on healthy streams, and forest management that minimizes disturbance in riparian zones and conserves soil and water resources (Chapter 11) will be beneficial for fish.

13.1.3 Education and culture

Forests provide educational opportunities to learn about and experience nature, ecology and the relationship between nature and humans. Specifically, forests can be used to demonstrate various aspects of ecosystem functioning, such as biological interactions, nutrient and energy cycling, and the relationships between different forest structures and functions. They can also be used to explain the significance of biodiversity, the role of forests in conservation of water resources and the contribution of forests to the culture and history of different regions. Forests also provide the opportunity to learn about forest management and the role of operations such as regeneration and tending in providing forest products (Figure. 13-1). The role of forests in education is enhanced if there is a variety of forests, from virgin forests to plantations, nearby.

13.2 Some examples of management of forested recreational areas

Fontainebleau is a city located about 65 km southeast of Paris in France. The forest of Fontainebleau (Figure 13-2) is noted for its wide and beautiful forests, various monuments such as the castle of Francois 1st and the work of artists (the Fontainebleau or Barvizon group) who worked in this forest. The forest begins on the left side of Seine River and covers an area of about 22,000 ha. It is one of the oldest forests in Europe and there

Figure 13-1 Demonstration of forestry operations and utilization of wood to the general public.

Figure 13-2 A view of Fortainebleau forest near Paris, France. (photograph by T. Tanimoto)

are many records of historical events that have occurred in it. It contains an area of 34 ha of broad-leaved deciduous forest characterised by snags and fallen logs that has been preserved for 600 years. About a half of the rest of the area of forest is a *Pinus sylvestris* (Scots pine) and *Pinus pinaster* (maritime pine) plantation, and the other half is broad-leaved deciduous secondary forests composed mainly of oak and beech. These areas are managed for a combination of wood production and maintenance of the aesthetic functions of the forest, and this reflects the opinions of local citizen groups. The hardwood forests are managed under a shelterwood method (Kitamura, 1996; Tanimoto, 2000).

Vienna in Austria is noted for the recreational forest that surrounds the city (Wienerwald; Figure 13-3). It extends for 50 km from east to west and 55 km from north to south on an area with gentle slopes. Meadows and farmlands are intermingled with the forest in this area. Roads providing access for recreational activities and sight-seeing occur throughout the forest. The forest contains many monuments associated with famous musicians and historical events. The northern part of the forest is broad-leaved deciduous forest dominated by oak, beech and maple and the southern part of the forest is predominantly *Pinus sylvestris* forest. Wood is produced from the forest, but clearcutting is seldom used and regeneration is mainly natural. Intensive silvicultural techniques are used, with consideration given to the opinion of the citizens (Okazaki, 1995; Kitamura, 1996).

In the broad-leaved evergreen forest zone of Japan, unmanaged stands are dominated by broad-leaved evergreen species as succession advances. Light-demanding pioneer species such as cherry and pines are an

Figure 13-3 A view of Wienerwald, Vienna, Austria. (photograph by M. Kitamura)

important component of these stands because of their aesthetic contribution. Broad-leaved deciduous trees are another important component appreciated for the seasonal changes of their crowns, and in some species, their flowers. Such species are often planted and maintained in evergreen forests to enhance their scenic beauty.

Arashiyama in Kyoto city, Japan, is an area with mountainous forests and rivers (Figure 13-4) noted as a scenic site. Nearly ten million people visit there annually. The Arashiyama National Forest was left unmanaged for 60 years to maintain its natural condition, and gradually the cherry and pine within it were suppressed then eliminated by broad-leaved evergreen species. Management of the forest was discussed by various groups with different interests, and it was decided to use a small group-selection method partially to reestablish cherry and pine in the forest. The results have been successful and have been approved by the citizens (Amano and Noda, 1990; Uchimura et al., 1991; Sugimura and Noda, 1992).

These examples illustrate how many forests in recreational areas around the world are carefully managed using tailored silvicultural techniques. Various management options are available to enhance the aesthetic beauty of forests, ranging from completely conserving forests in their natural condition, to maintaining a particular successional stage, or aggressively modifying the forest. In areas where wood production is combined with recreational and aesthetic activities, the silvicultural methods must be carefully selected to satisfy all functions.

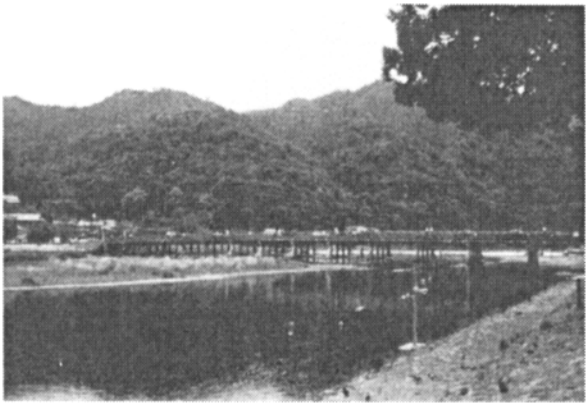


Figure 13-4 A view of Arashiyama in Kyoto city, Japan.

Chapter 14

Maintenance of forest contribution to global carbon cycles

Of all terrestrial ecosystems, forest ecosystems have the largest carbon pool and make the greatest contribution to global carbon cycles through stocks and flows of carbon. Increased use of fossil fuels and large-scale destruction of forests has resulted in increased concentrations of atmospheric carbon dioxide (CO_2). In terms of amount, CO_2 is the greatest contributor to greenhouse gases, and its increase is a major cause of global warming. It is anticipated that global warming will cause unusual climatic phenomena and disruption of terrestrial ecosystems (Section 15.3.2.1-1). It is therefore important to understand how forest ecosystems might be managed to mitigate CO_2 concentration in the atmosphere.

14.1 Global carbon cycles and carbon sequestration and storage in forest ecosystems

The carbon pool in the atmosphere is about 760 GtC (giga ton carbon, equivalent to a billion tonnes of carbon), and the carbon pool in the terrestrial ecosystems of earth is about 2,500 GtC (500 GtC in vegetation and 2,000 GtC in soils and detritus) (Figure 14-1, Table 14-1). The carbon pool in terrestrial ecosystems is thus more than three times the

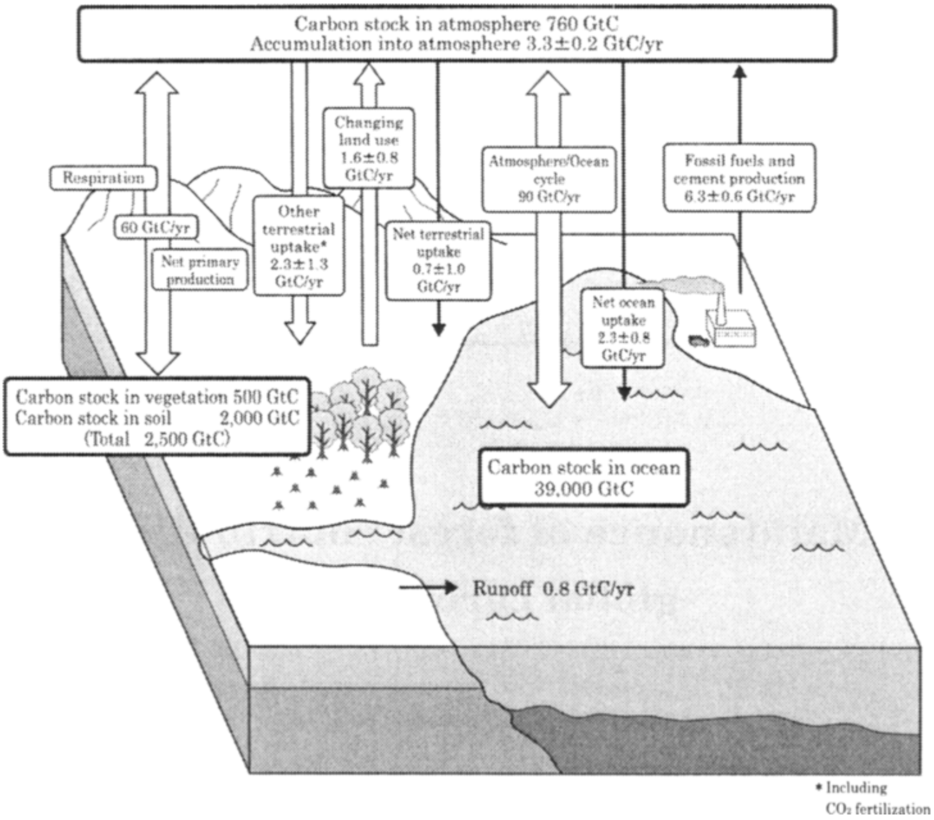


Figure 14-1 The global carbon cycle, showing the carbon stocks in reservoirs (in GtC = 10^9 tC) and carbon flows (in GtC yr^{-1}) relative to the atmospheric perturbation as annual averages over the decade from 1989 to 1998. Net ocean uptake of the anthropogenic perturbation equals the net air-sea input plus runoff minus sedimentation [Modified by Yamagata and Yamada (2000) from Bolin et al., 2000].

atmospheric pool. About 28% (by area) of terrestrial ecosystems is forested. About 77% of the carbon stored in vegetation and about 39% of the carbon pooled in soils are in forest ecosystems. Thus, about 46% of the total carbon in terrestrial ecosystems is in forests. Within forests, the proportion of the total carbon pool that is in the soil is about 69%. The proportion of carbon in a tree is about 50% of the dry weight.

The proportion of carbon in soil in terrestrial ecosystems, including forests, is far larger than that in the biomass. This implies that a high proportion of carbon in soil is a result of accumulation of carbon through a histrical long time. Even so, the proportion of pooled carbon that

Table 14-1 Global carbon stocks in vegetation and soil carbon pools down to a depth of 1 m (Bolin et al., 2000).

Ecosystem type	Area (10^7 ha)	Carbon stocks (GtC)			Carbon stock per ha (tC)		
		Vegetation	Soils	Total	Vegetation	Soils	Total
Tropical forests	176	212	216	428	120	123	243
Temperate forests	104	59	100	159	57	96	153
Boreal forests	137	88	471	559	64	344	408
Tropical savannas	225	66	264	330	29	117	146
Temperate grasslands	125	9	295	304	7	236	243
Deserts & semideserts	455	8	191	199	2	42	44
Tsundra	95	6	121	127	6	127	133
Wetlands	35	15	225	240	43	643	686
Croplands	160	3	128	131	2	80	82
Total	1,512	466	2,011	2,477	31	133	164

originates from carbon cycling in the present ecosystems must also be considerable. It is important to quantify the amounts of carbon from each source.

The annual carbon flux (transfer of carbon from one carbon pool to another in units of measurement of mass per unit area and time) in 1990 from the atmosphere to forests (+) and from forests to the atmosphere (-) was about +4.8 GtC in high latitudes, +2.6 GtC in middle latitudes, -16.5 GtC in low latitudes, and in total, about -9 GtC (Dixon et al., 1994). The negative fluxes in low latitudes are due to excessive deforestation. On the other hand, in temperate and boreal forests, carbon pools increased during the 1980s and 1990s as the rate of growth (sequestration) was higher than the rate of timber harvesting (Kauppi et al., 1992). The relatively high sequestration rate is regarded as being due to changes in land use and land management rather than changes in the environment such as increasing CO_2 concentration or atmospheric deposition of fertilizing nitrogen compounds (Schimel et al., 2000). Technological improvements in both agricultural production and wood processing have led to increased carbon sequestration(Wernick et al., 1998). For example, genetic improvements and refined use of fertilizer has increased carbon sequestration in agriculture (Paustian et al., 1997), and in wood processing, the percentage yield from round logs has been increasing (Wernick et al., 1998). Although carbon pools in temperate and boreal forests are increasing gradually, the current levels of carbon pools are still far smaller than those in pre-industrial or pre-historic times. Prevention of deforestation, reforestation, and improvement of forests are social and political rather than silvicultural issues, but the development of strategies to enhance carbon sequestration by forests is a silvicultural challenge.

14.2 Stocks and flows of carbon

The global carbon cycle consists of various stocks of carbon in the earth's ecosystems and flows of carbon between these stocks. A carbon stock is regarded as the absolute quantity of carbon held within a pool at a specified time. A carbon pool is a reservoir and is regarded as a system which has the capacity to accumulate or release carbon. Carbon pools include forest biomass, wood products, soils, and atmosphere. Sequestration is the process of increasing the carbon content of carbon pools other than the atmosphere (A special report of the IPCC, 2000).

It is often debated whether the rate of carbon sequestration or the total amount of accumulated carbon (carbon store or pool) in forest ecosystems is the more important measure for carbon mitigation. Sequestration (flux) and storage (pooling) of carbon in ecosystems cannot be maximized simultaneously. The relationship between sequestration and storage in vegetation after a disturbance is shown in Figure 14-2. The carbon flux (equivalent to net biomass production rate) increases until the later part of

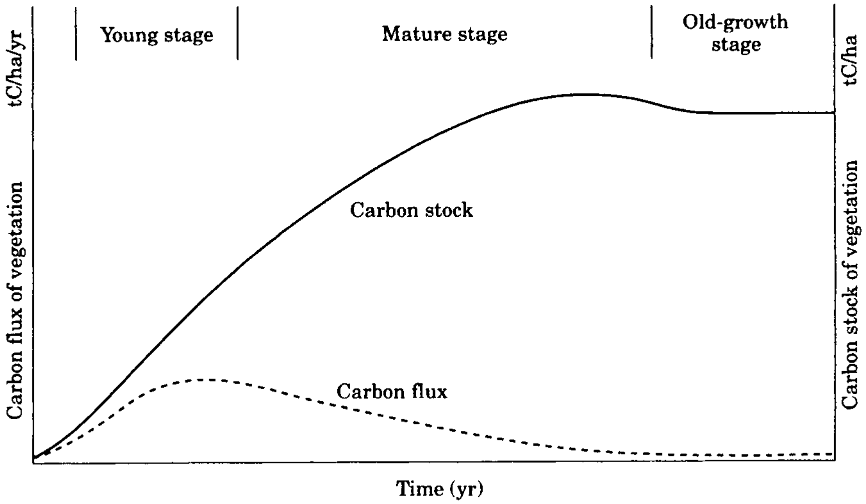


Figure 14-2 Carbon flux and carbon stock of vegetation in natural forest according to the stand development stage. This model was developed with reference to Kira and Shidei (1967), Borman and Likens (1979), Hatiya et al. (1989), Osumi et al. (1995), Oohata (1996), and Kurz and Apps (1999). (Modified from Fujimori, 1998)

the young stage, then decreases to an approximately constant level close to zero in the old-growth stage. By comparison, the accumulated carbon stock increases until the end of the mature stage, then declines slightly in the old-growth stage. In the old-growth stage, as individuals in the overstorey gradually die, the amount of vegetation in the overstorey decreases, but the increased growth of the understorey partially compensates for the decreased amount of overstorey vegetation. In the old-growth stage, the flux is approximately zero, because death and growth of trees in the stand is balanced.

Coarse woody debris (snags and fallen logs) in natural forests contributes to the carbon pool. If a large disturbance occurs, the amount of coarse woody debris is greatest just after the disturbance. It then decreases as the stand ages, reaching a minimum in the mature stage, before increasing and stabilizing in the old-growth stage. The pattern of carbon sequestration in vegetation, snags and fallen logs, litter of leaves and branches on forest floor, and soils in natural forests following a large disturbance is shown in Figure 14-3. The amount of vegetation decreases slightly in the old-growth stage, but the number of snags and fallen logs increases, so the total carbon pool within the stand remains constant at the highest level.

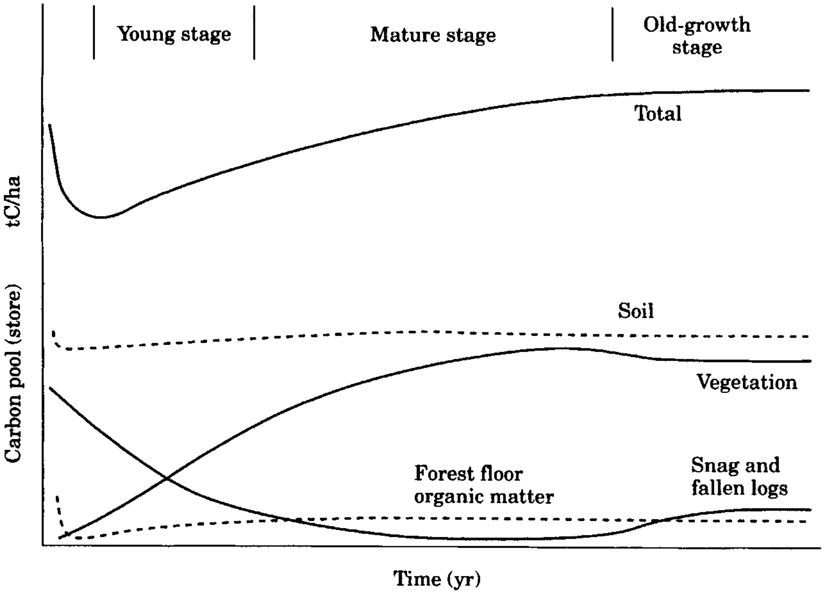


Figure 14-3 The amount of carbon pooled in natural forests, according to the stand development stage. This model was developed with reference to Kira and Shidei (1967), Borman and Likens (1979), Corvington (1981), Spies et al. (1988), Kobayashi (1991), Sanada and Takahashi (1995, 1996), Oohata (1996), Kurz and Apps (1999), and Ohta (2000). (Modified from Fujimori, 1998)

14.3 Strategies for carbon sequestration and pool

In the Second Assessment Report of IPCC (Sathaye et al., 1996), the following three options to reduce atmospheric CO_2 were proposed.

Conservation:	conserving existing carbon pools, thereby preventing emissions to the atmosphere.
Sequestration:	increasing the size of existing carbon pools, thereby extracting CO_2 from the atmosphere.
Substitution:	substituting biological products for fossil fuels or energy-intensive products, thereby reducing CO_2 emissions.

The implementation of sustainable forest management to enhance various functions of forests can mitigate atmospheric CO_2 concentration in all three ways.

14.3.1 Conservation of carbon pools in forest ecosystems

Conserving existing carbon pools is the most effective and lowest cost option for reducing atmospheric carbon. Preserving natural areas for biodiversity or soil and water conservation coincides with maintaining the largest carbon pools in forest ecosystems. Even if natural areas are not preserved by legislation, secondary or natural forests with large carbon pools should be conserved as much as possible, because if they are destroyed, recovering the lost carbon pool will take a very long time. Managed forests with large carbon pools should be managed to maintain the pool by using silvicultural methods, such as the selection method, that achieve a distribution of stands with various age classes.

Conservation of large carbon pools in forest ecosystems means maintaining mature and old-growth forests. Stands which have not yet reached the mature stage can be managed to achieve a mature or old-growth stand structure and maintained when they achieve such a structure. This approach is compatible with conservation of biodiversity and soil and water resources.

14.3.2 Sequestration to increase the size of existing carbon pools

This approach aims to increase the carbon pools in both forest ecosystems and wood products. Enrichment of secondary forests is an important strategy for both increasing the carbon pool in the forest ecosystems and producing usable timber. When secondary forests are harvested, appropriate regeneration and management techniques should be applied to establish valuable stands, as discussed in Parts II and III. In plantations, the silvicultural methods discussed in Part III can be used.

There are a range of silvicultural methods and rotation periods that can be used to manage forests for wood production. Figure 14-4 is a

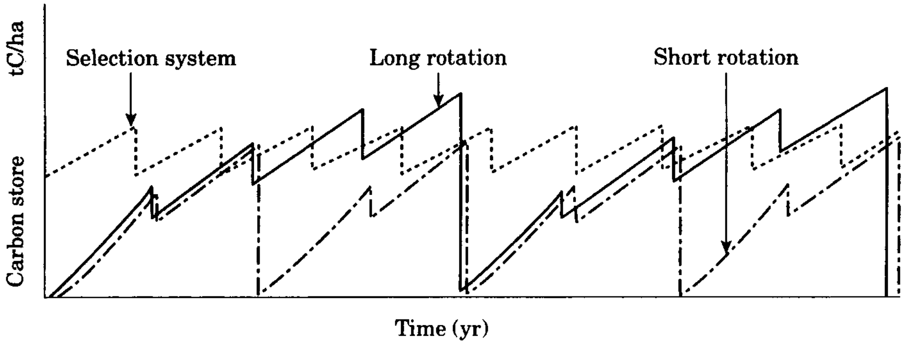


Figure 14-4 The amount of carbon stored in the vegetation of plantations managed by different silvicultural methods. This model was developed with reference to Oliver and Larson (1990) and Fujimori (1993b).

diagram of the hypothetical relationship between representative silvicultural methods and their corresponding rotation periods, and the dynamics of carbon stored in the vegetation (biomass) per unit area. The solid line represents the change in carbon store in a single storied stand managed under a long rotation that lasts until the end of the mature stage. The carbon store of the stand in this scenario ranges from zero at the start to a peak at the end of the rotation. The dotted line represents a single storey stand managed under a short rotation that lasts until the end of the young stage (half the length of the long rotation). In this scenario, the total carbon store over two rotations is less than that in a single long rotation, and the average carbon store in the short rotation stand over the long term is less than that of the long rotation stand if the age class distribution is even. However, if the biomass harvested through thinnings and final cuttings is all used for a same length of time, the total carbon pool stored in the vegetation and wood products is larger in the short rotation than in the long rotation, because the average carbon flux (growth rate) in the short rotation stand is larger than that in the long rotation stand. But, if the timber yield (yield percentage) of a large sized log is larger than that of a small sized log and the products from a large sized log are used for longer periods, the total carbon pool of the long rotation stand may be larger than that of the short rotation stand. Available data to prove this hypothesis are limited, so further research is required to obtain and analyze it.

The broken line in Figure 14-4 represents a selection method in which selection occurs mainly during the mature stage. The average total carbon stored in the vegetation of a selection stand is similar to that of a stand managed under a long rotation. The size of individual trees harvested from the overstorey of a selection stand may be larger than those harvested from a single storey stand managed under a long rotation, because the diameter growth of overstorey trees in a selection stand is greater than in a single storeyed stand with a long rotation. This is a result of a larger growing space being allocated to individual trees in the overstorey of a selection stand. As the timber yield from logs increases with increasing stem diameter, the timber yield may be greatest from the selection method.

Timber used for products such as building or furniture should be kept in use for as long as possible and then reused as much as possible. Cascade utilization of wood is required, with the final use being for energy production.

14.3.3 Substitution by wood to mitigate carbon concentration

This option reduces the utilization of fossil fuels by substitution with biofuels from wood. Fossil fuels are not part of the present ecosystems, so their continued use will result in continuing increases in atmospheric CO_2 concentrations. However, wood can be cycled within extant ecosystems, so substitution of fossil fuels with wood fuel can reduce the rate of increase of atmospheric CO_2 by the amount of substituted wood energy, on the condition that the biofuel is produced under sustainable forest management.

Figure 14-5 is a model that demonstrates the dynamics of CO_2 sequestration and reduction of CO_2 emissions by fossil fuels if reforestation with *Picea abies* (Norway spruce) on a 75 year rotation is undertaken. The carbon pooled in the biomass and litter of the forest ecosystem increases

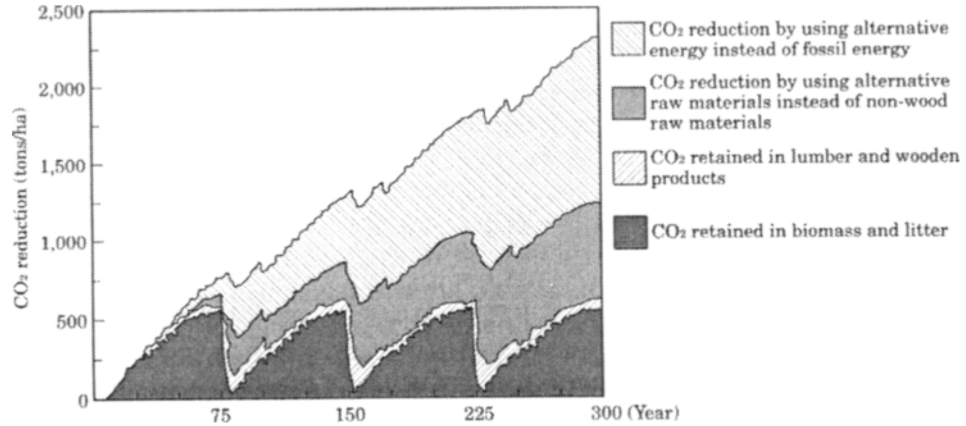


Figure 14-5 Model of CO_2 sequestration and reduction of CO_2 emission by reforestation of *Picea abies* (Norway spruce). (Nabuurs, 1996)

and decreases regularly as growth and harvesting occurs. As the stand age increases, the carbon pool in the wood products gradually increases as a result of harvesting by thinning, and is largest just after final cutting. In this way, the carbon pool in wood products fluctuates.

On the other hand, the reduced amount of atmospheric CO_2 resulting from substitution of fossil fuels with wood energy progressively accumulates. This demonstrates that substitution is significant when it is evaluated over the long term. The material for wood energy can be produced under short rotations with relatively fast growing species as described in Section 12.3.2. The coppice method is often used for fuelwood production (Section 8.2). Any solid wood products can be recycled and finally used for energy. Figure 14-5 also shows that the amount of CO_2 reduction achieved by substituting woody materials for non-woody material also continues to accumulate. This is due to the lower amount of energy necessary for processing timber to wood products compared to non-woody materials.

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Chapter 15

Maintenance of the Health and Vitality of Forest Ecosystems

Maintaining the health and vitality of forest ecosystems is fundamental to enhancing forest functions and implementing sustainable forest management. Natural disturbances, such as fire, strong wind, flood, pests or diseases are essential for the regeneration of natural forests (Section 2.4.3.2). However, unusual or extreme disturbances are regarded as disasters and disrupt forest management. Anything that disadvantages the provision of the benefits acquired from forest ecosystems is regarded as damage. Some damage is essential to the functioning of the forest ecosystem, but forest managers must reach a balance between the damage tolerated and that requiring intervention.

Some phenomena, such as the decline and dieback of trees and forests caused by air pollution, climate change, or ultraviolet B radiation, are clearly forms of damage that should be avoided by any means. Such damage generally cannot be controlled or repaired at the stand level by forest management or particular silvicultural techniques, but it is important to understand how forest ecosystems and stands change in response to changing environmental conditions, so that social, administrative, and political responses can be developed.

Forest management which pursues only one objective, such as wood production, tends to result in stands with a simple composition (e.g., monocultures) or structure that are vulnerable to damage from natural events such as strong winds, fires, insect pests, or disease. Harvesting systems or rotations that are applied without consideration of soil conservation can cause floods and degrade site productivity. Future forest management must avoid these mistakes, and they should be considered in the development of new silvicultural techniques.

Damage to forests is often the result of a combination of effects such as climatic factors (e.g., drought, wind, etc.) and biotic factors (e.g., insect pest, disease, etc.). As the factors causing forest damage are usually complicated, countermeasures are not always simple. However, to simplify the discussion in this Chapter, damage caused by multiple factors are discussed first, and then damage by individual factors is discussed. Decline or dieback of trees and forests is often the result of multiple factors, and recently it has been suggested that anthropogenic (human induced) factors such as climate change and air pollution have contributed to the decline or dieback of forests in many parts of the world.

15.1 Decline of forests caused by multiple factors

The terms "decline" and "dieback" are usually regarded as having a similar meaning, although dieback means a further progression of decline (Mueller-Dombois, 1992a). Ciesla and Donaubauer (1994) used decline and dieback without distinguishing between them. An agreed definition of decline has not been reached, but it is perhaps best described as: an episodic event characterized by premature, progressive loss of tree and stand vigor or health over a given period, without obvious evidence of a single clearly identifiable causal factor such as physical disturbance or attack by an aggressive disease or insect (Ciesla and Donaubauer, 1994).

Decline is caused by the complex interaction of many factors, which may be difficult to identify. According to Ciesla and Donaubauer (1994), there are three recognized types of factors which are important in decline. These are predisposing, inciting, and contributing factors (Manion, 1991; Sinclair, 1965).

Predisposing factors are those which change slowly and over the long term, such as soil, site, or climate. Changes in these factors can alter the tree's ability to withstand or respond to injury-inducing agents. Inciting factors are of short duration and may be physiological or biological in nature. They generally cause small branches to die. Examples include defoliating insects, a late spring frost, or drought. Contributing factors subsequently further weaken and ultimately kill the tree. Examples include bark beetles, canker fungi, or root decay fungi. These factors are persistent, visible and are often wrongly blamed for the death of trees. This is especially true of bark beetles, some species of which can reach epidemic levels in response to stress and kill large numbers of trees, many of which may not have been directly affected by the predisposing or inciting factors. It is anticipated that anthropogenic factors such as climate change and air pollution will increasingly act as predisposing or contributing factors, and that there will be an increase in forest decline.

Predisposing, inciting and contributing factors are integral components of forest dynamics (Mueller-Dombois, 1986, 1992b). Some diseases seem to only develop in the presence of all three types of factors. For example, dieback of *Acacia nilotica* in Sudan is regarded as combined response to senescence (predisposing factor), drought (inciting factor), and insect attack (contributing factor). *Acacia nilotica* is the most valuable timber producing species in the nothern Sudan. The main symptom of decline is an overall thinning of the crown. Other symptoms include abnormally small foliage, branch dieback and broken branches. There may be some recovery during the rainy season but symptoms reappear during the subsequent dry season. The decline is progressive and eventually leads to tree death (Ciesla and Donaubauer, 1994).

15.2 Classification of the causes of decline and damage

The causes of decline (dieback) and damage can be classified as non-anthropogenic or anthropogenic in origin. Non-anthropogenic causes include abiotic factors such as wind and snow and biotic factors such as diseases and pests. Anthropogenic causes include abiotic factors such as climate change and air pollution and biotic factors such as damage by introduced organisms. In the following sections, each agent is discussed as one factor of decline or as a single factor which can damage trees or forests. However, it is important to remember that decline is usually due to a number of different factors acting together.

15.3 Individual factors causing forest damage and protection measures

15.3.1 Non-anthropogenic factors

15.3.1.1 Abiotic factors

An abiotic factor is a non-living or non-infectious factor capable of causing disease. Abiotic factors can be non-anthropogenic or anthropogenic in origin. Non-anthropogenic abiotic damage agents include climatic factors such as drought, strong winds, or salt spray from oceans, or mechanical injury from snow, other falling trees or landslides. Anthropogenic abiotic damage agents include air pollution from emissions of toxic chemicals or the burning of fossil fuels, and poor forest management practices (Ciesla and Donaubauer, 1994).

15.3.1.1-1 Fire

As described in Section 2.4.3.2, the largest natural disturbance of forest ecosystems in the world is fire. Natural fire is liable to occur and spread widely in regions where the dry season and warm season are concurrent. The largest ignition source of natural fires is lightning. Drought and winds contribute to the spread of fire. Different stand structures are more or less susceptible to the ignition and spread of fire, depending on the amount of accumulated combustible materials such as dead trees, dead undergrowth, and litter. The decomposition rate in boreal forests is so slow that the potential for fire is large.

Salvage and sanitation cuttings (Section 5.5.2) may be an effective way of reducing the potential damage of fire. Stands in which pest or disease outbreaks have occurred may be more susceptible to fire because of the presence of dead, combustible matter. In these circumstances, sanitation cuttings may be an effective way to prevent or mitigate both the damage from the pests or disease and the risk of fire. However, retention of snags and fallen logs in forest ecosystems is important for the conservation of biodiversity. The balance between risk management and biodiversity conservation needs to be considered at the landscape level. Mixed, uneven-sized old-growth stands can have a high resistance to fire and even if a violent forest fire occurs in old-growth stands in boreal forests, a considerable part of standing stock can remain unscathed. This may be sufficient to maintain forest cover (Lähde et al., 1999).

15.3.1.1-2 Wind

Strong wind is another common agent that causes destruction of forests. Damage by strong winds is especially common in temperate and sub-tropical zones, where tropical depressions (typhoons, hurricanes, cyclones), temperate depressions, frontal passages, or tornadoes are common.

Dense, even-aged coniferous plantations are susceptible to wind, particularly in the young stage (from 20-30 to 50-60 years old) in Japan (Fujimori, 1995, Figure 15-1). This is thought to be due to the high stand density and the presence of tall trees with little taper and small diameters. This makes the center of gravity of the trees higher, and because the root systems are poorly developed, trees tend to be broken or uprooted. A high percentage of coniferous species have inherently shallow root systems.

In February 1990, Belgium and the regions of Alsace-Lorraine in France and Baden in Germany were subjected to a succession of violent storms. Large numbers of shallow-rooted trees like beech (*Fagus sylvatica*) and *Picea abies* (Norway spruce) were killed by uprooting or snapping

Figure 15-1 *Cryptomeria japonica* (Sugi) plantation disturbed by a severe typhoon in northern Kyushu, Japan.

(Schnitzler and Borlea, 1998). In Germany, a disproportionate amount of the destruction caused by these storms occurred in even-aged spruce plantations (Benecke, 1996). A similar catastrophic event occurred in the region of Banat, Romania, in 1965. In this storm, damage and destruction was widespread in managed forests, but there was only partial destruction (gap disturbance) in the old-growth forests (Schnitzler and Borlea, 1998). On the basis of such evidence, Benecke (1996) and Schnitzler and Borlea (1998) concluded that stands of shallow-rooted species are susceptible to wind if they have a regular canopy structure, but resistant to wind if they have an irregular structure. The resistance of irregular stands is due to the greater taper, and therefore greater resistance, of the overstorey trees which are subjected to most of the force of the wind. The overstorey trees also protect the less tapered trees in the lower stories from the energy of the winds.

In plantations or managed forests, selection methods (Section 8.1.2.3) can be used to convert the stands to an irregular (uneven-sized) structure. Appropriate thinning regimes (Sections 8.1.1.1 and 8.1.2.1) will increase the stand's resistance to wind as well as hasten the growth of selected, higher quality trees. Such regimes are characterised by maintaining a relatively high stand density until the early young stage to obtain a clear stem to a predetermined height, followed by a series of aggressive thinnings to give appropriate growing space to the selected promising trees.

15.3.1.1-3 Drought

Drought can be defined as a prolonged and abnormal water deficiency that is relatively extensive in time and space. Droughts are usually, but not always, accompanied by unusually warm conditions (Porter et al., 1994; cited in Barnes et al., 1998). Drought reduces the growth of forest trees and is often associated with attacks by pests and diseases. An epidemic of pole blight in northern Idaho in the United States of America from 1935 to 1940 that reduced growth and caused substantial mortality in pole-sized stands of *Pinus monticola* (western white pine) has been linked to adverse temperature and soil water conditions (Leaphart and Stage, 1971). Fir-death (Tannensterben) of *Abies alba* (European silver fir) peaked in the 1970s when summer drought often occurred (Kandler, 1990). Drought is also often associated with fire. The presence of diseases or pests is often the result of fire. As described in Section 15.3.1.1-1, sanitation and salvage cuttings may mitigate the effects of pests and diseases.

15.3.1.1-4 Cold injury

As described in Section in 2.2.1, cold injuries can be divided into two categories; frost damage (freezing damage) and winter desiccation damage (frost drought damage). Frost damage tends to occur in low hollows where the temperature falls below that of surrounding land. Plans for newly established plantations should exclude such sites or identify alternative, cold resistant species to be planted on them. Winter desiccation damage often occurs near the margins of the natural distribution of a species, so species selection should be made with particular attention to this. The use of non-clearcutting methods (Section 8.1.2) is usually effective for avoiding winter desiccation damage and frost damage.

15.3.1.1-5 Snow

There are two forms of snow damage; snow pressure damage and crown snow damage. Crown snow damage includes stem bending, stem breakage, uprooting, and branch breakage (Fig. 15-2) and tends to occur when wet snow falls. Snow pressure damage arises from the creep and glide pressures of settled snow and bends seedlings or saplings, usually tearing the roots on the upper side of the tree. In many cases, snow pressure damage starts with crown snow damage, but crown snow damage can occur on its own. Conifers are more susceptible to damage than hardwoods (Katuta, 1987). In *Cryptomeria japonica* (sugi) plantations, dense 20 to 30 year-old stands are most susceptible to crown snow damage (Fujimori, 1987b). Stands susceptible to snow damage have a similar structure to those susceptible to wind damage. Therefore, the tending regime described for wind damage (15.3.1.1-2) that considers the relationship between crown structure and stem growth can be applied to stands which need improved resistance to crown snow damage. A domino

Figure 15-2 Crown snow damage of *Cryptomeria japonica* (sugi) plantation in Hokuriku, Japan.

effect of damage can occur following crown snow damage, and planting hardwoods in a mixture with conifers can be an effective way of avoiding widespread crown snow damage.

15.3.1.2 Biotic agents

In forest ecosystems, the consumer and decomposer elements of the ecosystem usually negatively affect the producers (trees), but if the ecosystem is healthy, the effects are usually limited. In forestry, if the effects of consumers or decomposers is beyond a level which can be tolerated commercially, it is regarded as damage. Biotic damage in forests can be caused by diseases, pests, or mammals. Disease is caused by biological agents but often develops if there have been unusual environmental conditions, caused by either natural agents or human impacts.

15.3.1.2-1 Pests and diseases

Pests cause damage to trees in various ways, such as inhibiting growth, reducing seed production, causing stem deformation, or damaging the xylem. These effects sometimes cause death. Outbreaks of pests tend to occur in stands with a simple species composition and structure, such as monoculture plantations, especially in unthinned dense plantation. An example is the sucking insect todomatsu-oaburamushi (Todo-fir aphid, *Cinara todocola*) which lives on the shoots of seedlings and saplings of *Abies sachalinensis* (todomatsu) and weakens and/or kills them. Outbreaks of Todo-fir aphid seldom occur in natural forests because of the interaction between the aphid and a wide range of organisms, including symbionts and natural enemies of the aphid. However, an outbreak occurred when a wide area of pure *Abies sachalinensis* plantations was established in Hokkaido, Japan in the late 1950s. This produced favorable conditions for the Todo-fir aphid to expand. Todo-fir aphid only occurs in the seedling and/or sapling stages, and the level of damage can vary. At low levels of damage, growth is reduced for a time, but recovers without any long term effects. However, in cases of serious damage, a high proportion of seedlings and/or saplings die (Furuta, 1984; Yamaguchi, 1989).

Disease is generally regarded as a harmful disruption of physiological processes caused by pathogens (Ford-Robertson, 1971). Disease often occurs when trees are stressed by one or more of a variety of conditions, such as pest attack, drought, cold injuries, or physical injuries by wind and snow. It may also be exacerbated by air pollution and climatic change. Diseases cause similar damage to that caused by pests; i.e., reduction of growth or death of the trees due to death of the tissues, degradation of xylem, deformation of stem, etc. Pathogenic fungi or viruses are a common cause of disease, although there are many diseases in the world that have not had a causal agent identified.

In areas with extensive plantations, natural forests should be retained or established to help prevent the spread of pests and diseases. Retention of natural forests in an appropriate distribution throughout the landscape provides habitats for natural enemies of pests as well as corridors for mammals. To reduce disease, it is important that predisposing and inciting factors be minimized. Nature-oriented mixed uneven-sized stands may have the structure to mitigate the predisposing and inciting factors (Lähde et al., 1999), and thus confer higher resistance to disease. In plantations, appropriate species selection and implementation of adequate tending operations such as thinnings is required to minimize the incidence of pests and diseases. Maintaining stands of a variety of age classes or creating and maintaining mixed uneven-sized stands may also be effective in limiting or preventing outbreaks of pests and diseases. Breeding of resistant varieties may be justified for intensively managed species. Applications of pesticides may be required in the nursery stage and very intensively managed short rotation stands used for the production of energy wood (Gruppe et al., 1999).

15.3.1.2-2 Mammal damage

Damage caused by mammals is usually in the form of browsing damage, and mostly affects regenerating seedlings and saplings. Seedlings or saplings may be killed or injured, but if the injured plants survive, they often develop with persistent deformities. Adult trees may be seriously damaged and even killed by deer or bears peeling or scraping the bark off stems. Populations of herbivorous mammals such as voles, hares, and deer generally increase as the area of pasture or regeneration sites following clearcutting increases, as these sites provide suitable food sources. In Japan, for example, during the period from the end of World War II until the 1970s when the area of monoculture plantations was rapidly expanding, damage to planted seedlings and saplings by voles and hares increased greatly, because such regenerating stands produced favourable conditions for these animals.

The population of sika deer (*Cervus nippon,* Nihonjika) also increased when the area of regeneration increased, and although most stands have now closed, the population is still increasing. Recently, damage to the stems of mature trees caused by sika deer has become a serious problem in a number of areas (Miura and Horino, 1996). Sika deer peels off the stem bark to eat the phloem, cambium, and sap, causing many trees to die (Fig. 15-3). In some areas, most of the standing trees are dying as a result of the removal of bark from the stem, and most seedlings and saplings have also been eliminated. This level of damage destroys the forest ecosystem. The recent increase in the population of sika deer is thought to be due to reduced hunting pressure and improved winter food supply in recent warm winters (Miura and Horino, 1996). It is thought that one factor contributing to the increased sika deer population is the extinction over 100 years ago of the Japanese wolf (*Canis hodophilax*) which was its natural enemy.

Population control of sika deer is now essential in areas where ecosystems are being destroyed and the damage to forestry is serious. This

Figure 15-3 A larch tree injured by sika deer (*Cervus nippon*) in Kanto, Japan.

must be done in a way which conserves the genetic diversity of the deer population (Miura and Horino, 1996). Damage can be avoided by fencing regenerating areas, and is effective in areas where damage is serious. This method is used in many parts of the world, but is expensive. An adequate distribution of natural forests that provide a suitable habitat for mammals can reduce mammal damage to production stands, as well as reducing the incidence of pests and diseases.

15.3.2 Anthropogenic factors

15.3.2.1 Abiotic factors

15.3.2.1-1 Climate change

The global mean surface air temperature has increased by between about 0.3 and 0.6°C since the late 19th century. Global sea levels have risen by between 10 and 25 cm over the past 100 years and this may be related to the increase in temperature. The atmospheric concentrations of greenhouse gases, especially carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) have increased significantly since the industrial revolution; by about 30%, 145%, 15% respectively (1992 values) (Scimel et al., 1996). These trends can be attributed to human activities, mostly fossil fuel use, land-use change (deforestation), and agriculture. Many greenhouse gases remain in the atmosphere for a long time (CO_2 and N_2O can persist for several decades or centuries), and hence continue to have an effect over a long time-scale.

According to IPCC Working Group I (1996), a range of carbon cycle models indicate that stabilization of atmospheric CO_2 concentrations at 450, 650 or 1000 ppmv could be achieved only if global anthropogenic CO_2 emissions drop to 1990 levels by, respectively, 40, 140 or 240 years from now, and drop substantially below 1990 levels subsequently. If CO_2 emissions are maintained at 1990 levels, modelling predicts that the global mean surface air temperature would increase by about 2°C above 1990 levels by 2100 and the sea level would increase by about 50 cm over the same interval (Houghton et al., 1996).

Human-induced global warming could cause considerable impairment of ecosystem functioning including species extinction, and disruption of various aspects of human society (Wood, 1988; Rosenzweig and Perry, 1994; Minami, 1995; Graves and Reavey, 1996; Houghton et al., 1996; Uchijima, 1996). As forest ecosystems are a significant component of the global carbon cycle, impairment of forest ecosystems could in turn affect global warming.

Greenhouse gases increase temperatures which causes changes in the water availability of a given site. In many cases, the change in water availability will have a greater effect on plants than that of temperature (King and Neilson, 1992; Neilson, 1995; Graves and Reavy, 1996). Changes in the concentration of CO_2, which is the main element of global warming, have great effects on the growth of plants. Given that changes in global CO_2, temperature, and water availability are interrelated, it is complex to predict the overall effect of global climate change on the growth of plants. In addition, the effects of CO_2 concentration, temperature, and water availability on plant growth differ depending on soil conditions. This is especially true of water availability. This makes predicting future changes to forest ecosystems extremely difficult.

Increased CO_2 may have a direct "fertilizing" effect on the growth of plants. It can also enhance growth by increasing the efficiency of use of nitrogen, water, and light. Changes in these efficiencies can also increase growth, particularly in areas where carbon, nitrogen, water, and light have been limiting. Individual species responses also differ (Graves and Reavy, 1996). Different species responses to CO_2 include changes in biomass increment, timing of flowering, the proportion of resources allocated to seed production, and seed quality (Bazzaz, 1990; Graves and Reavy, 1996).

Gross production increases with increasing CO_2 and temperature, but respiration and decomposition also increase with increasing temperature. Therefore, it is difficult to predict changes in the level of CO_2 sequestration in forest ecosystems. Decomposition in soils in cool regions could increase. The incidence of catastrophes caused by diseases, pests, or fire could increase as a result of the rapid increase in temperature and increased frequency of drought in many regions of the world (Graves and Reavy, 1996). It is, therefore, possible that the CO_2 sequestration by forest ecosystems will decrease as the climate changes.

Different species have different ranges of temperature within which they can grow and temperatures at which they cannot survive. As global temperature increases, it is likely that many plant species will move to higher latitudes and/or altitudes. However, each species will respond and migrate at different speeds, so the composition and structure of communities will change. Some species may be exterminated if they lose their niche because of a rapid change in the relationship between species. Barriers formed by extensive areas of plantations or agriculture may interrupt the movement of many species. The rates of dispersion of plant species differ depending on the dispersion strategy. Dissemination vectors include wind, gravity, animals and water (Section 2.4.3.1). The distance that seed is dispersed in each of these strategies ranges from several meters to several kilometers. The age at which a tree species is able to produce seeds are differs from within a decade to 50 or 60 years (Kamitani, 1986b, Hashizume, 1991). These factors mean that the rate of spread or shift of many tree species is low. Plants in and around ecotones would be particularly sensitive to changes in the environment and interspecific competition in these areas could be severe. Ecosystems would be disrupted and it is anticipated that there will be an increase in the incidence of pests and diseases (Melillo, et al., 1996).

Even if a species is not directly affected by climate change, it could be indirectly affected because of its dependence on other species. For example, if an insect species was unable to adapt to the changed temperature in an area, a tree species reliant on the insect for pollination may not survive, and vice versa. If the time lag between flowering and seed production in a tree species changes, it may cause a negative effect, not only for the propagation of the species itself, but also for any other species which rely on the honey or seeds, because the timing of the life cycles of the different species may no longer coincide (Washitani and Yahara, 1996).

The emission of greenhouse gases by human activities should be controlled and reduced by any means possible. Any decrease in the area of forest should be avoided. This requires action by all citizens. Degradation of forests by mismanagement should be avoided and any degraded forests should be restored and enriched. Biodiversity in forest ecosystems should be maintained at as high a level as possible, because species diversity within forests and genetic diversity within populations will enhance the buffering capacity of the forest as a result of the better adaptation of some species and genotypes to the new conditions (Perry, 1994). As widespread plantations prevent the migration of other tree species, natural forests should be maintained and restored, and corridors of reserves developed so that natural forests are not isolated.

Changes in stand structure due to climate change must be monitored. If a species is expected to be lost because its refuge is subject to climate change, it should be transplanted to a preferable site. Interspecific competition may also need to be controlled to allow threatened species to migrate. Appropriate thinning can modify competition regime of stands by mitigating limited water availability in the areas where drought is anticipated to occur as a result of global warming (Cescatti and Piutti, 1998). Strategies of forest management for improved carbon sequestration and pooling for mitigation of atmospheric CO_2 concentration were described in Section 14.3.

15.3.2.1-2 Air pollution

Air pollution is the pollution of the air by toxic substances which are anthropogenic in origin, such as sulfates, nitrate, and ozone. Air pollution may be one of the most widespread potential causes of forest decline in many parts of the world (Skelly, 1989). Serious forest decline has been observed in the past around refineries. In Ashio and Naoshima in Japan, most trees around the refineries died and the soils eroded until equipment controlling emissions of SO_2 and NO_2 was installed nearly 50 years ago. The cause of the forest decline is clear in these cases. Nowadays, however, the cause of air pollution over a wide area cannot usually be pinpointed to a specific source. The decline of hardwood and softwood forests in many parts of Europe (Schutt and Cowling, 1985; Plochmann, 1984; Kandler, 1990), the decline of maple forests in the eastern Canada and the eastern United States of America (Manion, 1991), and that of *Picea rubens* (American spruce) in the eastern United States of America (Friedland et al., 1984) are regarded as examples of forest decline due to expansion of air pollution beyond the boundary of the polluting countries (Ciesla and Donaubauer, 1994).

Air pollution, including acid rain, is regarded as one of the factors contributing to forest decline, but the causal relationship between pollution and decline has not been identified. However, air pollution can be a predisposing factor for forest decline. It is important to obtain long term data on the condition of forests and their environment, and to supply a scientific analysis of the data to society. These can be used to debate ways in which predicted developments can be prevented or changed.

15.3.2.1-3 Fire

Although lightning is the major natural cause of forest fire, humans have been the most significant cause of fire worldwide (Spur and Barnes, 1980). Human-induced forest fires are caused by the accidental spread of fires established for cultivation, careless use of bonfire and tobacco, or arson. In regions where the warm and dry seasons occur concurrently, such as the coniferous forests in the western part of the United States of America and the eucalypt forests of southern Australia, small or accidentally lit fires can rapidly develop into large scale fires. Formerly, it was acknowledged that great fires seldom occurred in tropical rain forests (Mutch, 1970). However, recently the incidence of historically large forest fires in the tropics has increased. For example, two of world's largest fires occurred in 1982-83 and 1997-98 in the eastern part of Borneo, Indonesia. Exceptional drought caused by strong El Niño Southern Oscillation (ENSO) events occurred in these years and the fires originated from fires used to cultivate oil palm plantations. On each occasion, the fires affected about 5 million hectares (Toma, 1998, 1999; Mori, 2000).

Most of the forest fires which occur in Indonesia are human induced, and result from the spread of poorly managed agricultural or plantation fires (Figures 15-4, 15-5). Traditionally, prescribed burning was practiced by local inhabitants and was ecologically appropriate. Recently, however, the burning has been conducted over wider areas and with less control, and this has become the main cause of the large scale forest fires (Toma, 1998; Mori, 2000). This is also true of many other tropical rainforest areas.

15.3.2.2 Biotic factors (Damage by introduced organisms)

Introduced organisms often cause serious diseases or become pests which disrupt the forest ecosystem and forestry. Most introductions of these organisms have resulted from the global trade of seedlings and timber over the past 200 years, and can therefore be regarded as anthropogenic. Introduced pathogens are often more pathogenic to susceptible trees than

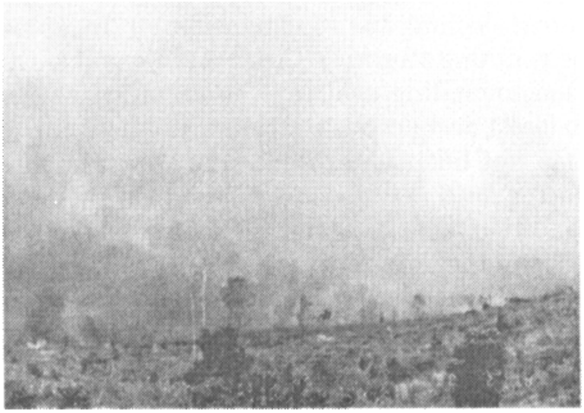

Figure 15-4 Fire spread from prescribed burning in the eastern part of Borneo Island, Indonesia. (Photograph by T. Toma)

Figure 15-5 Widespread burning for establishment of industrial plantations in the eastern part of Borneo Island, Indonesia. (Photograph by T. Toma)

they were to trees in their original environment, even if the trees were from the same genus. Trees from the pathogen's original environment have usually developed some level of resistance to the pathogen.

Chestnut blight in the United States of America and Europe is a typical example of a disease caused by an introduced pathogen (*Cryphonectria parasitica*). Chestnut blight expanded rapidly in the eastern United States of America around the beginning of 20th century, killing *Castanea dentata* (American chestnut) (Figure 15-6). The pathogen was first found in 1904, and it was later postulated that it was introduced from Japan. Chestnut blight was then found in Europe and was probably introduced with imported timber from the United States of America (Kaneko, 2000).

White pine blister rust is serious disease which causes death of white pines in Europe and North America. The pathogen (*Cronartium ribicola*) is thought to have been introduced to Europe from eastern Siberia with the transportation of seedlings of soft pine species (5-needle pines) and introduced to North America with seedlings of white pine species. In Europe, soft pine species have suffered seriously from the pathogen, and in North America, *Pinus strobus* (eastern white pine) and *Pinus monticola* (western white pine) have been seriously damaged (Kaneko, 2000).

Pine wilt disease has been serious in Japan, southeastern China, and Taiwan, and is anticipated to spread into Korea (Figure 15-7). The pine wood nematode was identified as the pathogen causing pine wilt disease in 1971 (Kiyohara and Tokushige, 1971). In Japan, *Pinus densiflora*

Figure 15-6 *Castanea dentata* (American chestnut) stand affected by *Cryphonectria parasitica* in eastern United States of America in early 1900s. (Photograph by J. F. Collins)

(akamatsu) and other two pine species are highly susceptible to the pine wood nematode (*Bursaphelenchus xylophilus*) which was probably introduced from North America in the early 20th century (Mamiya, 1980; Kobayashi, 1981). This disease has killed large numbers of pine trees every year despite efforts to prevent the disease. The disease was most rampant in the later part of the 1970s, when more than two million cubic meters of wood was lost annually in Japan.

Figure 15-7 *Pinus densiflora* (akamatsu) stand affected by pine wood nematode (*Bursaphelenchus xylophilus*) in Kanto, Japan (Photograph by S. Kaneko).

The introduction of the Asian gypsy moth (*Limantria dispar*) from Asia to North America has greatly affected many hardwood species and larch (Kaneko, 2000). These examples demonstrate that introduced organisms can cause abnormal levels of damage and it is hard to control the damage once the organisms spread. Therefore, care must always be taken to prevent invasion of foreign organisms.

15.4 Managing forest decline and damage

The discussion above focused on the individual factors that contribute to forest decline or cause damage to individual trees. However, in many cases, decline and damage are the result of various factors acting as predisposing, inciting, or contributing factors, and interacting in a highly complex way. Therefore, the causes of decline or damage to forests must be always analyzed carefully to identify all the responsible agents. Climate change and air pollution are new and difficult to quantify factors important in the decline of forests. The environmental degradation caused by climate change and air pollution cannot be controlled by silviculture. Changes to the environment and the effects of these changes on forests must be monitored, and this information provided to society so that citizens, administrators, and politicians can develop plans to both decrease the emissions of air pollutant and greenhouse gases and to manage forests in a changing environment.

The decline or damage to forests by factors other than climate change and air pollution can be prevented or lessened by good forest management and specific silvicultural techniques. For example, wind and crown snow damage can be lessened or prevented by managing stand density. Surface soil erosion in young plantations can be avoided by thinning or pruning in such a way that the undergrowth is maintained. Healthy stands can be established by proper site selection and appropriate use of species, varieties, or cultivars. Abnormal outbreaks of pests and diseases can be prevented or lessened by forest management if there is sufficient ecological knowledge. Monitoring systems to prevent the introduction of foreign organisms anticipated to cause damage should be established, and if they are introduced, the pests should be eliminated or controlled as early as possible. If this fails, the situation may become serious.

Creation of anthropogenic factors disadvantageous to the health of forests must be avoided or minimized. A single disadvantageous factor can become a predisposing or inciting factor for other agents. Forest management should be based on a good understanding of the ecosystem. Monitoring at a local, national, and international level is essential to ensure the management is effective.

Ecological and silvicultural measures that can lessen the impact of damage agents and the decline of forests generally take the form of creating mixed stands or converting simple stands to mixed, uneven-sized stands, and maintaining them when they reach the desired structure. Mixed, uneven-sized stands are considered to have a high resistance to various damaging agents such as wind, snow, diseases and pests as well as against anthropogenic factors including air pollution and climate change (Lähde et al., 1999). Plantations comprising a single species in a single storey should be distributed such that they intermingle with natural forests or naturally oriented forests at a landscape level. In general, it is desirable to conduct optimal thinnings and extending rotation periods.

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Chapter 16

Summary and Conclusion

Sustainable forest management

Sustainable forest management is essential to the establishment and maintanence of a society which uses resources, products and energy sustainably. Forests fulfil a range of functions for society, including provision of biodiversity, soil and water resources, recreation, CO_2 sequestration and carbon pooling, as well as supplying forest products. Sustainable forest management can be defined as the management of forest ecosystems in a healthy and vital condition such that they can fulfil the needs of the present generation for wood products, biodiversity, soil and water resources, recreation, and sequestration and pooling of carbon, without compromising the ability to fulfil the needs of future generations. Criteria and indicators for assessing the sustainability of forest management were defined in the Helsinki and Montreal Processes under the United Nations (Section 9.1).

Framework of the contents of this book

To recover, maintain or enhance each forest function, or to manage forests such that various functions are harmonized, requires an understanding of forest ecology. Part I reviewed forest ecology as the foundation of sustainable forest management. Formerly, forest management was focused primarily on the production of timber and silvicultural techniques and methods were developed to optimise wood production. Traditional silvicultural techniques and methods were reviewed in Parts II and III respectively, and the applicability to sustainable forest management of these methods and improvements to them were discussed in Part III.

Although many of the traditional silvicultural methods used for wood production can be applied to maintain, enhance, or recover other forest functions such as biodiversity and water yield, this requires the development of new perspectives and strategies. Part IV discusses the ecological and silvicultural strategies primarily aimed at enhancing individual forest functions, and managing the relationship between individual and other forest functions. Finally, this chapter provides a summary and conclusion of the whole book.

Target stand structures and stand development stages for different management objectives

Target stand structures need to be determined to implement sustainable forest management. These should be based on the objectives of management and the natural and social conditions surrounding the forest. Silvicultural methods appropriate to these conditions should be applied to achieve the target structure. When the target structure is achieved, it should be maintained to continue to achieve the management objectives, and this is a further technological challenge.

An understanding of disturbance regimes and the associated regeneration mechanisms and stand development stages is essential to establishing a basic theory of ecological and silvicultural strategies for sustainable forest management. After a large disturbance, if there are no further influential disturbances, stand development stages follows a general pattern (Sections 2.4.3 and 2.4.4) that can be divided into four stages, i.e., the herb/brush (stand initiation) stage, the young (stem exclusion) stage, the mature (understorey reinitiation) stage, and the old-growth stage. Each stage is distinguished by its stand structure. As stand structure is closely related to forest function, stand development stages can be used as target stand structures to fulfil the forest functions primarily being sought.

Patterns of stand development vary according to the frequency and intensity of disturbances. However, understanding the basic pattern of the stand development stages assists development of silvicultural theories, and experiencing variations in the frequency and intensity of disturbances and their impact on stand development contributes to modifying various silvicultural methods for the sustainable forest management.

The herb/brush stage is relatively short and species composition changes quickly due to severe interspecific competition. Species diversity in this stage is high, especially in natural forests, because snags and fallen logs that were elements of the former old-growth stage are retained, and these function as habitats and niches for various organisms from fungi to mammals. Advanced growth of shade tolerant species can survive in the microclimate created by snags and fallen logs, enabling regeneration of mixed stands of light-demanding and shade-tolerant species (Section 10.5). Water holding capacity in this stage is low (Sections 2.4.4, 11.3). Productivity in the herb/brush stage increases rapidly (Section 3.3). For plantations and managed stands, vegetation management such as weeding and climber cutting is required during this stage in many areas in the world. Vegetation management is a key technology for the successful regeneration of desired species, especially in the summer wet areas (Sections 4.3, 4.4, 5.2, 5.3).

In the young stage, a limited numbers of high tree species dominate and the canopy of the stand closes, reducing illumination on the forest floor such that the undergrowth cannot survive. As a result, the species diversity is lowest of all the stages at this time (Sections 2.4.4, 7.1.4), but productivity is at its peak (Section 3.3). As the undergrowth is very poor, soil development can be limited and in some forests, soil erosion may occur (Sections 6.1.4, 10.1, 10.3). In the mature stage when undergrowth develops again, structural and species diversity increase, the surface soil structure is protected by the undergrowth and the soil structure matures, enhancing the water holding capacity (Section 11.1). Productivity in the mature stage declines towards the level reached during the old-growth stage (Section 3.3).

In the old-growth stage, large trees which were dominant in the overstorey begin to decline and snags and fallen logs gradually appear. The stratification of the stand becomes complex with various sized and aged trees. Structural diversity is highest in this stage, and species diversity is also high. The diversity of types of organisms is highest in this stage because the declining trees, snags, and fallen logs provide habitats and niches for various organisms such as mammals, birds, insects, ferns, mosses and fungi. (Sections 2.4.4, 7.1.4, 10.5). Fallen logs protect the soil from surface erosion by dissipating the energy of overland flow (Section 2.4.4). The water yield of the old growth stage is likely to be larger than that of the young stage owing to the lower evapotranspiration of the old-growth stage (Section 11.1.1). Productivity in the old growth-stage approaches zero and remains stable at that level if there is no significant disturbance (Sections 2.4.4, 3.3).

The relationship between stand development stage and the primary forest functions discussed above is shown in Figure 16-1. The functions drawn in Figure 16-1 are net production (t/ha/yr) or carbon flux of vegetation (tC/ha/yr), surface soil organic matter (t/ha), water yield (mm/yr), and biodiversity, and is an amalgamation of Figures 10-2, 11-3, 14-2, and 14-3. The dynamics of the total carbon pool in forest ecosystems is similar to that of surface soil organic matter (Figure 14-3). The peak and

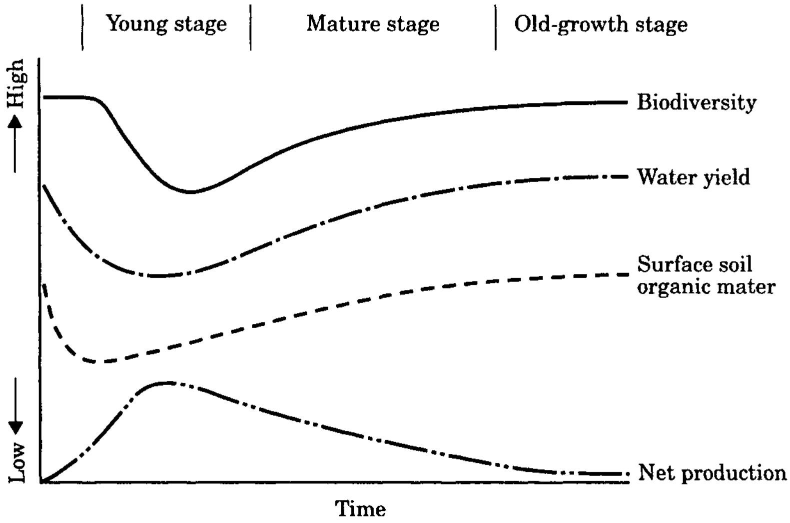

Figure 16-1 Relationship between stand development stage and stand function. Net production (t/ha/yr) or carbon flux of vegetation (tC/ha/yr) is based on Figure 14-2. Surface soil organic mater (t/ha or Ct/ha) is that of broad-leaved deciduous forest in eastern North America (Covington, 1981; Figure 14-3). Water yield (mm/yr) is that of *Eucalyptus regnans* (mountain ash) forests (Watson et al., 1999; Figure 11-3). Biodiversity is the species diversity of mammals in the Pacific Northwest of the United States of America (Franklin and Spies, 1991; Oliver, 1992).

trough of the functions both occur in the young stage. This type of information is critical to the successful implementation of sustainable forest management, but many of the trends shown in Figure 16-1 are only hypothetical and it is likely that the specific relationships would vary according to site and disturbance regimes. So, research to accumulate the information on the dynamics of these functions is urgently required for the implementation of sustainable forest management.

Information about the relationship between stand development stages and their functions can be used to define target stand structures that will best fulfil the primary objectives, or functions, of a forest. The main objectives, or functions, of forest management are: conservation of biodiversity; conservation of soil and water resources; wood production; and maintenance and enhancement of cultural and recreational functions. Enhancement of the sequestration and pooling of carbon in forest ecosystems can be achieved simultaneously with these functions (Sections 9.2, 9.3).

For the conservation of biodiversity, the target stand structure should be the old-growth stage. Although various forest types and stand development stages contribute to the conservation of biodiversity, the existence of the stands of old-growth stage is essential for it. For the conservation of soil and water resources, the target stand structure should also be the old-growth stage, although the mature stage can also effectively fulfil this function. The target stand structure for wood production will vary according to the production objectives. For the production of sawlogs, the target structure should be the mature stage (Section 7.1.4), while the target structure for the production of biomass uses such as fuel (energy) wood and pulp wood is the young stage (Section 8.2).

Distribution of forest types in a landscape

An important aspect of sustainable forest management beyond manipulating the stand development stages as described above, is the distribution of forest types and stands throughout the landscape. Adequate distribution of forest types on a landscape scale is especially important for the conservation of biodiversity (Sections. 10.4.2, 12.5). Zones of forest areas with primary functions can be defined across the landscape, and the target stand structures which best suit the function can be developed and maintained.

In areas where wood production is primary objective, the wood production and other functions should be harmonized as much as possible. Complicated land ownership or other social conditions can make the zoning mentioned above difficult, further necessitating that a range of functions be fulfilled simultaneously (Sections 10.4.2, 12.5).

Silvicultural strategies for sustainable forest management

The combination of sawlog production and conservation of biodiversity or conservation of soil and water resources, can be achieved using a long rotation that extends into the mature stage. The structure of the mature stage enhances the conservation of biodiversity and the conservation of soil and water resources in comparison with the young stage. The longer the rotation period is, the larger the ecosystem diversity is, because various stand development stages can be distributed throughout the landscape. Although the mean growth rate decreases as rotation period increases, the quality and yield percentage of the crop increase, providing economic benefits (Section 7.1.4). As the rotation period increases, weeding and climber cutting costs as a proportion of the regeneration costs decreases, especially in areas with wet summers (Section 8.1.1).

Appropriate thinning regimes are especially important for long rotation management systems. Without thinning, the stand structure will be susceptible to strong wind or wet snow, and because diameter growth of individual trees is delayed, it takes a long time before suitable diameter stems can be harvested (Sections 12.3.1, 15.3.1-2, 15.3.1-5). Generally, it is worthwhile maintaining a high stand density until the beginning of the young stage to control branching and develop a straight single stem with small knots close to the pith. Thinning is then required to maintain growth rates and develop wind and snow resistance in the future crop trees. In hardwood stands, dominant trees of a relatively inferior quality should be removed to give enough growing space to the selected crop trees, but subdominant trees and suppressed trees should be left as trainers to prevent epicormic bud production on the stems of the crop trees (Sections 6.2.4.2, 8.1.1.1).

Appropriate thinning regimes during the young stage increase the light on the forest floor and allow undergrowth to grow. This modification of the structure of the young stage can improve conservation of biodiversity and water resources (Sections 8.1.2, 10.5.2, 11.3). Although the first or second thinning may be precommercial thinnings, yields can be expected from the second or third thinnings. The precommercial thinnings contribute to the production of high quality timber and make earlier harvests in the successive commercial thinnings possible. The commercial thinnings create better conditions for the more rapid production of high quality, larger-sized timber, because the growth of individual crop trees is enhanced and the proportion of timber in the final crop trees that is knot-free and has uniform annual rings increases (Sections 8.1.1, 12.3.1).

One of the most important techniques for the production of sawlogs is crown management to control the growth and quality of the stems of crop trees. Stem wood quality depends on the processes of tree growth throughout the life of the tree. The development of the crown throughout the life of the tree determines the size and distribution of knots in the stem and the width of the annual rings. Crown control is obtained by stand density control, selection of trees to retain or remove in thinning, and pruning. Crown control management for wood production can simultaneously control light on the forest floor and thus be a form of undergrowth management (Sections 6.1.1, 6.2.1, 8.1.2, 12.3.1).

A managed series of thinnings can create preferable conditions for undergrowth development, including regeneration of crop species. Therefore, if an appropriate series of thinnings is undertaken, this approach resembles a type of shelterwood method. The method can be modified to suit the natural or social conditions of the site. For example, in areas where the undergrowth is abundant, but the crop species is absent, the last thinning can be timed to occur in the mast year of the crop species and the undergrowth thinned or removed to promote regeneration of crop species (Section 8.1.2.1).

For the production of wood, the cutting, or harvesting, pattern is an important determinant of the structure of the regenerated stand. Traditional silvicultural systems were classified on this basis, and it remains important, because the size and type of cut and the resulting regenerated stand structure are closely related to the maintenance or enhancement of other forest functions such as biodiversity, soil and water resources, and recreation. Traditionally, discussion on cutting and regeneration methods have focused on clearcutting and single-tree selection methods, but it is important to discuss and adopt a broader range of methods including shelterwood, selection and small clearcutting methods and their variants, and improve or mix their use. The use of these methods should be determined on the basis of the target structure of the future stand. If a mixed stand established from natural regeneration is desired, the size and type of cut should be determined by traits of the target species such as light tolerance. Knowledge about the ecological adaptations of key species to the microenvironment is important for this (Sections 2.2, 2.4.3, 8.1.1, 8.1.2).

Clearcutting is often regarded as an environmentally destructive method. Widespread clearcutting used only for the convenience of the operation and to minimise immediate costs but neglecting the environment and long term sustainability should be avoided. However, clearcutting is appropriate where it is necessary for the regeneration of light-demanding species such as pines, some eucalypts, and *Pseudotsuga menziesii* (Douglas fir). Clearcutting can be an ecologically appropriate silvicultural method in fire climax forests such as in areas of southeastern Australia and western North America (Section 8.1.1.1). However, the size, process, and distribution of clearcutting may need modification to give consideration to biodiversity, soil and water resources, scenic beauty, sustainable production of wood, and the ecological requirements for regeneration of the target species (Section 8.1.2.4, 12.2.3).

In response to the need to modify clearcutting techniques, various cutting methods such as aggregated retention and scattered retention have been proposed and implemented in the Pacific Northwest of the United States of America. Aggregated retention can be either perpetual or temporary. The important element in these methods is the retention and distribution of natural elements such as declining trees, snags, and fallen logs in clearcutting systems, in order to conserve biodiversity. Variations on the techniques of aggregated retention and scattered retention could be applied to situations with different natural and social conditions (Section 10.5.1).

Shelterwood methods have been regarded as a form of clearcutting because the series of final cuttings is undertaken within a short period. However, this is only the case if viewed from the perspective of harvesting wood. Environmentally, clearcutting has major impacts, including the destruction and erosion of the surface soil, increased suspended sediments in streams, more rapid decomposition of organic matter, increased nutrient run-off into streams, reduced soil fertility and decreased water holding capacity on the cutting site (Section 8.1.1.1). Nowadays, the major public concern about clearcutting is related to soil conservation. Shelterwood methods are less environmentally destructive than clearcutting, and should therefore not be regarded as a form of clearcutting (Section 7.1.2).

For sawlog production, a long rotation is recommended for both economic benefits and for harmonization of timber production with other functions. However, in the case of wood production for biomass uses such as energy and pulp, a short rotation is required. Coppice methods play an important role in the short rotation method. Biomass production on a short rotation is usually based on clearcutting, and therefore should be applied on sites with a flat or gentle slope for the conservation of soil, especially if the coppice method is not used. Short rotation forestry can be regarded as being close to agriculture. However, using fertilizer, chemicals, and herbicide should be minimised, because the identity of forestry should be environmentally friendly (Section 8.2.1).

Atmospheric CO_2 is the largest contributor to the increasing greenhouse gases and its concentration continues to increase as a result of human activity. Forest ecosystems contribute to the global carbon cycle. The maintenance, enhancement and recovery of carbon cycling in forest ecosystems is an important way of mitigating atmospheric CO_2 concentration. For forest ecosystems to contribute to reducing atmospheric CO_2, three options are available: conservation of forest ecosystems; increasing carbon pools in both forests and wood products; and/or substituting fossil fuels with biofuels.

Protecting and conserving existing carbon pools is the most effective option and least costly. Protection and conservation of forest ecosystems for the conservation of biodiversity and the conservation of soil and water resources simultaneously pools the largest amount of carbon in the ecosystems over a long period. The second option (increased carbon pools) can be achieved by using long rotation periods with frequent thinning and by using and recycling wood products for as long as possible. The third option (substitution of fossil fuels with biofuels) can be effective over the longer term. Biofuels can be produced under short rotation management and the coppice method can often be applied. In addition to the use of biofuels, the energy required for processing timber to wood products is far smaller than that for other materials such as cement and iron and the long-term, accumulated effect of substituting wood products for other materials would also be significant to atmospheric carbon levels. These benefits demonstrate that the enhancement of forestry and utilization of forest products can contribute to creating a sustainable society. Sustainable forest management is therefore essentially important (Section 14.3).

Management of forest ecosystems to maintain and enhance health and vitality

A fundamental condition to achieving sustainable forest management is healthy and vital forest ecosystems, and so it is important to be able to maintain, enhance or recover the health and vitality of forests. Natural disturbances caused by agents such as insects, fungi, animals, fire or wind are normal phenomena in forest ecosystems, and should not be regarded as damage. However, these natural disturbances are often exacerbated by anthropogenic factors such as inappropriate silvicultural treatment of forests, air pollution, climate change, and introduced exotic organisms. The decline of trees and forests is usually caused by a complex interaction of many factors (Section 15.1). Inappropriate silvicultural treatment can be alleviated by silvicultural technology, but other anthropogenic factors are social issues.

Plantations and managed stands can be manipulated using an appropriate series of thinnings to maintain resistance to wind (Section 15.3.1-2) or snow (Section 15.3.1-5). As well as producing high quality timber, this approach can also increase the resistance of the forest to outbreaks of pests or diseases (Section 15.3.1.2-1). Thinning can also alleviate the monoculture of plantations during the young stage by encouraging the development of undergrowth, which assists the development soil structure and enhances biodiversity (Sections 10.5.2, 11.3). Long rotations with frequent thinnings are desirable for establishing stands resistant to various agents. Uneven-sized stands are generally resistant to various agents, and naturally oriented mixed stands are even more resistant. By using appropriate cutting, regeneration, and tending methods, various kinds of uneven-sized mixed stands can be developed and maintained (Section 8.1.7.2).

Consensus building for the sustainable forest management

Consensus building was not discussed in this book, but is very important for the implementation of the sustainable forest management, because many forests are in areas where there is diverse ownership and many stakeholders with a wide range of needs from the forest. All of the owners and stakeholders should be involved in decisions relating to the management of the forests, and the concept of sustainable forest management must be understood not only by foresters but also by these people. It is important for them to learn about forest ecosystems and the various functions of forests in order to understand sustainable forest management and the strategies available to realize it. Scientific data based on monitoring systems is essential for consensus building to make forest management plan.

References

* Denotes in Japanese with English summary.
** Denotes in Japanese only.

A Special Report of the IPCC. 2000. Land-Use, Land-Use Change, and Forestry. Cambridge University Press. Cambridge. 377pp.

Abe, K. 1984. Characteristics of tree root distribution and effects on slope stability. *J. Jpn. Soc. Reveget. Tech.* **10**(1). 14-19.**

Abe, K. 1997. A method for evaluating the effect of tree roots in preventing shallow-seated landslides. Bull. For. & For. Prod. Res. Inst. 373. 105-181.*

Abe, M. 1963. Growth of buna (*Fagus crenata*) plantations. Bull. Niigata Pref. For. Exp. Sta. 9. 11-139.**

Agriculture, Forestry and Fisheries Division of Kagoshima Prefecture. 1990. Guideline for silvicultural techniques for kojii forests (Sendai river watershed). Agriculture, Forestry and Fisheries Division of Kagoshima Prefecture. 11pp.**

Aiba, Y., K. Haibara, and Y. Kinoshita. 1981. The effects of intensive tending works on soil productivity (I) Nutrient status and discharge of a young stand (sapling stage) compared with an established stand. *J. Jpn. For. Soc.* **63**. 425-434.*

Aiba, Y., K. Haibara, H. Kondo, and N. Ikeda. 1985. The effects of intensive tending works on soil productivity (III) Nutrient discharge from young stands caused by weeding, fertilization, and the first pruning. *J. Jpn. For. Soc.* **67**. 73-81.*

Akai, T. 1991. Technical systems for extensive afforestation-Laying key subject on natural regeneration of *Chamaecyparis obtusa*. Rep. Kyoto Univ. For., 21. 1-53.**

Akai, T., K. Yoshimura, I. Manabe, K. Arimitsu, Y. Aiba, and T. Sugiura. 1981. Flowing of litter, soil, and other materials under artificial rainfall in the *Chamaecyparis obtusa* stands (II) Movement of litter and surface soil in young stands with different undergrowth. Trans. 92th Ann. Mtg. Jpn. For. Soc. 212-214.**

Akenaga, K. 1927. Relationship between cutting season and sprouting. Rep. of the Gov. For. Exp. Sta. 21. 1-23.**

Amano, M. and I. Noda. 1990. Landscape analyses and landscape management of Arashiyama National Forest (1). Significance of scenic beauty of Arashiyama National Forest. Res. Information of Kansai Res. Center., For. and For. Prod. Res. Inst. 17. 2.**

Anderson, M. L. 1949. Some observations on Belgian forestry. Empire Forestry Review. 28. 117-130.

Ando, T. 1968. Ecological studies on stand density control in even-aged pure stands. Bull. Gov. For. Exp. Sta. 210. 1-153.*

Ando, T. 1984. Thinning of dominants-Effects on qualitative and quantitative growth and health. *Ringyo Gijutsu.* **503**. 11-15.**

Ando, T. 1985. *Points on the Management for Multi-storied Forests.* Extension series of forestry research 79. Japan Forest Technology Association. Tokyo. 80pp.**

Ando, T. 1994. Stand density control. *In* S. Sasaki, H. Yagi, K. Ohba, S. Asakawa, K. Harada, T. Fujimori, T. Ando and T. Maeda. *Silviculture.* Kawashima Shoten. Inc. Tokyo. 147-172.**

Ando, T., K. Sakaguchi, T. Narita, and S. Sato. 1962. Growth analysis of natural stands of Japanese red pine (*Pinus densiflora*) I. Effects of improvement cutting and relative growth. Bull. Gov. For. Exp. Sta. 144. 1-30.*

Aomori Regional Forestry Office. 1974. Guideline for the management of *Pinus densiflora* (akamatsu) natural forests. Aomori Regional Forestry Office. 102pp.**

Arakawa, K. 1936. Damage of trees by lianas in the warm-temperate zone in Kyushu. *J. Jpn. For. Soc.* **18**(3), 15-28.**

Araki, M., K. Miyagawa, S. Kobayashi, M. Kato, and K. Arimitsu. 1987a. Effects of soil conservation in multi-storied *Chamaecyparis obtusa* stands (II) Differences in the physical properties of surface soils at *Chamaecyparis obtusa* stands in Imaichi following different treatments. Trans. 98th Ann. Mtg. Jpn. For. Soc. 219-220.**

Araki, M., K. Miyagawa, S. Kobayashi, M. Kato, and K. Arimitsu. 1987b. Effects of soil conservation in multi-storied *Chamaecyparis obtusa* stands (III) Changes in the physical properties of surface soil early after establishing a two-storied *Chamaecyparis obtusa* stand. Trans. 98th Ann. Mtg. Jpn. For. Soc. 221-222.**

Araki, M., K. Miyagawa, S. Kobayashi, M. Kato, and K. Arimitsu. 1988. Effects of soil conservation in multi-storied *Chamaecyparis obtusa* stands (V) Diffrences in the physical properties of surface soils of *Chamaecyparis obtusa* stands in Mt. Fuji following different treatments. 99th Ann. Mtg. Jpn. For. Soc. 161-162.**

Araki, M. and K. Miyagawa. 1989. Effects of soil conservation in multi-storied *Chamaecyparis obtusa* stands (VII) Differences in the physical properties of surface soils between a multi-storied satnd of *Zelkova serrata* (overstory) and *Chamaecyparis obtusa* (understory) and single-storied *Chamaecyparis obtusa* stand in Kawazu, Izu. Trans. 100th Ann. Mtg. Jpn. For. Soc. 225-226.**

Araki, M. and K. Miyagawa. 1990. Effects of soil conservation in multi-storied *Chamaecyparis obtusa* stands (IX) Changes in the physical properties of surface soils in a harvested stand of *Chamaecyparis obtusa* stand the overstory of which was harvested in Imaichi. Trans. 101th Ann. Mtg. Jpn. For. Soc. 65-66.**

Arimitsu, K. 1987. *Mechanisms of Water Holding in Forest Soil.* Message from forests. I. Sobun. Tokyo. 199pp.**

Arimitsu, K., Y. Osumi, M. Matsui, and S. Ohta. 1973. Effects of forest cutting on the soil environment (II) Dynamics of soil water in *Cryptomeria japonica-Chamaecyparis obtusa* stands in Kamikitayama-Mura in Nara-Prefecture, Trans. 84th Ann. Mtg. Jpn. For. Soc. 102-104.**

Arioka, T. 1994. Silviculture for keyaki plantations. *In* T. Fujimori and T. Kawahara (eds.), *Management of Hardwood Forests.* Forestry extention books 118. National Forestry Extension Association in Japan. Tokyo. 114-130.**

Asakawa, R. 1939. The relation between cutting season and the sprouting capacity of konara. *J. Jpn. For. Soc.* **21**. 350-360.**

Asanuma, S. 1987. Current methods of vegetation control and herbicide use in forestry. *Shokucho.* **21**(8). 7-13.**

Asanuma, S. 1988. Controlling vegetation in forests. *In* K. Hatiya et al. (eds), *Raising Forests.* Forestry extension books 101. National Forestry Extension Association in Japan. Tokyo. 104-113.**

Ashton, D. H. and D. G. Martin. 1996. Regeneration in a pole-stage forest of *Eucalyptus regnans* subjected to different fire intensities in 1982. *Australian Journal of Botany* **44**. 393-410.

Attwill, P. M. 1994. Ecological disturbance and the conservative management of eucalypt forests in Australia. *For. Ecol. and Manage.* **63**. 301-346.

Baker, F. S. 1934. *Theory and Practice of Silviculture.* McGraw-Hill Book Company, Inc. New York. 502pp.

Barnes, B. V., D. R. Zak, S. R. Denton, and S. H. Spurr. 1998. *Forest Ecology.* John Wiley & Sons, Inc. New York. 774pp.

Barret, J. W. 1968. Pruning of pondelosa pine, effect on growth. Pacific Northwest Forest and Range Exp. Sta., USDA Forest Service Res. Pap. PNW-68. 9pp.

Bäumler, R. and W. Zech. 1999. Effects of forest thinning on the streamwater chemistry of two forest watersheds in the Bavarian Alps. *For. Ecol. and Manage.* **116**. 119-128.

Bazzaz, F. A. 1983. Characteristics of population in relation to disturbance in natural and man-modified ecosystems. *In* H. A. Mooney and M. Godron (eds.), *Disturbance and Ecosystems: Components of Response.* Springer-Verlag, Inc., New York. 259-275.

Bazzaz. F. A. 1990. The response of natural ecosystems to the rising CO_2 levels. Annual Reviews of Ecology and Systematics 21. 167-196.

Benecke, U. 1996. Ecological Silviculture: The application of age-old methods. New Zealand Forestry, August 1996. 27-33.

Biolley, H. 1920. L'amënagement des forêts par la mêthode êxperimentale et specialement la mêthode du contrôle. Attinger Frères, Paris.

Bolin, B., S. Sukumar, P. Cias, W. Cramer, P. Jarvis, H. Kheshgi, C. Nobre, S. Semenov, and W. Steffen. 2000. Global Perspective. *In* R. T. Watson, I. R. Noble, B. Bolin, N. H. Ravindranath, D. J. Verardo, and D. J. Dokken (eds.), Land Use, *Land-Use Change, and Forestry. A Special Report of the IPCC.* Cambridge University Press. Cambridge. 23-51.

Boring, L. R., C. D. Monk, and W. T. Swank. 1981. Early regeneration of a cleracut southern Appalatchian forest. *Ecology* **62**. 1244-1253.

Bormann, F. H. and G. E. Likens. 1979. Catastrophic disturbance and the steady state in northern hardwood forests, *American Scientists* **67**. 660-669.

Bosch, J. M. and J. D. Hewlett. 1982. A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. *Journal of Hydrology* **55**. 3-23.

Brockman, C. R. 1968. *Trees of North America.* Golden Press. New York. 280pp.

Brown, A. A. and K. P. Davis. 1973. *Forest Fire-Control and Use.* 2nd ed. McGraw-Hill. New York. 686pp.

Bruschel, P. and J. Huss. 1987. *Grundriss des Waldbaus.* Paul Parey. 352pp.

Buffet, M. 1980. La régénération du Chene rouvre. Bulletin Technique, No. 12. Office National des Forêts. Paris. 201-224.

Buffet, M. 1981. La régénération du Hetre en plaine. Bulletin Technique, 13. Office National des Forêts. Paris. 29-47.

Cafferata, S. L. 1986. Douglas-fir stand establishment overview: Western Oregon and Washington. *In* C. D. Oliver, D. P. Hanley, and J. A. Johnson (eds.), *Douglas-fir: Stand Management in the Future.* Institute of Forest Resources Contribution 55. College of Forest Resources, University of Washington. Seattle, Washington. 211-218.

Calvert, G. M. 1986. The ecology and management of the Kalahari sand forest vegetation of south-western Zimbabwe. *In* G. D. Piearce (ed.), *Zambezi Teak Forests.* Forest Dept. Zambia. 121-158.

Canada-Britsh Columbia Partnership Agreement on Forest Resource

Development. 1992. Tending the stand. managing your woodland. Canada-British Columbia Partnership Agreement on Forest Resource Development: FRDA II. 1-23.

Cannell, M. G. R. 1982. *World Forest Biomass and Primary Production Data*. Academic Press. London. 391pp.

Cescatti, A. and E. Piutti. 1998. Silvicultural alternatives, competition regime and sensitivity to climate in a European beech forest. *For. Ecol. and Manage.* **102**. 213-223.

Ceulemans, R. and W. Deraedt. 1999. Production Physiology and growth potential of poplars under short-rotation forestry culture. *For. Ecol. and Manage.* **121**. 9-23.

Chen, J., J. F. Franklin, and T. A. Spies. 1992. Vegetation responses to edge environments in old-growth Douglas-fir forests. *Ecological Applications* **2**(4). 387-396.

Chiba, Y., T. Fujimori, and Y. Kiyono. 1988. Another interpretation of the profile diagram and its availability with consideration of the growth process of forest trees. *J. Jpn. For. Soc.* **70**. 245-254.

Chikarashi, H., S. Hattori, M. Takeuchi, Y. Tsuboyama, and K. Taira. 1987. Changes in heat water conditions in a forest caused by thinning. Creation of a preferable environment for production. Green energy contribution series III (Production environment) 2. Agriculture, Forestry, and Fisheries Research Councel Secretariat. 102-111.*

Chou, C. H., S. Y. Hwang, C. I. Peng, Y. C. Wang, F. H Hsu, and N. J. Chung. 1987. The selective allelopathic interaction of a pasture-forest intercropping in Taiwan. *Plant Soil* **98**. 31-34.

Chou, C. H., S. J. Chang, C. M. Cheng, Y. C. Wang, F. H. Hsu, and W. H. Den. 1989. The selective allelopathic interaction of a pasture-forest intercropping in Taiwan II. Interaction between kikuyu grass and three hardwood plants. *Plant Soil* **116**. 207-215.

Ciesla, W. M. and E. Donaubauer. 1994. *Decline and Dieback of Trees and Forests-A Global Overview*. FAO Forestry Paper 120. FAO. Rome. 90pp.

Clatterbuck, W. K. and J. S. Meadows. 1993. Regeneration oaks in the bottomlands. *In* D. L. Loftis and C. E. MaGee (eds.), *Oak Regeneration. Serious Problems, Principal Recommendations.* Symposium Proceedings. 8-10 September 1992. Knoxville, TN. Gen. Tech. Rep. SE-84, USDA Forest Service, Southeastern Forest Experiment Station. Asheville, NC. 184-195.

Clements, F. E. 1916. *Plant Succession: An Analysis of the Development of Vegetation*. Carnegie Institute, Washington, D. C., 512 pp.

Cornish, P. M. 1993. The effects of logging and forest regeneration on water yields in moist eucalypt forest in New South Wales, Australia. *Journal of Hydrology* **150**. 301-322.

Covington. W. W. 1981. Changes in forest floor organic matter and nutrient content following clearcutting in northern hardwood. 6 *Ecology* **62**(1). 41-48.

Curtis, J. T. 1955. A prairie continuum in Wisconsin. *Ecology*. **36**(4). 558-566.

Dixon, R. K., S. Brown, R. A. Houghton, A. M. Solomon, M. C. Trexler, and J. Wisniewski. 1994. Carbon pools and flux of global forest ecosystems. *Science* **263**(14). 185-190.

Doi, K. 1984. Studies on water feature of leaves of *Cryptomeria japonica* and mechanisms of winter desiccation damage. Doctoral thesis of Tokyo Univ. 6758. 1-130.**

Doi, Y. 1977. *Ecology and Observation of Fungi*. Tsukiji Shokan, Inc. Tokyo. 133pp.**

Drew, T. J. and J. W. Flewelling. 1977. Some recent Japanese theories of yield-Density relationship and their application to Monterey pine plantations. *Forest Science* **23**. 517-534.

Drew, T. J. and J. W. Flewelling. 1979. Stand density management: An alternative approach and its application to Douglas-fir plantations. *Forest Science* **25**. 518-532.

Egler, F. E. 1954. Vegetation science concepts: I. Initial floristic composition: A factor in old-field vegetation development. *Vegetatio* **4**. 412-417.

Ellenberg, H. 1953. Physiologisches und okologishes Verhalten serselben Pflanzenarten. *Ber. Deut. Botan.* Ges. 65. 351-362. (Refered from Mueller-Dombois, D. and H. Ellenberg. 1974. *Aims and Methods of Vegetation Ecology*. John Wiley & Sons. New York. 547pp.)

Emborg, J., M. Christensen, and J. Heilmann-Clausen. 2000. The structural dynamics of Suserup Skov, a near-natural temperate deciduous forest in Denmark. *For. Ecol. and Manage.* **126**. 173-189.

Emmett, B. A., J. M. Anderson, and M. Hornung. 1991. The controls on dissolved nitrogen losses following two intensities of harvesting in sitka spruce forest (N. Wales). *For. Ecol. and Manage.* **41**. 65-80.

Endo, T. and T. Tsuruta. 1969. On the effect of tree roots on the shearing strength of soil. 1968 Annu. Rep. Hokkaido. For. & For. Prod. Res. Inst. 167-182.**

FAO. 1992. Forest resources assessment 1990 tropical countries. FAO Forestry Paper. Food and Agriculture Organization of the United Nations. Rome, Italy. 61pp.

Favre, L.-A. 1994. Naturgemäßle Wardwirtshaft in Couvet. *In* Hatzfeldt. H Graf. (ed.), *Ökologische Waldwirtshaft-Gruntlagen, Aspekte, Beispiele.* Verlag C. F. Müller. Heidelberg. 232-249.

Fire Defense Agency of Japan. 1990. Data on measure for forest fires. Fire Defense Agency of Japan. 119pp.**

Flöhr, W. 1969. Results of the conservation of pure Scots pine stands into mixed forest by underplanting in the Sauen district. *Archiv für*

Forestwesen **18**. 991-994.

Ford-Robertson, F. C. (ed.). 1971. *Terminology of Forest Science, Technology Practice and Products*. Society of American Foresters. Washington D. C. 349pp.

Forestry Agency of Japan. 1978-1983. Stand density control diagrams (A series of 19 diagrams). Japan Forest Technological Association. Tokyo.**

Forestry Agency of Japan. 1979. Stand density control diagram for *Cryptomeria japonica* stands in the National Forests of the Shikoku Region. Japan Forest Technological Association. Tokyo. 1-7.*

Forestry Agency of Japan. 1982. Research on indicators of wood quality. Report of forestry research in 1980, 3. Forestry Agency of Japan. 47pp.**

Forestry Agency of Japan (ed.). 1990. *Forestry Technology Handbook*. National Forestry Extension Association in Japan. Tokyo. 348-517.**

Forestry Agency of Japan. 1991. Studies on forest management for by-products. Forestry Agency of Japan. 108pp.**

Forestry Agency of Japan. 1996. Dvelopment of techniques for managing multi-storied forests. Results of major research project 9. 156pp.**

Forestry Agency of Japan (Board for Analyses of Forests and Forestry). 1997. Forests and Forestry in Japan. Nihon Ringyo Chosakai. Tokyo. 365pp.**

Franklin, J. F. 1989. Toward a New Forestry. American Forests. November/ December 1989. 1-8.

Franklin, J. F. 1993. Preserving biodiversity: Species, ecosystems, or landscape? *Ecological Applications* **3**. 202-205.

Franklin, J. F. 1997. Ecosystem management: an overview. *In* M. S. Boyce and A. Haney (eds.), *Ecosystem Management: Applications for Sustainable Forest and Wildlife Resources*. Yale University Press. New Haven. CT. 21-53.

Franklin, J. F. and C. T. Dyrness. 1973. Natural vegetation of Oregon and Washington. USDA Forest Service General Technical Report PNW-8. 417pp.

Franklin, J. F. and R. H. Waring. 1980. Distinctive features of the northwestern coniferous forest: Development, structure, and function. *In* R. H. Waring (ed.), Forests: *Fresh Perspectives from Ecosystem Analysis*. Proc. 40th Anni. Biol. Colloq. 1979. Oregon State Univ. Press. Corvallis. 59-86.

Franklin, J. F. and M. A. Hemstrom. 1981. Aspects of succession in the coniferous forests of Pacific Northwest. *In* D. C. West, H. H. Shugart, and D. B. Botkin (eds.), *Forest Succession: Concepts and Application*. Springer-Verlag, Inc., New York. 212-229.

Franklin, J. F., K. Cromack, Jr., W. Denison, A. McKee, C. Maser, J. Sedell, F. Swanson, and G. Juday. 1981. Ecological characteristics of old-growth Douglas-fir forests. USDA Forest Service General Technical Report PNW-118. 48pp.

Franklin, J. F. and T. A. Spies. 1991. Composition, function, and structure of old-growth Douglas-fir forests. Wildlife and vegetation of unmanaged Douglas-fir forests. USDA Forest Service General Technical Report. PNW-GTR-285. 71-80.

Franklin, J. F., D. R. Berg, D. A. Thomburgh, and C. Tappeiner. 1997. Alternative silvicultural approaches to timber harvesting: variable retention harvest systems. *In* K. Kohm and J. F. Franklin. *Creating a Forestry for the 21st Century*. Island Press. Washington, D. C. 111-139.

Friedland, A. J., R. A. Gregory, L. Karenlampi, and A. H. Johnson. 1984. Winter damage to foliage as a factor in red spruce decline. *Can. J. For. Res.* **14**. 963-965.

Fujieda, M., T. Kishioka, A. Kikuya, and T. Shimizu. 1988. Assessing and predicting the effects of land use changes on the function of forests in flood control. Materials for country resources 22. Agriculture, Forestry, and Fisheries Research Councel Secretariat. 25-29.**

Fujimori, T. 1971. Primary productivity of a young *Tsuga heterophylla* stand and some speculations about biomass of forest communities on the Oregon coast. USDA Forest Service Research Paper PNW-123. 1-11.

Fujimori, T. 1972. Fundamental studies on pruning III. Different pruning methods and the subsequent variation of stand structure (1). Bull. Gov. For. Exp. Sta. 246. 55-67.

Fujimori, T. 1975. Study of the technical system of pruning. Bull. Gov. For. Exp. Sta. 273. 1-74.*

Fujimori, T. 1976. *Pruning and Its Theory.* Extension series for forestry research 57. Japan Forest Technological Association. Tokyo. 75pp.**

Fujimori, T, 1977. Stem biomass and structure of a mature *Sequoia sempervirens* stand on the Pacific Coast of North California. *J. Jpn. For. Soc.* **59**(12). 435-441.

Fujimori, T. 1984. *Pruning-Foundation and Application-*. Japan Forst Technology Association. Tokyo. 180pp.**

Fujimori, T. 1985. *Pruning and Silvicultural Techniques*. Nihon Ringyo Chosakai. Tokyo. 224pp.**

Fujimori, T. 1987a. Control of production environment in forest ecosystem. Green energy contribution series III (production environment) No. 2. Agriculture, Forestry and Fisheries Research Councel Secretariat. 83-91.*

Fujimori, T. 1987b. Crown snow damage and stand structure. *In* M. Ishikawa, R. Nitta, M. Katsuta, and T. Fujimori. *Crown Snow Damage*. Extension series for forestry research 83. Forest Development Technical Institute. Tokyo. 30-51.**

Fujimori, T. 1989a. *Ecology of Multi-soried Forests and their Management.* Extension series for forestry research 93. Japan Forest Technology

Association. Tokyo. 96pp.**

Fujimori, T. 1989b. Dry matter production of forests. *Journal of Japanese Agriculture System Society*. **15**(2). 9-17.**

Fujimori, T. 1990. Multi-storied forest method. *In* Forestry Agency of Japan (ed.), *Forestry Technology Hundbook*. National Forestry Extention Association in Japan. Tokyo. 580-589.**

Fujimori, T. 1991a. *Diversity-oriented Forest Management*. Forestry extension books 107. National Forestry Extention Association in Japan. Tokyo. 191pp.**

Fujimori, T. 1991b. Exotic pines-*Pinus taeda and Pinus elliottii* of the United States of America. *Protection of Pines in Japan* **46**. 8-12.**

Fujimori, T. 1992a. Guideline for silvicultural treatment. *In* Forestry Agency of Japan (ed.), *Record of Forest Damage by Typhoon 19 and Other Typhoons in 1991*. Nihon Zorin Kyokai. Tokyo. 39-50.**

Fujimori, T. 1992b. Silvicultural methods for multi-storied forests. *In* F. Fujimori (ed.), *Manual for Multi-storied Forests-Management and Silviculture*. National Forestry Extention Association in Japan. Tokyo. 45-61.**

Fujimori, T. 1993a. Dynamics of crown structure and stem growth based on knot analysis of a hinoki cypress. *For. Ecol. and Manage*. **56**. 57-68.

Fujimori, T. 1993b. Forest management techniques for carbon dioxide storage. A report from the second U.S./Japan workshop on global change research: Environmental response technologies. U.S. Committee on Earth and Environmental Sciences (CEES). 273-270.

Fujimori, T. 1994. Crown control for the establishment of healthy and valuable forests-Thinning and pruning. *In* Editing committee of forest science (ed.), *Review and Perspective of Forest Science*. National Forestry Extension Association in Japan. Tokyo. 116-119.**

Fujimori, T. 1995. Relationship between stand age and wind resistance of stand-Forest damage by Typhoon 7 in 1959 in the area of Tokyo Regional Forestry Office, Japan-. *J. Jpn. For. Soc*. **77**(6), 602-605.

Fujimori, T. 1996. Silvicultural techniques 1/Management of plantations. *In* National Forestry Extension Association in Japan (ed.), *A new Forester's Guide*. National Forestry Extension Association in Japan. Tokyo. 81-108.**

Fujimori, T. 1997a. How to manage "10 million hectare plantations" to achieve the forests desired for the future in Japan. *Shinrin Kagaku* (Bull. Jpn. For. Soc.) **19**. 2-8.**

Fujimori, T. 1997b. New forest management-Ecosystem management. *Shinrin Kagaku* (Bull. Jpn. For. Soc.) **21**. 46-49.**

Fijimori, T. 1998. Contribution of forests for mitigation of global worming. *Research Journal of Food and Agriculture* **21** (4). 43-49.**

Fujimori, T. 1999. Classification of forest functions and the management of them. *In* T. Fujimori, M. Yui, and N. Ishii, *Conservation and*

Management of Wildlife in Forests. Nihon Ringyo Chosakai. Tokyo. 17-19.**

Fujimori, T. 2000. *Coexistence with Forests*. Maruzen Library 322. Maruzen Inc., Tokyo. 236pp.**

Fujimori, T., S. Kawanabe, H. Saito, C. C. Grier, and T. Shidei. 1976. Biomass and primary production in forests of three major vegetation zones of the nothwestern United States. *J. Jpn. For. Soc.* **58**(10). 360-373.

Fujimori, T. and Y. Kiyono. 1983. Canopy structure and light intensity in a young closed stand of *Cryptomeria japonica*. Trans. 94th Mtg. Jpn. For. Soc. 343-345.**

Fujimori, T., T. Suzuki, O. Waseda, E. Uchimura, K. Yamamoto, and K. Saito. 1983. Structure and growth of an experimental stand in a selection forest in Imasu. Bull. For. & For. Prod. Res. Inst. 323. 202-206.**

Fujimori, T., K. Izawa, Y. Kanazawa, and Y. Kiyono. 1984. Fundamental studies of pruning IV. Cause of wood discoloration following artificial pruning. Bull. For. Prod. Res. Inst. 328. 119-143.**

Fujimori, T., H. Utsugi, and M. Ishiduka. 1995. Growth of sugi cedar and hinoki cypress planted in several types of forest stand. *J. Jpn. For. Soc.* **77**(4). 297-304

Fujishima, S. 1932. *Silviculture Based on Regeneration Theory*. Yokendo, Inc., Tokyo. 546pp.**

Furukoshi, T. 1983. Seed orchard. *In* K. Sakaguchi (ed.), *All of Sugi*. National Forestry Extension Association in Japan. Tokyo. 166-176.**

Furuta, K. 1984. *Protection of Forest-Ecosystems and Natural Control of Insects*. Baifu Kan, Inc. 194pp.**

Gholz, H. L. 1986. Canopy development and dynamics in relation to primary production. *In* T. Fujimori and D. Whitehead (eds.), *Crown and Canopy Structure in Relation to Productivity*. Forestry and Forest Products Research Institute. Ibaraki, Japan. 224-242.

Gholz, H. L., G. M. Hawk, A. Campbell, and K. Cromack, Jr. 1985. Early vegetation recovery and element cycles on a clear-cut watershed in western Oregon. *Can. J. For. Res.* **15**. 400-409.

Graves, J. and D. Reavey. 1996. *Global Environmental Change-Plants, Animals, and Communities*. Longman Group Limited. Essex. 226pp.

Grier, C. C. and R. H. Waring. 1974. Conifer foliage mass related to sapwood area. *For. Sci.* **20**. 205-206.

Grime, J. P. 1977. Evidence for the existence of three primary strategies in plants and its relevance to ecological and evolutionary theory. *American Naturalist* **111**. 1169-1194.

Grinnell, J. 1917. The niche-relationships of the California thrasher. *Auk*. **34**. 427-433.

Gruppe, A., M. Fueder, and R. Schopf. 1999. Short rotation plantations of aspen and balsam poplar on former arable land in Germany: defoliating insects and leaf constituents. *For. Ecol. and Manage.* **121**. 113-122.

Haibara, K., Y. Aiba, and S. Hidaka. 1983. Decomposition and nutrient disapearance in leaves of weeds in a young sugi (*Cryptomeria japonica*) plantation. *J. Jpn. For. Soc.* **65**. 237-242. *

Halpern, C. D. 1988. Early successional pathways and the resistance and resilience of forest communities. *Ecology*. **69**. 1703-1715.

Hara, M., T. Sengoku, and T. Fujimori. 1995. Establisment of a two-layered forest of *Betula maximowicziana* and *Chamaecyparis obtusa* in a stand where *Chamaecyparis obtusa* was planted. *Jpn. J. For. Environment*, **37**. 89-93.*

Harada, H. 1983. Seedlings. *In* K. Sakaguchi (ed.), *All about sugi*. National Forestry Extension Association in Japan. Tokyo. 190-198.**

Harmon, M. E., W. K. Ferrel, and J. F. Franklin. 1990. Effects on carbon storage of conversion of old-growth forests to young forests. *Science*. **247**(4943). 699-703.

Harper, J. L. 1977. *Population Biology of Plants*. Academic, Inc., London. 892 pp.

Harris, L. D. 1984. *The Fragmented Forest: Island Biogeography Theory and the Preservation of Biotic Diversity*. The University of Chicago Press. Chicago. 211pp.

Hashizume, H. 1991. Seeds. In A. Kawana, H. Kataoka, Y. Kakubari, G. Iwatsubo, Y. Aiba, K. Ohba, H. Hashizume, I. Migita, S. Sasaki, K. Nogami, T. Ando, T. Ito, S. Sudo, K. Yoshikawa and H. Watanabe. *Silviculture* 3rd ed. Asakura Shoten, Inc., Tokyo. 67-82**

Hasse, D. L. and R. Rose. 1993. Soil moisture stress induces transplant stock in stored and unstored 2 + 0 Douglas-fir seedlings of varing root volumes. *Forest Science* **39**. 275-294.

Hatano, K. and S. Sasaki. 1987. *Growth of Trees and the Environment*. Yokendo. Tokyo. 383pp.**

Hatiya, K. 1970. Law of stand density and stand density control. Thity-three selected new forestry techniques. National Forestry Extension Association in Japan. Tokyo. 164-191.**

Hatiya, K., I. Takeuchi, and K. Tochiaki. 1989. Primary productivity of high density stands of *Pinus densiflora* SIEB et Zucc.. Bull. For. & For. Prod. Res. Inst. 354. 39-97.*

Helms, J. A. 1998. (ed.). *The Dictionary of Forestry*. The Society of American Foresters and CABI Publishing. 210pp.

Hemstorm, M. 1990. Alternative timber harvest patterns for landoscape diversity. Coastal Oregon Productivity Enhancemant Report, 3(1). Oregon State University. U.S.A. 8-11.

Henman, D. W. 1963. Pruning conifers for the production of quality timber. Forestry Commision. Bul. 35. Edinburgh: Her Majesty's Stationary

Office. 55pp.

Hiley, E. E. 1959. Two-storied high forest. *Forestry* **32**. 113-116.

Hodges, J. D. 1989. Regeneration of bottomland oaks. *Forest Farmer*, **49**(1). 10-11.

Hodges, J. D. and G. Janzen. 1987. Studies on the biology of cherrybark oak: recommendations for regeneration. *In* D. R. Phillips (Compiler). Proceedings of the Fourth Biennial Southern Silvicultural Research Conference. 4-6 November 1986. Atlanta GA. Gen. Tech. Rep. SE-42. USDA Forest Service. Southeastern Forest Experiment Station. Asheville. NC. 133-139.

Hofmann-Schielle, C., A. Jug, F. Makeschin, and K. E. Rehfuess. 1999. Short-rotation plantations of balsam poplas, aspen and willows on former arable land in the Federal Republic of Germany. I. Site-growth relationships. *For. Ecol. and Manage.* **121**. 41-55.

Hongo, I. and H. Kataoka. 1987. Low temperature storage of beech seedlings and the action of ethylene in bud breaking. Trans. 98th Mtg. Jpn. For. Soc. 277-278.**

Hori, S., K. Saito, A. Shimomura, and T. Kagawa. 1997. *Forest Cape*. National Forestry Extension Association in Japan. Tokyo. 191pp.**

Horiuchi, T. 1976. Studies of forest damage on basal stems in young *Cryptomeria* and its prevention. Bull. Ibaraki Pref. For. Exp. Sta. 10. 1-59.*

Hornbeck, J. W., C. W. Martin, R. S. Pierce, F. H. Borman, G. E. Likens, and J. S. Eaton. 1987. The Northern hardwood ecosystem: Ten years of recovery from clear cutting. Res. Pap. No. 596. Northwestern Forest Experiment Station, USDA Forest Service. 30pp.

Hotta, I. 1991. Material cycling and water purification in forested catchment. Forest and water resources. *In* Committee for water resources issue (ed.), *Forest and Water Resources*. Japan Erosion Control and Water Regulation Society. Tokyo. 81-89**

Houghton. J. T., L. G. Meira Filho, B. A. Callander, N. Harris, A. Kattenberg, and K. Maskell (eds.), 1996. Climate change 1995. *The Science of Climate Change*. Cambridge University Press. Cambridge. 572pp.

Howell, B. N., R. M. Harley, R. D. F. White, and R. G. M. Lamb. 1983. The Dartington story II. *Quarterly Fournal of Forestry* **77**. 5-16.

Hozumi, K., K. Shinozaki, and Y. Tadaki. 1968. Studies on the frequency distribution of the weight of individual trees in a forest stand. 1. A new approach toward the analysis of the distribution function and the -3/2 th power distribution. *Jpn. J. Ecol.* **18**. 10-20. 1968.

Hutchinson, G. E. 1957. Concluding remarks. Cold spring harbor symp. *Quant. Biol.* **22**. 415-417. (Reffered from J. P. Kimmins. 1987. *Forest ecology*. Macmillan, Inc. New York. 531pp.)

Iida, S. and T. Nakashizuka. 1995. Forest fragmentation and its effect on species diversity in a suburban coppice forest in Japan. *For. Ecol. and Manage.* **73**. 197-210.

Iizumi, S. and T. Kikuchi. 1980. *Plant Community and Its Life*. Tokai University Press. Tokyo. 199 pp.**

Imada, M. 1972. Study on the high forest system of mizunara. Bull. Kyushu Univ. For. 45. 81-225.*

Inoue, Y. 1960. *Management of Akamatsu Forests*. Japan Forest Technological Association. Tokyo. 390pp.**

IPCC Working Group I. 1996. Summary for policy makers. Climate change 1995 (Eds. J. H. Houghton, L. G. Nwrira Fillo, B. A. Callander, N. Harris, A. Kattenberg and K. Maskell). Cambridge University Press. New York. 1-7.

Isamoto, N and T. Takamiya. 1992. Factor analysis of forest damages by typhoon 19th (1991. 9) in Oita Prefecture. Research Report of the Forest Experiment Station 18. 1-43.**

Ishihara, T. 1980. *The Way to a Forest Factory*. Seibun, Inc. Tokyo. 198pp.**

Ishizuka, M. 1980. Structure and dynamics of mixed conifer-hardwood forests. *In* Hokkaido Regional Forestry Office (ed.), *Analyses of the Structure and Regeneration of Patches* (Intermediate Report). Hokkaido Regional Forestry Office. Sapporo. 79-100.**

Ishizuka, M. 1981. Development processes of mixed conifer-hardwood forests. *In* Hokkaido Regional Forestry Office (ed.), *Analyses in the Structure and Regeneration of Patches* (2). Hokkaido Regional Forestry Office. Sapporo. 89-101.**

Ishizuka, M. 1984. Spatial patterns of trees and their crowns in natural mixed forests. *Jpn. J. Ecol.* **34**. 421-430.

Ishizuka, M. 1989. Development processes in mixed conifer-hardwood forests in Central Hokkaido. Unpublished doctoral dissertation. Tsukuba University. 110 pp.*

Ishizuka, M. 1994. Silvicultural methods for mixed stands of coniferous and broad-leaved species. *In* T. Fujimori and T. Kawahara (eds.), *Management of Hardwood Forests*. National Forestry Extension Association in Japan. Tokyo. 37-56.**

Ishizuka, M. and S. Sugawara. 1986. Composition and structure of natural mixed forests in central Hokkaido (I) Composition differences and species characteristics by elevation and from disturbances. *J. Jpn. For. Soc.* **68**. 79-86.

Ito, K. and M. Haruki. 1984. Revegetation surveys of Mt. Usu over six years following the eruption in 1977-1978. A follow-up survey of environmental changes caused by the 1977-1978 eruptions of Mt. Usu and related events. Graduate School of Environ. Sci., Hokkaido Univ. 61-84.*

Iwai, Y. 1992. *Forests and Forest Products in Europe*. Nihon Ringyo

Chosakai. Tokyo. 138pp**

Jackson, N. A., J. S. Wallace, and C. K. Ong. 2000. Tree pruning as a means of controlling water use in an agroforestry system in Kenya. *For. Ecol. and Manage.* **126**. 133-148.

Janzen, G. C. and J. D. Hodges. 1987. Development of advanced oak regeneration as influenced by removal of midstory and understory vegetation. *In* D. R. Phillips (Compiler). Proceedings of the Fourth Biennial Southern Silvicultural Research Conference. 4-6 November 1986. Atlanta, GA. Gen. Tech. Rep. SE-42. USDA Forest Service. Southeastern Forest Experiment Station. Asheville. NC. 455-461.

Japan Forest Technology Association. 1975. *Research on Silvicultural Systems*. Japan Forest Technnology Association. Tokyo. 261pp.**

Japan Wildlife Research Center. 1991. A study report on planning methods in consideration with conservation of ecosystems (1990). Japan Wildlife Research Center. Tokyo. 103pp.**

Jobidon, R. 1991. Some future directions for biologically based vegetation control in forestry research. *The Forestry Chronicle* **67**(5). 514-519.

Jobidon, R., J. R. Thibault, and J. A. Fortin. 1989a. Phytotoxic effect of barley, oat, and wheat straw mulches in eastern Quebec forest plantations 1. Effects on red raspberry (*Rubus idaeus*). *For. Ecol. and Manage.* **29**. 227-294.

Jobidon, R., J. R. Thibault, and J. A. Fortin. 1989b. Phypotoxic effect of barley, oat, and wheat straw mulches in eastern Quêbec forest plantations 2. Effects on nitrification and black spruce (*Picea mariana*) seedling growth. *For. Ecol. and Manage.* **29**. 295-310.

Jobidon, R., J. R. Thibault, and J. A. Fortin. 1989c. Effect of straw residues on black spruce seedling growth and mineral nutrition, under greenhouse conditions. *Cana. J. For. Res.* **19**. 1291-1293.

Johnson, R. L. and R. M. Krinard. 1989. Survival and growth of Nuttal oak seedlings following selection cutting. 28-year remeasurement. South. J. Appl. For., 13. 43-46.

Kamitani, T. 1986a. Studies on the process of formation of secondary beech forest in a heavy snowfall region (II) The relationship between stump age and the reproductive capacity for coppice sprouts of the main woody species. *J. Jpn. For. Soc.* **68**. 127-134.*

Kamitani, T. 1986b. Studies on the process of formation of secondary beech forest in a heavy snowfall region (III) Seed production in secondary beech forests with six different diameter classes. *J. Jpn. For. Soc.* **68**. 447-453.*

Kanazawa, Y., Y. Kiyono, T. Fujimori, and K. Kamo. 1984. Seasonal changes in the above-ground biomass of a young *Zelkova serrata* stand. *J. Jpn. For. Soc.* **66**. 167-173.

Kandler, O. 1990. Epidemiological evaluation of the development of Waldsterben in Germany. *Plant Disease* **74**. 4-11.

Kaneko, S., T. Kubono, T. Sasa, S. Ikeda, and T. Shoji. 1991. Butt rot damage of Japanese larch in Iwate Prefecture-A survey based on the analysis of stumps. Trans. 102th Ann. Mtg. Jpn. For. Soc. 327-328.**

Kaneko, S. 2000. Damages by introduced pathogens in the forests in Japan and the world-Situation in the past and present. *Sanrin* **1396**. 62-68.**

Kaneko, Y. 1995. Disturbance regimes in a mountainous riparian forest and the effects of disturbance on tree population dynamics. *Jpn. J. Ecol.* **45**. 311-316.*

Katagiri, S. 1986. Studies on mineral cycling in a clear-cut area (I) changes in the amount of nutrients in the above ground biomass over two years following cutting. Bull. Fac. Agr. Shimane Univ. 20. 59-66.

Kataoka, H. 1982. *Sustainability of Beech Forests*. Norin Shuppan, Inc., Tokyo. 135pp.**

Kataoka, H. 1989. Treetment of broad-leaved forests. *Ringyo Gijutsu*. **565**. 24-27.**

Kataoka, H. 1991a. Preferred silviculture of beech forests. *In* H. Murai, K. Yamaya, H. Kataoka, and M. Yui (eds.), *Natural Environment and Conservation of Beech Forests*. Soft Science Inc. Tokyo. 351-394.**

Kataoka, H. 1991b. Regeneration by planting for beech. *Shinrin Kagaku (Bull. Jpn. For. Soc.)* **2**. 39-48.**

Kato, R. 1971. New techniques of natural regeneration for *Pinus densiflora*. *In* T. Yanagisawa, K. Yamaya, M. Nakano, T. Maeda, K. Miyagawa, R. Kato, and N. Ogata. *New Techniques of Natural Regeneration*. Sobun, Inc., Tokyo. 253- 300.**

Kato. R. 1975. Management of *Pinus densiflora* forests. *In* K. Sakaguchi (ed.), *Forest Management in the Future*. National Forestry Extension Association in Japan. Tokyo. 317-328.**

Kato. R., Y. Tadaki, and H. Ogawa. 1978. Plant biomass and growth increment studies in Pasoh forest. *Malay Nat. J.* **30**. 221-224.

Katsuta, M. 1987. Crown snow damage in different tree species and varieties. *In* M. Ishikawa, R. Nitta, M. Katsuda, and T. Fujimori. *Crown snow damage*. Extension series of forestry research 83. Forest Development Technical Institute. Tokyo. 96pp.**

Kaufman, Y. J., A. Setzer, C. Justice, C. J. Tucker, M. G. Pereira, and I. Fung. 1990. Remote seising of biomass burning in the tropics. *In* J. G. Goldmmer (ed.), *Fire in the Tropical Biota* (Ecological Studies 84). Springer-Verlag. New York. 371-399.

Kauppi, P. E., K. Mielkainen, and K. Kuusela. 1992. Biomass and carbon budget of Europian forests, 1971-1990. *Science* **256**. 70-74.

Kawaguchi, T. 1987. Function of forests for landslide prevention. Explanatory series on the function of forests for public benefits. 6. Japan Erosion Control and Water Regulation Society. 98pp.**

Kawahara, T. 1988. Control of light intensity to induce multi-storied forests. *Jpn. J. For. Environment* **15**(1). 10-13.**

Kawahara, T., Y. Kanazawa, and S. Sakurai. 1981. Biomass and net production of man-made forests in the Philippines. *J. Jpn. For. Soc.* **63**. 320-327.

Kawahara, T. and K. Yamamoto. 1982. Studies on mixed stands of akamatsu (*Pinus densiflora*) and hinoki (*Chamaecyparis obtusa*) (I) productivity and rates of decomposition of organic matter. *J. Jpn. For. Soc.* **64**. 331- 339.*

Kawakami, H. 1958. Actual condition of regeneration by sprouting and its management in the future. *Sapporo Rinyu* **53**. 17-35.**

Kawana, A., H. Kataoka, Y. Kakubari, G. Iwatsubo, Y. Aiba, K. Ohba, H. Hashizume, K. Migita, S. Sasaki, K. Nogami, T. Ando, T. Ito, S. Sudo, K. Yoshikawa, and H. Watanabe. 1992. *Silviculture*. Asakura Shoten. Tokyo. 53-116.**

Keys, M. R. and C. C. Grier. 1981. Above- and below-ground net production in 40-year-old Douglas-fir stands on low and high productivity sites, *Can. J. For. Res.* **11**. 599-605.

Kikuzawa, K. 1978. Yield-density diagram of natural deciduous hardwood forest stands in Hokkaido. *J. Jpn. For. Soc.* **60**. 56-63.*

Kimmins, J. P., K. A. Scoullar, R. E. Bigley, W. Kurz, P. G. Comeau, and L. Chatarpaul. 1986. Yield prediction models: The need for a hybrid ecosystem-level approach incorporating canopy function and archirecture. *In* T. Fujimori and D. Whitehead (eds.), *Crown and Canopy Structure in Relation to Productivity*. Forestry and Forest Products Research Institute. Ibaraki, Japan. 26-48.

Kimmins. J. P. 1987. *Forest Ecology*. Macmillan Publishing Company. New York. 531pp.

King, G. A. and R. P. Neilson. 1992. The transient response of vegetation to climate change: a potential source of CO_2 to the atmosphere. *Water, Air, and Soil Pollution* **64**. 365-383.

Kira, T. (ed.). 1957. Stand density, competition, and production. Miyama (Osaka Regional Forestry Office). 8. 13-24., 9. 9-18., 11/12. 34-35.**

Kira, T. 1977. Primary productivity of Japanese forests. *In* T. Shidei and T. Kira (eds.), *JIBP Synthesis 16*. Univ. of Tokyo Press. Tokyo. 101-114.

Kira, T., H. Ogawa, and Y. Sakazaki. 1953. Intraspecific competition among higher plants. I. Competition-density-yield interrelationship in regularly dispersed populations. Jour. Inst. Polyteck. Osaka City Univ. Ser. D4. 1-16.

Kira, T., H. Ogawa, and K. Hozumi. 1954. Intraspecific competition among higher plants. II. Further discussion on Mitscherlich's law. Jour. Inst. Polytech. Osaka City Univ. Ser. D5, 1-7.

Kira, T., H. Ogawa, K. Hozumi, H. Koyama, and K. Yoda. 1956. Intraspecific competition among higher plants. V. Supplementary notes on the C-D effects. Jour. Inst. Polytech. Osaka City Univ. Ser. D7, 1-14.

Kira, T. and T. Shidei. 1967. Primary production and turnover of organic matter in different forest ecosystems of the western Pacific. *Jpn. J. Ecol.* **17**(2). 70-87.

Kitamura, M. 1996. Forest of Fontainebleau. *In* T. Ota, M. Kitamura, M. Kumasaki, K. Suzuki, S. Sudo, Y. Tadaki, and T. Fujimori. *Encyclopedia of Forests.* Maruzen, Inc. Tokyo. 826pp.**

Kitamura, Y. and S. Namba. 1981. The function of tree roots in landslide prevention as presumed through the uprooting test. Bull. For. & For. Prod. Res. Inst. 313. 175-208.**

Kiyohara, T. and Y. Tokushige. 1971. Inoculation experiments of a Nematode, *Bursaphelenchus* sp. into pine trees. *J. Jpn. For. Soc.* 53. 210-218.*

Kiyono, Y. 1990. Dynamics and control of understories in *Chamaecyparis obtusa* plantations. Bull. For. & For. Prod. Res. Inst. 359. 1-122.*

Kobashi, S. 1983. Latest knowledge about the influences of roots upon slope stability. *J. Jpn. Soc. Reveget. Tech.* **10**(1). 14-19.

Kobayashi, F. 1981. Consideration in preventing pine mortality given the high possibility of the exotic origin of the pine wood nematode. *Forestry Culture* **2**(1). 49-53.**

Kobayashi, S. 1982. Changes in soil caused by forest clearcutting. *Pedologist* **26**. 150-163.*

Kobayashi, S. 1991. Change of soil following cutting of forests. *Japanese Journal of Forest Planning* **16**. 159-170.**

Koide, R. 1941. Study on pruning 4. Process of branch death upwards and its fall. *J. Jpn. For. Soc.* **23**(7). 1-15.**

Koizumi, T. 1993. *Why Japane's mountains are beautiful.* Kokon Shoin Inc. Tokyo. 228pp.**

Kondo, T. 1951. *Systems for Hardwood Timber Production.* Asakura Shoten, Inc. Tokyo. 158pp.**

Kozlwoski, T. T. 1971a. *Growth and Development of Trees. Volume I.* Academic Press, Inc. New York. 443pp.

Kozlowski, T. T. 1971b. *Growth and Development of Trees. Volume II.* Academic Press, Inc. New York. 514pp.

Kozlowski, T. T., P. J. Kramer, and S. G. Pallardy. 1991. *The Physiological Ecology of Woody Plants.* Academic Press, Inc. New York. 657pp.

Kramer, P. J. and T. T. Kozlowski. 1979. *Physiology of Woody Plants.* Academic Press, Inc. New York. 811pp.

Kuczera, G. A. 1987. Prediction of water yield reductions following a bushfire in ash-mixed species eucalypt forest. *J. Hydrol.* **94**. 215-236.

Kurashima, A. 1973. *Calender of Weather.* Asahi News Press (ed.), Kawade Shobo, Inc. Tokyo. 276 pp.**

Kurz, W. A. and M. J. Apps. 1999. A 70-year retrospective analysis of carbon fluxes in the Canadian forest sector. *Ecological Applications* **9**(2). 526-547.

Lähde, E. 1992. Nature oriented silviculture in an ecocommune. K. Heikurainen (ed.), Suomussalmi Eco-municipality. Suomussalmi Eco-municiparity. 44-50.

Lähde, E. 1993. Diversity of Forests as a Global Goal. *In* M. Linddal and A. Naskali (eds.), Proceedings of the Workshop Valuing Biodiversity on the Social Costs of and Benefits from Preserving Endangered Species and Biodiversity of the Boreal Forests. Espoo. Finland. October 1992. *Scandinavian Forest Economics* **34**. 105-109.

Lähde, E., O. Laiho, and Y. Norokorpi. 1999. Diversity-oriented silviculture in Boreal Zone of Europe. *For. Ecol. and Manage.* **118**. 223-243.

Lamhamedi, M. S. and C. H. R. Jobidon. 1998. Phisiology and growth responses of three sizes of containerized *Picea Mariana* seedlings outplanted with and without vegetation control. *For. Ecol. and Manage.* **110**. 13-23.

Lancaster, K. F. and W. B. Leak. 1978. Silvicultural guide for white pine in the northeast. USDA, Forest Seervice, NE For. Exp. Stn. Gen. Tech. Rep. NE-41.

Lanier, L. 1986. Présis de Silviculture. École Nationale du Genie Rural, des Eaux et des Forêts. Nancy.

Larcher. W. 1985. Winter stress in high mountains. *In* H. Turner and W. Tranquillini (eds.), *Establishment and Tending Subalpine Forest: Research and Management.* Proc. 3rd IUFRO Workshop P1.07-00 1984. Edig. Anst. Forstl. Versuchswes. Ber. 270 (1985). 11-19.

Larsen, J. B. 1995. Ecological stability of forests and sustainable silviculture. *For. Ecol. and Manage.* **73**. 85-96.

Leaphart, C. D. and A. R. Stage. 1971. Climate: a factor in the origin of the pole blight disease of *Pinus monticola. Ecology* **52**. 229-239.

Liang, N. 1995. *Effects of CO_2 Concentrations, Irradiance, Temperature and Drought Stress on Photosynthetic Characteristics of Seedlings of Japanese Beech (Fagus crenata).* Wakou Press Corporation. Niigata. 129pp.

Liesebach, M., G. von Wuehlisch, and H.-J. Muhs. 1999. Aspen for short-rotation coppice plantations on agricultural sites in Germany: Effects of spacing and rotation time on growth and biomass production of aspen progenies. *Fore. Ecol. and Manage.* **121**. 25-39.

Likens, G. E., F. H. Borman, N. M. Johnson, and W. A. Reiners. 1978. Recovery of a deforested ecosystem. *Science* **199**. 492-496.

Lindenmayer, D. B. 1995. Forest disturbance, forest wildlife conservation and the conservative basis for forest management in the mountain ash forests of Victria - comment. *For. Ecol. and Manage.* **74**. 223-231.

Lindenmayer, D. B. and J. F. Franklin. 1997. Managing stand structure as part of ecologically sustainable forest management in Australian mountain ash forests. *Conservation Biology* **11**. 1053-1068.

Lindroth, A. and A. Båth. 1999. Assesment of regional willow coppice yield in Sweden on basis of water availability. *For. Ecol. and Manage.* **121**. 57-65.

Löf, M., P. Gemmel, and N. T. Welander. 1998. The influence of site preperation on growth in *Quercus robur* L. seedling in southern Sweeden clear-cut and shelterwood. *For. Ecol. and Manage.* **109**. 241-249.

Loftis, D. L. 1990. A shelterwood method for regenerating red oak in the southern Appalachians. *Forest Science* **36**. 917-929.

Lüpke, B. V. 1998. Silvicultural methods of oak regeneration with special respect to shade tolerant mixed species. *For. Ecol. and Manage.* **106**. 19-26.

Madsen, P. and J. B. Larsen. 1997. Natural regeneration of beech (*Fagus sylvatica*) with respect to canopy density, soil moisture and soil carbon content. *For. Ecol. and Manage.* **97**. 95-105.

Maeda, T. 1988. Studies on natural regeneration of beech. Special Bulletin of the College of Agri. Utsunomiya Univ., 46. 79pp.*

Maeda, Y., M. Fujita, Y. Ueda, and T. Tanimoto. 1989. Analysis of keyaki-sugi two-storied forests. Trans. 100th Ann. Mtg. Jpn. For. Soc. 249-251.**

Maguire, D. A. and D. W. Hann. 1987. A stem dissection technique for dating branch mortality and reconstructing past crown recession. *For Sci.* **33**(4). 858-871.

Mallik, A. U., F. W. Bell, and Y. Gong. 1997. Regeneration behavior of competing plants after clearcutting: implications for vegetation management. *For. Ecol. and Manage.* **95**. 1-10.

Mamiya, Y. 1980. Discovery of the pine wood nematode in the U.S.A. *Forest Pests* **29**. 54-58.**

Manion, P. D. 1991. Tree disease concepts (Second edition). Prentice-Hall Inc. Engelwood Cliffs. N. J., 402pp.

Manuwal, D. A. and M. H. Huff. 1987. Spring and winter bird populations in a Douglas-fir forest sere. *Journal of Wildlife Management* **51**. 586-595.

Marks, P. L. and F. H. Borman. 1972. Revegetation following forest cutting: mechanisms for return to steady-state nutrient cycling. *Science* **176**. 914-915.

Marquis, D. A. 1989. Alternative silvicultural systems: east. *In* Silvicultural Challenges and Opportunities in the 1990s: Proceedings of the National Silviculture Workshop, 10-13 July 1989. Petersburg, AK. USDA Forest Service, Washington D. C. 36-43.

Matsukawa K. 1935. Silvicultural methods for hiba natural forests based on patches. Aomori Regional Forestry Office. 79pp.**

Matthews, J. D. 1963. Factors affecting the production of seed by forest trees. *For. Abst.* **24**. 1-13.

Matthews, J. D. 1989. *Silvicultural Systems*. Clarendon Press. Oxford.

284pp.

McCarthy, M. A., A. M. Gill, and D. B. Lindenmayer. 1999. Fire regimes in mountain ash forest: evidence from forest age structure, extinction models and wildlife habitat. *For. Ecol. and Manage*. **124**. 193-203.

McKnight, J. S. and R. L. Johnson. 1980. Hardwood management in southern bottomlands. *Forest Farmer* **39**(5). 31-39.

McNeeley, J. A., K. R. Miller, W. V. Reid, R. A. Mittermeier, and T. B. Werner. 1990. Conserving the world's biological diversity. IUCN, Gland, WRI, CI, SSF-US, and the World Bank. Washington, D. C.

Meadows, J. M. and J. A. Stanturf. 1997. Silvicultural systems for southern bottomland hardwood forests. *For. Ecol. and Manage*. **90**. 127-140.

Melillo, J. M., I. C. Prentice, C. D. Farquhar, E.-D. Schulze, and O. E. Sala. 1996. Terrestrial biotic responses to environmental change and feedbacks to climate. *In* J. T. Houghton, L. G. Meira Filho, B. A. Callander, N. Harris, A. Kattenberg and K. Maskell (eds.), *Climate Change 1995-The Science of Climate Change*. Cambridge University Press. Cambridge. 445-481.

Miguchi, H. and K. Maruyama. 1984. Ecological studies on a natural beech forest (XXXVI) Development and dynamics of beech nuts in a mast year. *J. Jpn. For. Soc*. **66**. 320-327.*

Minami, K. (ed.). 1995. *Global Environmental Change and Agriculture and Forestry*. Asakura Shoten. Tokyo. 176pp.**

Mitchell, C. P., E. A. Stevens, and M. P. Watters. 1999. Short-rotation forestry-operations, productivity and costs based on experience gained in the UK. *For. Ecol. and Manage*. **121**. 123-136.

Miura, S. and S. Horino. 1996. Damage in agriculture and forestry by sika deer and their population control. *Plant Protection* **3** (1996). 171-181.**

Miyagawa, K., M. Araki, S. Kobayashi, M. Kato, and K. Arimitsu. 1987. Effects of soil conservation in multi-storied *Chamaecyparis obtusa* stands (I) Differences of ground cover and surface soils in *Chamaecyparis obtusa* stands treated with different methods in Imaichi. Trans. 98th Ann. Mtg. Jpn. For. Soc. 15-218.**

Miyagawa, K. and M. Araki. 1988. Effects of soil conservation in multi-storied *Chamaecyparis obtusa* stands (IV) Differences of ground cover and surface soils in *Chamaecyparis obtusa* stands treated with different methods at Mt. Fuji. Trans. 99th Ann. Mtg. Jpn. For. Soc. 157-160.**

Miyagawa, K. and M. Araki. 1989. Effects of soil conservation in multi-storied *Chamaecyparis obtusa* stands (VI) Differences of ground cover and surface soil in a multi-storied stand of *Zelkova serrata* (overstory) and *Chamaecyparis obtusa* (understory) and a single-storied *Chamaecyparis obtusa* stand in Kawazu, Izu. Trans. 100th Ann. Mtg.

Jpn. For. Soc. 221-224.**

Miyagawa, K. and M. Araki. 1990. Effects of soil conservation in multistoried *Chamaecyparis obtusa* stands (VIII) Changes of ground cover and surface soils in a harvested *Chamaecyparis obtusa* stand. Trans. 101th Ann. Mtg. Jpn. For. Soc. 61-64.**

Miyawaki, A. 1985. The Phisiological optimum and the ecological optimum. *In* M. Numata (ed.), *Outlines of Modern Biology*. Nakayama Shoten. Inc. Tokyo. 41-43.**

Möller, A. 1922. *Der Dauerwaldgedanke*. Sein Sinn und Bedeutung. Springer Verlag. Heidelberg. (Interpreted into Japanese by K. Hirata, 1937)

Monsi, M. and T. Saeki. 1953. Uber den Lichtfaktor in den Pflazengesellschaften und seine Bedeutung für die Stoffproduktion. *Jpn. J. Botany* **14**(1). 22-52.

Mori, T. 2000. Effects of droughts and forest fires on *Dipterocarps* forest in East Kalimantan. *In* E. Guhardja, M. Fatawi, M. Sutisna, T. Mori, and S. Ohta (eds.) *Rainforest Ecosystems of East Kalimantan*. Springer-Verlag. Tokyo. Ecological Studies 140. 29-45.

Mori, T., T. Nakashizuka, T. Sumizono, and S. K. Yap. 1990. Growth and photosynthetic responses to temperature in several Malaysian tree species. *Journal of Tropical Forest Science* **3**(1). 44-57.

Morikawa, Y., S. Sasaki, and S. Asakawa. 1983. Special composition of light on the forest floor and the growth of tree seedlings. *Jpn. J. For. Environment*. **25**. 1-7.**

Morikawa, Y., S. Hattori, and Y. Kiyono. 1986. Transpiration of a 31-year-old *Chamaecyparis obtusa* Endl. stand before and after thinning. *Tree Physiology* **2**. 105-114.

Mueller-Dombois, D. 1986. Perspective for an etiology of stand level dieback. Annual Review of Ecology and Systematics 17. 221-241.

Mueller-Dombois, D. 1992a. A natural dieback theory, cohort senescence as an alternative to the decline disease theory. *In* P. D. Manion and D. Lachance (ed.), *Forest Decline Concepts*. APS Press. St. Paul, Minesota. 26-37.

Mueller-Dombois, D. 1992b. Potential effects of the increase in carbon dioxide and climate change in the dynamics of vegetation. *Water, Air, and Soil Pollution* **64**. 61-79.

Mutch, R. W. 1970. Wildland fires and ecosystem - a hypothesis. *Ecology* **51**. 1046-1051.

Nabuurs, G. J. 1996. Significance of wood products in forest sector carbon balance. *In* M. J. Apps and D. T. Price (eds.), F*orest Ecosystems, Forest Management and the Global Cycle*. Springer-Verlag. Berlin. 245-255.

Nakamura, K. 1956. *Silviculture*. Kinbara Shuppan. Inc. Tokyo. 342pp.**

Nakamura, M. 1954. Forest fire and its defense. Japan Fire Defense

Administration Research Society. 220 pp.**

Nakamura, H. and T. Kobayashi. 1984. Who makes mizunara forests. *Anima*, 1984(10). 22-27.**

Nakano, H. 1971. Effect on streamflow of forest cutting and change in regrowth on cut-over area. Bull. Gov. For. Exp. Sta. 240. 1-125.*

Nakano, M. 1971. New techniques of natural regeneretion for birch-Mainly for dakekanba (*Betura ermanii*). In T. Yanagisawa, K. Yamaya, M. Nakano, T. Maeda, K. Miyagawa, R. Kato, and N. Ogata. *New Techniques of Natural Regeneration*. Sobun. Inc. Tokyo. 131-186.**

Nakashizuka, T. 1991. Ecology of beech forests. *In* H. Murai, K. Yamaya, H. Kataoka, and M. Yui (eds.), *Natural Environment and Conservation of Beech Forests*. Soft Science. Inc. Tokyo. 89-95.**

Nakashizuka, T. and S. Iida. 1996. Species diversity in coppice. *In* A. Kameyama (ed.), *Vegetation Control of Coppice*. Soft Science, Inc. Tokyo. 17-24.**

Nakashizuka, T. and Yamamoto, S. 1987. Natural disturbance and the stability of a forest community. *Jpn. J. Ecol.* **37**. 19-30.*

Neilson, R. P. and L. H. Wullstein. 1983. Biogeography of two southwest American oaks in relation to atmospheric dynamics. *Journal of Biogeography* **10**. 275-297.

Neilson, R. P. 1995. A model for predicting continental-scale vegetation distribution and water balance. *Ecological Applications* **5**(2). 362-385.

Newton, P. F. 1997. Stand density management diagrams: Review of their development and utility in stand-level management planning. *For. Ecol. and Manage.* **98**. 251-265.

Nobuchi, T., Y. Kamizono, and H. Harada. 1976. Cytological changes of parenchyma cells associated with heartwood formation-On three softwood species, sugi, momi, and akamatsu. Bull. Kyoto Univ. Forests. 48. 178-186.*

Noss, R. F. 1990. Indicators for monitoring biodiversity: A hierarchical approach. *Conservation Biology* **4**. 355-364.

Numata, M. 1974. Conception of plant succession study. *In* M. Numata (ed.), *Succession and Its Mechanisms of Communities*. Asakura Shoten, Inc., Tokyo. 1-11.**

Nykvist N. and K. Rosen. 1985. Effect of clear-felling and slash removal on the acidity of northern coniferous soils. *For. Ecol. and Manage.* **11**. 157-169.

Ochiai, Y., I. Takeuchi, and T. Ando. 1987. Crown snow damage of understory trees in multi-storied forests. Trans. 38th Ann. Mtg. Kansai Jpn. For. Soc. 267-270.**

Odum, E. P. 1971. *Fundamentals of Ecology*, 3rd ed. W. B. Sunders. Philadelphia. 574pp.

Ogata, N. 1971. New techniques for natural regeneration of hinoki. *In* T. Yanagisawa, K. Yamaya, M. Nakano, T. Maeda, K. Miyagawa, R.

Kato, and N. Ogata. *New Techniques of Natural Regeneration*. Sobun. Inc. Tokyo. 301-340.**

Ogawa, H. 1977. Principles and methods of estimating primary production in forests. *In* T. Shidei and T. Kira, *JIBP Synthesis 16. Primary Productivity of Japanese Forests*. University of Tokyo Press. Tokyo. 29-37.

Ogawa, H., K. Yoda, and T. Kira. 1961. *Nature and Life, S. E. Asia* **1**. 21-157.

Ogawa, H. and T. Kira. 1977. Methods of estimating forest biomass. *In* T. Shidei and T. Kira, *JIBP Synthesis 16. Primary Productivity of Japanese Forests*. University of Tokyo Press. Tokyo. 15-25.

Ohba, K. 1992. Forest tree breeding, seed orchard and scion garden. *In* A. Kawana, H. Kataoka, Y. Kakubari, G. Iwatsubo, Y. Aiba, K. Ohba, H. Hashizume, K. Migita, S. Sasaki, K. Nogami, T. Ando, T. Ito, S. Sudo, K. Yoshikawa and H. Watanabe. *Silviculture*. 3rd ed. Asakura Shoten. Inc. Tokyo. 53-67.**

Ohta, S. 2000. Conservation of forest soils. *In* T. Fujimori (ed.), *Strategies for Mitigation of Global Worming*. Hakuyusha Inc. Tokyo. 102-131.**

Ohta, T. 1986. Social benefit of forests and forest management-Function of forests for prevention of sediment disaster. *Bull. Japan Association for Forest Planning*. **298**. 16-26.**

Ohta, T. 1991. Model of forest management for soil conservation. *Shinrin Kagaku (Bull. Jpn. For. Soc.)* **3**. 36-40.**

Okabe, H. 1997. Mycorrhizal fungi associated with plant roots. *In* Soil Microorganisms Study Group (ed.), *New, Soil Microorganisms (2) Growth of Plants and Microorganisms*. Hakuyusha Inc., Tokyo. 75-111.**

Okazaki, A. 1995. *A Record of Trip for Gardening in Germany*. Yokendo, Inc. Tokyo. 189.**

Oliver, C. D. 1981. Forest development in North America following major disturbances. *For. Ecol. and Manage*. **3**. 153-168.

Oliver, C. D. 1992. A landscape approach-Achieving and maintaining biodiversity and economic productivity. *Journal of Forestry* **90**(9). 20-25.

Oliver, C. D., A. D. Adams, and R. J. Zaspski. 1985. Disturvance patterns and forest development in a recent deglaciated vally in the northwestern Cascade Range of Washington, U.S.A. *Can. J. For. Res.* **15**. 221-232.

Oliver, C. D. and B. Larson. 1990. *Forest Stand Dynamics*. McGraw-Hill, Inc., NewYork. 467pp.

Onaka, F. 1950. The longitudinal distribution of radial increments in trees. Bull. Kyoto Univ. Forests. 18. 1-53.*

Ono, T., S. Takemoto, and K. Osawa. 1994. Low thinning and the development of epicomic buds in hardwood. *Hoppo Ringyo* **46**(2). 24-

26.**

Onodera, H. 1990. *Snow and Forests*. Extension series of forest research 96. Forest Development Technical Institute. Tokyo. 81pp.**

Oohata, S. 1996. Material production mechanisms of forests. *In* G. Iwatsubo (ed.), *Forest Ecology*. Buneido, Inc. Tokyo. 84-104.**

Oohata, S. and K. Shinozaki. 1979. A static model of plant form. Further analysis of the pipe model theory. *Jpn. J. Ecol.* **29**. 323-335.

Osako, Y., T. Tsutsumi, and T. Nobuchi. 1974. Studies on forest management from the viewpoint of wood qiality (2) Development of Botan in connection with pruning. Bull. Kyoto Univ. Forests. 46. 103-114.*

Osako, Y., T. Tsutsumi, T. Nobuchi, and M. Morita. 1978. Studies on the forest management from the viewpoint of wood quality (3) Development of Botan in connection with the season of pruning. Bull. Kyoto Univ. Forests. 50. 69-78.*

Osawa, A. 1992. Development of a mixed-conifer forest in Hokkaido, Northern Japan, following a catastrophic windstorm: A "pararell" model of plant succession. *In* M. J. Kelty, B. C. Larson, and C. D. Oliver (eds.), *The Ecology and Silviculture of Mixed-species Forests*. Kluwer Academic Publishers. Dordrecht. 29-52.

Osawa, A., M. Ishizuka, and Y. Kanazawa. 1991. A profile theory of tree growth. *For. Ecol. and Manage*. **41**. 33-63.

Osawa, M. 1937. Growth of climbers in plantations and their control. *Goryorin* **108**. 6-27.**

Osumi, Y., K. Arimitsu, M. Matsui, and R. Hirayama. 1973. Effects of forest cutting on the soil environment (I) Subalpine coniferous forests on the Pacific Ocean side of Japan. Trans. 84th Ann. Mig. Jpn. For. Soc. 100-102.**

Osumi, K., M. Mori, K. Sito, and S. Sakurai. 1995. Growth of mature sugi plantations in Akita district. Proceedings of summary for 106th Ann. Mtg. of Jpn. For. Soc. 453.**

Outcalt, K. W. and E. H. White. 1981. Understory biomass and nutrients 2 years after timber harvest in northern Minnesota. *Canadian J. For. Res.* **11**. 305-308.

Paustian, K., O. Andren, H. H. Janzen, R. L .P. Smith, G. Tian, H. Tiessen, M. V. Noordwijk, and P. L. Woomer. 1997. Agricultural soils as a sink to mitigate CO_2 emissions. *Soil Use and Management* **13**. 230-244.

Perreault, F. N., J. G. Brouillette, and D. Robert. 1993. Quebec's new-policy-no herbicides, larger seedlings-rationale and economics. *In*: Proc. 1993 Meeting of the Forest Nursery Association of British Columbia, Courtenay, B. C., 27-32.

Perry, D. A. 1994. *Forest Ecosystems*. The Johns Hopkins University Press Ltd., London. 649pp.

Pickett, S. T. A. and P. S. White (eds.). 1985. *The Ecology of Natural*

Disturbance and Patch Dynamics. Academic. Inc. New York. 472pp.

Pinard, M. A. and F. E. Putz. 1994. Vine infestation of large remnant trees in logged forests in Sabah, Malaysia: biomechanical facilitation in vine succession. *Journal of Tropical Forest Science* **6**. 302-309.

Piussi, P. and E. P. Farrell. 2000. Interaction between society and forest ecosystems: challenges for the near future. *For. Ecol. and Manage.* **132**. 21-28.

Plochmann, R. 1984. Air pollution and the dying forests of Europe. *American Forests* **90**. 17-21.

Ramstedt, M. 1999. Rust disease on willows - virulence variation and resistance breeding strategies. *For. Ecol. and Manage.* **121**. 101-111.

Rapraeger, E. F. 1939. Development of branches and knots in weatern white pine. *J. For.* **37**. 239-245.

Riviere, A. 1982. Invasion and recovery of plants after the 1977-1978 eruption of Usu volcano, Hokkaido, Japan. A preriminary note. *Environ. Sci. Hokkaido*, **5**. 197-209.

Rosenzweig, C. and M. L. Perry. 1994. Potential impact of climate change on world food supply. *Nature* **367**. 133-138.

Roxburgh, S. and I. Noble. 2001. Terrestrial ecosystems. *In* S. A. Levin (ed.), *Encyclopedia of Biodiversity*. Volume 5 (R-Z). Academic Press. San Diego. 637-646.

Runkle, J. R. 1981. Gap regeneration in some old-growth forests of the eastern United *States. Ecology* **62**. 1041-1051.

Saito, M. J. Minai, and C. Ishido. 1986. Snow damage in Asakawa Experiment Forest on March 23, 1986. Trans. 38th Ann. Mtg. of Kanto Jpn. For. Soc. 125-128.**

Sakai, A. 1982. *Plant Cold Hardiness and Cold Acclimation-Physiology and Ecology in Winter*. Gakkai Shuppan Center. Tokyo. 469pp.**

Sakaguchi, K. 1952. *Silviculture of Chamaecyparis obtusa*. Yokendo, Inc., Tokyo. 339pp.**

Sakaguchi, K. 1953. *Nurseries*. Forestry course 12. Asakura Shoten. Inc. Tokyo. 149pp.**

Sakaguchi, K. (ed.). 1975. *Forest Management for the Future*. National Forestry Extension Association in Japan. Tokyo. 444pp.**

Sakaue, T. 1984. Stand regeneration after clearcutting beech forest (1) *Betula maximovicziana* invation into poorly growing *Cryptomeria japonica* plantations. Trans. 32th Ann. Mtg. of Chubu Jpn. For. Soc. 155-158.**

Sakio, H. 1995. Dynamics of riparian forest region with respect to stream disturbance and life-history strategy of trees. *Jpn. J. Ecol.* **45**. 307-310.**

Sakio, H., F. Nakamura, and Y. Oshima. 1995. Overview of studies on riparian vegetation; past, present and future perspective. *Jpn. J. Ecol.* **45**. 291-294.**

Sakurai, S. 1990. Planting. *In* Forest Agency (ed.), *Forestry Techniques Handbook.* National Forestry Extension Association in Japan. Tokyo. 489-517.**

Sakurai, S. 1994. Management of mizunara forests. *In* T. Fujimori and T. Kawahara (eds.), *Management of Hardwood Forests.* National Forestry Extension Association in Japan. Tokyo. 57-75.**

Sakurai, S. and K. Saito. 1989. Development of natural regeneration methods by the seed-tree method (In Dvelopment of swalog production method for main hardwood species such as *Quercus crispula*). Research Report of Agriculture and fisheres Research Councel Secretariat. 206. 17-23.**

Sanada, E. and M. Takahashi. 1995. Carbon accumulation in forest soils on the Pacific Ocean side of Japan. *Hoppo Ringyo.* **47**(12). 279-271.**

Sanada, E. and M. Takahashi. 1996. Material cycling in the A_0 layer of coniferous palantations and natural forests. *Hoppo Ringyo.* **48**(1). 15-16.**

Sasaki, S. 1982. Site and forest type of tropical rain forests in Malaysia. *Tropical Agriculture Research Series* **43**. 74-77.

Sasaki, S. 1992. Biomass silviculture. *In* A. Kawana, H. Kataoka, Y. Kakubari, G. Iwatsubo, Y. Aiba, K. Ohba, H. Hashizume, K. Migita, S. Sasaki, K. Nogami, T. Ando, T. Ito, S. Sudo, K. Yoshikawa, and H. Watanabe. *Silviculture.* Asakura Shoten. Tokyo. 116-126.**

Sasaki, Y. 1986. How to establish kunugi plantations. *In* S. Asakawa and Y. Kuroda (eds.), Silvicultural *Practices for Hardwood Forests.* National Forestry Extension Association in Japan. Tokyo. 188-202.**

Sathaye, J., M. Cannell, and P. Kauppi. 1996. Management of forests for mitigation of greenhouse gas emissions. In the Second Assessment Report of IPCC Workung Group II. Cambridge University Press. New York. 773-797.

Sato, K. 1962. *Pines in Japan. 2. Natural regeneration.* Forestry extension books. 15. National Forestry Extension Association in Japan. Tokyo. 190pp.**

Sato, K. 1971. *Hinoki in Japan (1).* National Forestry Extension Association in Japan. Tokyo. 275pp.**

Satoo, T. 1983. *Silviculture.* Buneido Inc. Tokyo. 288pp.**

Satoo, T. and T. Takegoshi. 1952. Seasonal change of starch content in *Quercus myrsinaefolia and Q. acutissima.* Bull. Tokyo Univ. For. 9. 17-23.*

Schabel, H. G. and S. L. Palmer. 1999. The Dauerwald: Its role in the restration of natural forests. *Journal of Forestry* **97**. 20-25.

Schimel, D., D. Alves, I. Enting, M. Heimann, F. Joos, D. Raynaud and T. Wigley. 1996. *In* J. T. Houghton, L. G. Meira Filho, B. A. Callander, N. Harris, A. Kattenberg, and K. Maskell (eds.), CO_2 and Carbon Cycle. Climate Change 1995-*The Science of Climate Change.* Cambridge

University Press. Cambridge. 76-86.

Schimel, D., J. Melillo, H. Tian, A. D. McGuier, D. Kicklinger, T. Kittel, N. Rosenbloom, S. Running, T. Thornton, D. Ojima, W. Parton, R. Kelly, M. Sykes, R. Nielson, and B. Rizzo. 2000. Contribution of increasing CO_2 and climate to carbon storage by ecosystems in the United States. *Science* **287**. 2004-2006.

Schlaepfer, R., J. Innes, R. Stewart, and F. Langevin. 1993. Workshop on Environmental Criteria/Indicators for the sustainable development of boreal and temperate forests. Document by the chairman, repporteur, scientific assistant, and CSCE seminar secretariat for a seminar held at Montreal, Canada in September, 1993.

Schnitzler, A. and F. Borlea. 1998. Lessons from natural forests as keys for sustainable management and improvement of naturalness in managed broadleaved forests. *For. Ecol. and Manage.* **109**. 293-303.

Schoonmaker, P. and A. Mckee. 1988. Species composition and diversity during secondary succession of coniferous forests in the western Cascade Mountains in Oregon, *Forest Science* **94**. 960-979.

Schutt, P. and E. B. Cowling. 1985. Waldsterben, a general decline of forests in central Europe: Symptoms, development and probable causes. *Plant Desease* **69**. 1-9.

Shidei, T. 1965. Countermesures for forest disasters. *In* K. Sakaguchi and S. Ito (eds.), *Silviculture Handbook*. Yokendo Inc., Tokyo. 720-727.**

Shidei, T. 1985. *Forests*. Publication Department of Hosei University. Tokyo. 291pp.**

Shimaji, K. and T. Higuchi. 1978. Formation of xylem. *In* T. Satoo and T. Tsutsumi (eds.), Tree-Architecture and Function. Buneido. Tokyo. 40-101.**

Shimaji, K. and S. Kurata. 1978. Tree architecture and its formation. *In*. T. Sato and T. Tsutsumi (eds.), *Tree-Architecture and Function*. Buneido. Tokyo. 10-40.**

Shimizu, T., M. Fujieda, A. Kikuya., and T. Kishioka. 1986. Water quality of forest and quarry watersheds in the headwater areas of the Sakura river-Water temperature, pH, electrical conductivity, turbidity. Trans. 37th Ann. Mtg. Kanto Jpn. For. Soc. 173-176**

Shimizu, T., M. Fujieda, and M. Kato. 1994. Water yield, flood control, and water quality conservation. *In* Forest Science Working Group (ed.), *Present and Future View of Forest Science*. National Forestry Extension Association in. Japan. 72-75.**

Shimizu, T. and S. Yoshino. 1997. Effect of contour-line strip-cutting of trees on snowmelt runoff. *J. Jpn. Soc. of Snow and Ice* 58(1). 3-10.*

Shinozaki, K. 1959. Self-thinning. *In* M. Numata (ed.), *Forest Ecology* (1). Kokon-Shoin, Inc. Tokyo. 178-180.*

Shinozaki, K. and T. Kira. 1956. Intraspecific competition among higher plants. VII. Logistic theory of the C-D effect. Jour. Inst. Polyteck.

Osaka City Univ. Ser. D.7. 35-72.

Shinozaki, K. and T. Kira. 1961. Intraspecific competition among higher plants. X. The C-D rule, its theory and practical uses, Jour. Biol. Osaka City Univ. 12. 69-8.

Shinozaki, K., K. Yoda, K. Hozumi, and T. Kira. 1964a. A quantitative analysis of plant form-the pipe model theory I. Basic analysis. *Jpn. J. Ecol.* **14**(3). 97-105.

Shinozaki, K., K. Yoda, K. Hozumi, and T. Kira. 1964b. A quantitative analysis of plant-form pipe model theory II. Further evidence of the theory and its application in forest ecology. *Jpn. J. Ecol.* **14**(4). 133-139.

Sinclair, W. A. 1965. Comparison of recent declines of white ash, oaks and sugar maple in the north eastern woodlands. Cornell Plantations. Ithaca. NY. 20. 62-67.

Skelley, J. M. 1989. Forest decline versus tree decline-The pathological considerations. *Environmental Monitoring and Assesment* **12**. 23-27.

Slabaugh, P. E., 1957. Effect of live crown removal on the growth of Red Pine. *Journal of Forestry* **55**. 904-906.

Smidt, M. F. and K. J. Puettmann. 1998. Overstory and understory competition after underplanted eastern white pine. *For. Ecol. and Manage.* **105**. 137-150.

Smith, D. M. 1986. *The Practice of Silviculture.* 8th ed., John Wiley & Sons, Inc., New York. 527pp.

Spies, T. A., J. F. Franklin, and T. B. Thomas. 1988. Coarse woody debris in Douglas-fir forests of western Oregon and Washington. *Ecology* **69**(6). 1689-1702.

Spies, T. A. and J. F. Franklin. 1991. The structure of natural young, mature, and old-growth Douglas-fir forests in Oregon and Washington. Wildlife and vegetation of unmanaged Douglas-fir forests. U.S.D.A. Forest Searvice. Pacific Northwest Research Station. General Technical Report PNW-GTR-285. 91-109.

Sprugel, D. G., T. M. Hinkley, and W. Schaap. 1991. The theory and practice of branch autonomy. *Annu. Rev. Ecol. Syst.* **22**. 309-334.

Spurr, S. H. and B. V. Barnes. 1980. *Forest Ecology.* 3d ed., John Wiley & Sons, Inc., New York. 687pp.

Study Group on *Forests and Water* in Forestry Agency of Japan. 1996. Forests and Water. Japan Forest Conservation and Flood Control Association. Tokyo. 115pp.**

Sugimura, K. and I. Noda. 1992. Landscape management of the Arashiyama National Forest, Kyoto, Japan: An evaluation of alternatives. *In* R. Tabata, J. Yamashiro, and G. Cherem (eds.), *Proceedings of the Heritage Interpretation International Third Global Congress.* University of Hawaii, Sea Grant College Program. 380-382.

Suzuki, M. 1994. Water and energy cycling and forests. In proceedings of a seminor, promotion of forest treatment. Japan Water Conservation and Erosion Control Society and Japan Forest Road Society. 54-72.**

Suzuki, W. 1984. Tree damage caused by vines in Hinoki plantations. Bull. For. & For. Prod. Res. Inst. 323. 145-155*

Suzuki, W. 1989. Tree damage caused by climbing plants and the mechanizm of their development in Hinoki plantations. *J. Jpn. Soc.* **71**(10), 395-404**

Swank, W. T., L. W. Swift, Jr., and J. E. Douglas. 1987. Streamflow changes associated with forest cutting, species conversions, and natural disturbances. *In* T. Wayne, D. A. Swank, and D. A. Crossley, Jr. (eds.), *Forest Hydrology and Ecology at Coweeta.* Springer-Verlag, Inc. New York. 297-312.

Swanson F. J. and J. F. Franklin. 1992. New Forestry principles from ecosystem analysis of Pacific Northwest forests. *Ecological Applications* **2**(3). 262-273.

Tadaki, Y. 1964. Effect of thinning on stem volume yield-studies with competition density. Bull Gov. For. Exp. Sta. 166. 1-22.*

Tadaki, Y. and T. Shidei. 1960a. Proposal of production structure diagram for stem volume (1). Trans. 70th Ann. Mtg. Jpn. For. Soc. 294-295.**

Tadaki, Y. and T. Shidei. 1960b. Proposal of production structure diagram for stem volume (2). Trans. 70th Ann. Mtg. Jpn. For. Soc. 295-297.**

Tadaki, Y. and Hatiya, K. 1968. *Forest Ecosystems and Their Productivity.* Series of comments for studies on forestry 95. Forest Development Technical Institute. Tokyo. 64pp.**

Tadaki, Y., A. Sato, S. Sakurai, I. Takeuchi, and T. Kawahara. 1977. Studies on the production structure of forests. XVII. Structure and primary production in subalpine "dead tree strips" *Abies* forest near Mt. Asahi. *Jpn. J. Ecol.* **27**. 83-90.*

Tadaki, Y., Y. Takeuchi, T. Kawahara, A. Sato, and K. Hatiya. 1979. Growth analysis of natural stands of Japanese red pine (*Pinus densiflora*) III. Results of experiment. Bull. For. & For. Prod. Res. Inst. 305. 121-144.*

Tagawa, H. 1964. A study of the volcanic vegetation in Sakurajima, Southwest Japan. I. Dynamics of vegetation. Mem. Facult. Sci. Kyushu Univ. Ser. E, 3. 165-228.

Takahashi, I. 1991. Studies on the mycofloral succession on Yezo spruce (*Picea jezoensis* Carr.) in various stages of growth, with special reference to the role of fungi in natural regeneration of the host. Bull. Tokyo Univ. Forests. 86. 201-273.*

Takahashi, K. 1971. *Weather of Japan.* Iwanami Shinsho 489. Iwanami Shoten, Inc., Tokyo. 220pp.**

Takahashi, N. 1971. *Silvicultural Methods for Stands-Theory and Practice.* National Forestry Extension Association in Japan. Tokyo. 127pp.**

Takahashi, T. 1996. Study on the soil productivity and nutrient dynamics of Japanese cypress (*Chamaecyparis obtusa*) plantations, Doctral thesis. The United Graduate School of Agricultural Science. Tokyo University of Agriculture and Technology. 137pp.**

Takeshita, K. and J. Takagi. 1977. Soil physical and topographical study. Bull. Fukuoka Prefecture For. Exp. Sta. 26. 1-51.**

Takeuchi, I. 1987. Cutting to controll light conditions and planning large size nursery stock-Present situation of production of large size nursery stock by high density control. *Ringyo Gijutsu* **546**. 11-12.**

Takeuchi, I. and K. Hatiya. 1977a. Effect of pruning on growth (I) A pruning experiment on model stands of *Cryptomeria Japonica*. *J. Jpn. For. Soc.* **59**(9). 313-320.*

Takeuchi, I and K. Hatiya. 1977b. Studies on occlusion after artificial pruning. Bull. Gov. For. Exp. Sta. 292. 161-180.*

Tamate, S., T. Kashiyama, T. Sasanuma, K. Takahashi, and H. Matsuoka. 1977. Distribution maps of forest wind damage by Typhoon No 15, 1954 in Hokkaido. Bull. Gov. For. Exp. Sta. 289. 43-67.*

Tamm, C. O. 1951. Seasonal variation in composition of birch leave. *Physiolo.* Plant. 4. 461-469.

Tanaka, S., K. Osawa, and S. Takemoto. 1989. Low thinning and the resulting epicomic buds in a mizunara forest. *Hoppo Ringyo* **41**(4). 85-90.**

Tanimoto, T. 1982. Fundamental studies on release cutting in forest plantations (I) Analysis of growth of *Cryptomeria japonica* and natural vegetation in a young *Cryptomeria japonica* plantation. Bull. For. & For. Prod. Res. Inst. No. 320. 53-121.*

Tanimoto, T. 1983. Fundamental studies on release cutting in forest plantations (II) Relationship between planted trees and weed community in a young plantation of *Cryptomeria japonicai*-Theoretical analysis and its practical consideration. Bull. For. & For. Prod. Res. Inst. No. 324. 55-79*

Tanimoto, T. 1990. *Ecology for Hardwood Management.* Message from forests 5. Sobun, Inc., Tokyo. 245 pp.**

Tanimoto, T. 2000. The oldest hardwood forest in Europe near Paris. *Zuiso Shinrin* **43**. 39-41. **

Tanimoto, T., K. Miyagawa, and T. Maeda. 1987. Regeneration after shelterwood strip cutting in a subalpine coniferous forest in Yatsugatake mountaines, central Japan. *In* T. Fujimori and M. Kimura (eds.), *Human Impact and Management of Mountain Forests.* Forestry and Forest Products Research Institute, Ibaraki, Japan. 361-371.

Taoda, H. 1990. *Structure of Forests.* Forestry extension books 105. National Forestry Extension Association in Japan. Tokyo. 173pp.**

Taoda, H. 1994. Management of shii and kashi forests. *In* T. Fujimori and T. Kawahara (eds.), *Management of Hardwood Forests.* National

Forestry Extension Association in Japan. Tokyo. 98-113.**

Taylor, A. R., 1974. Forest fire. *In* D. N. Lapedes (ed.), *MacGraw-Hill Yearbook of Science and Technology*. McGrow-Hill Book Co., Inc., New York (Refered from Spurr and Barnes, 1980. *Forest Ecology*. 3rd ed., John Wiley & Sons, Imc., New York).

Toda, M. 1987. Stratified structure of drosophilid flies in forests. *In* S. Kimata and H. Takeda (eds.), *Insect Communities in Japan*. Tokai Univ. Press. Tokyo. 133-140.**

Toma, T. 1998. Large scale El Niño and forest fire in Indonesia. *Sience Journal Kagaku* **68**. 920-924.**

Toma, T. 1999. Exceptional droughts and forest fires in easrern part of Borneo Island. *Tropics* **9**(1). 55-72.*

Toyooka. H. 1977. Damage of planted trees by climbers and their control. *Ringyo Gijutsu* **436**. 12-15.**

Toyooka, H., M. Ishizuka, A. Sato, J. Samejima, and K. Hayashi. 1983. Change of forest vegetation after the eraption of Mt. Usu (II). Trans. 32th Ann. Mtg. Hokkaido Jpn. For. Soc. 160-162.**

Tsukamoto, Y. 1963. Erosion by raindrops and forests. Report for the studies by the subsidy by agriculture, forestry and fishery studies for fiscal year 1963. 33-45.**

Tsukamoto, Y. 1987. Evaluation of the effect of tree roots on slope stability, Bull. Exp. Forests of Tokyo Univ. of Agriculture and Technology 23. 65-124.*

Tsukamoto, Y. 1991. How forests contribute to prevention of slope failure. *Shinrin Kagaku* (Bull. Jpn. For. Soc.) 3. 45-51.**

Tsukamoto, Y., O. Kusakabe, T. Kido, and K. Komiyama. 1984. Geological structure of hill slope surfaces and the effects of tree roots on slope stability. *J. Jpn. Soc. Reveget. Tech.* **11**(1). 1-7.

Tsumura, S. 1929. Forest damge caused by the eruption of Mt. Koma and the recovery of the forests. Bull. Hokkaido For. Soc. 323. 753-769**

Tsumura, S. 1935. Vegetation 7 years after the eruption of Mt. Koma in Oshima. Bull. Hokkaido For. Soc. 395. 567-575**

Tsutsumi, T. (Group for the study on ecology of natural forest). 1972. Vegetation of the natural forest of Kyoto University. Bull. Kyoto Univ. For. 43. 33-52*.

Tsutsumi, T. 1989. *Life of Forests-Material Cycling Between Trees and the Soil*. Chuko Shinsho 943. Chuokouronsha. Tokyo. 197pp.**

Uchijima, Z. 1982. Distribution of solar energy on farm and forest land. *In* S. Uchijima (ed.), *Agriculture, Forestry, Fishery and Meteorology*. Asakura Shoten. Tokyo. 18-45.**

Uchijima, Z. 1996. *Global Warming and Its Effects*. Shokabo. Tokyo. 202pp.**

Uchimura, M., I. Noda, K. Sugimura and M. Amano. 1991. Landscape analyses and landscape management of the Arashiyama National

Forest (4). Treatment of aethetic forest. Research information of For. & For. Prod. Res. Inst., Kansai Research Center 20. 2.**

Uesugi, T. 1953. Treatment of akamatsu natural forests. Text book for silviculture for pulpwood 2.**

Uhl, C. Kauffman, J. B., and Cummings, D. L. 1998. Fire in the Venezuelan Amazon 2: environmental conditions necessary for forest fires in the evergreen rainforest of Venezuera. *Oikos* **53**. 176-184.

Ushiyama, R. 1954. Thinning method based on breast height-Thinning by Ushiyama method. Bull. Nagano Regional Forestry Office. 21. 12-23.**

Ushiyama, R. 1955. Explanation of thinning by Ushiyama method. Bull. Nagano Regional Forestry Office. 22. 25-32.**

van den Driessche, R., 1991. Influence of container nursery regimes on drought resistance of seedlings following planting. I. Survival and growth. *Can. J. For. Res.* **21**. 555-565.

van der Meer, P. J., P. Dignan, and A. G. Saveneh. 1999. Effect of gap size on seedling establishment, growth and survival at three years in mountain ash (*Eucalyptus regnans*) in Victoria, Australia. *For. Ecol. and Manage.* **117**. 33-42.

Vidal, E., J. Johns, J. J. Gerwing, P. Barreto, and C. Uhl. 1997. Vine management for reduced-impact logging in eastern Amazonia. *For. Ecol. and Manage.* **98**. 105-114.

Vitousek, M. P., J. R. Gozets, C. C. Grier, J. M. Melillo, W. A. Reiners, and R. L. Todd. 1979. Nitrate losses from disturbed ecosystems. 20 *Science* **4**. 469-474.

Wagner, R. G. 1993. Research directions to advance forest vegetation management in North America. *Can. J. For. Res* **23**. 2317-2327.

Waguchi, Y., E. Shibata, Y. Yoda, and T. Sumi. 1992. Snow damage of underplanted trees in a two-storied stand of Japanese cedar, *Cryptomeria japonica. J. Jpn. For. Soc.* **74**(2). 87-90.*

Wahlenberg, W. G. 1950. Epicormic branching of young yellow-poplar. *Journal of Forestry*. September 1950. 417-419.

Walker, D. and G. Singh. 1981. Vegetation history. *In* R. H. Groves (ed.), *Australian Vegetation*. Cambridge University Press. Cambridge. 26-43.

Waring, R. H. and J. F. Franklin. 1979. The evergreen coniferous forests of the Pacific Northwest. *Science* **204**(4400). 1380-1386.

Waring, R. H. and W. H. Schlesinger. 1985. *Forest Ecosystems-Concepts and Management*. Academic Press, Inc., Orlando. 340pp.

Waseda, O. 1975. Non-clearcutting methods (General remarks). *In* K. Sakaguchi (ed.), *Forest Management in the Future*. National Forestry Extension Association in Japan. Tokyo. 360-373.**

Waseda, O. 1981. *Methods of Establishing Multi-storied Forests*. Extension books 77. National Forestry Extension Association in Japan. Tokyo.

249pp.**

Washitani, I. and T. Yahara. 1996. *Introductuin to Conservation Ecology: from Genes to Landscapes*. Bunichi Sogo Shuppan Inc. Tokyo. 279pp.**

Watanabe, S. 1994. *Specia of Trees*. University of Tokyo Press. 450pp.**

Watanabe, S. and S. Sasaki. 1994. The silvicultural management system in temperate and boreal forests: A case history of the Hokkaido Tokyo University Forest. *Can. J. For. Res.* **24**. 1176-1185.

Watson, F. G. R., R. A. Vertessy and R. B. Grayson. 1999. Large-scale modelling of forest hydrological processes and their long-term effect on water yield. 1 *Hydrological Processes* **13**. 689-700.

Watt, A. S. 1947. Pattern and process in the plant community. *J. Ecology* **35**. 1-22.

Wernick, I. K., P. E. Waggoner, and J. H. Ausbel. 1998. Searching for leverage to consearve Forests. The Industrial Ecology of Wood Products in the United States - *Journal of Industrial Ecology* **1**. 125-145.

Wessely, J. 1853. Die Österreichishen alpenlander untihre forsten. Vol. 1. Vienna. 300p.

White, P. S. 1979. Pattern, process, and natural disturbance in vegetation. *Botanical Review* **45**. 229-299.

White, P. S. and S. T. A. Pickett. 1985. Natural disturbance and patch dynamics: An introduction. *In* S. T. A. Pickett and P. S. White (eds.), *The Ecology of Natural Disturbance and Patch Dynamics*. Academic, Inc., New York. 121 pp.

Whittaker, R. H. 1956. Vegetation of the Great Smoky Mountains. *Ecol. Monographs*. **26**(1). 1-80.

Whittaker, R. H. 1970. *Communities and Ecosystems*. The Macmillan Company, Collier-Macmillan Limited. London. 158pp.

Whittaker, R. H., S. A. Levin, and R. B. Root. 1973. Niche, habitat and ecotone. *American Naturalist* **107**. 321-338.

Wilcox, B. A. 1984. In situ conservation of genetic resources: determinants of minimum area requirements. *In* McNeely, J. and K. Miller (eds.), *National Parks, Conservation, and Development: the Role Protected Areas in Sustaining Society*. Smithonian Institution Press. 24-33.

Willson, M. F. 1983. *Plant Reproductive Ecology*. John Willey & Sons, Inc., New York. 282pp.

Wilson, E. O. 1992. *The Diversity of Llife*. Harverd University Press. Canbridge.

Wood, F. B., Jr. 1988. The need for systems research on global climate change. *Systems Research* **5**. 225-240.

Working Group on Multi-storied Forests. 1983. Studies on the treatment of artificial multi-soried forests. Bull. For. & For. Prod. Res. Inst. 323. 218pp.*

Yamada, K. 1975. Silvicultural methods for hiba forests. *In* K. Sakaguchi (ed.), *Forest Management in the Future*. Tokyo. 242-252.**

Yamagata, Y. and K. Yamada. 2000. International trends of project for carbon sequastration in relation to Kyoto Protcol. National Institute for Environmental Studies, Environment Agency of Japan. 131pp.**

Yamaguchi, H. 1989. *Life History of Forest Insects*. Mesage from forests 4. Sobun Inc. Tokyo. 185pp.**

Yamamoto, M. 1986. Low cost management adapted to natural vegetation. *Ringyo Gijutsu* **535**. 42-45.**

Yamamoto, S. 1995. Gap characteristic and gap regeneration in subalpine old-growth coniferous forests, central Japan. *Ecological Research* **10**. 31-39.

Yamauchi, S. and T. Yanagisawa. 1973. Silviculture. *In* Japan Forest Technology Association (ed.), *History of Forestry Technology (3)*. Japan Forest Technology Association. Tokyo. 135-408.**

Yamaya, K. 1993. *Discussion of Forest Management from a Soil Ecosystem Perspective*. Forestry Extension Books 101. National Forestry Extension Association in Japan. Tokyo. 93pp.**

Yanagisawa, T. 1965. Collection of seeds. *In* K. Sakaguchi and S. Itoo (eds.), *Silvicultural Handbook*. Yokendo, Inc., Tokyo. 415-431.**

Yatagai, M. 1995. *Wonder of Forests*. Gendai Shorin, Inc. Tokyo. 221pp.**

Yoda, K., T. Kira, H. Ogawa, and K. Hozumi. 1963. Self-thinning in overcrowded pure stands under cultivated and natural conditions (Intraspecific competition) among higher plants 11). J. Biol. Osaka City Univ. 14. 107-129.

Yokoi, S. 1997. Management of hardwood forests on the basis of clear length (1). *Ringyo Shin Chishiki* **528**. 22-23.**

Yokoi, S. and K. Yamaguchi. 1996. Origin of epicormic branches and effect of thinning on their development in *Quercus crispula*. *J. Jap. For. Soc.* **78**. 169-174.

Yoshida, K. 1983. Heterogeneous environment in a moth community of Tomakomai Experiment Forest, Hokkaido University. *Jap. J. Ecol.* **33**. 445-451.

Young, H. E. and P. J. Kramer. 1952. The effect of pruning on the height and diameter growth of Loblolly Pine. *Journal of Forestry* **50**, 474-479.

Yoshimura, K., T. Akai, I. Manabe, Y. Aiba, T. Sugiura, K. Arimitsu, and N. Honjou. 1981. Flowing drift of litter, soil, and others under artificial rain fall in Hinoki Stands (III) Movement of litter and surface soil in thrifty stands with different process of thinning. Trans. 92th Ann. Mtg. Jpn. For. Soc. 215-216.**

Yuasa, Y., I. Mashimo, and M. Minami. 1981. Vegetation on a site disturbed by avalanche. Trans. 29th Ann. Mitg. Chubu Jpn. For. Soc. 57-60.**

Yui, M. 1994. Coexistence with wildlife. *Shinrin Kagaku* (Bull. Jpn. For. Soc.) **11**. 7-13.**

Yui, M. and N. Ishii. 1994. *Toward the Coexistence between Forestry and Wildlife*. Nihon Ringyo Chosakai. 279pp.**

Zimmermann, M. H. and C. L. Brown. 1971. *Trees-Structure and Function*. Springer-Verlag. New York. 336pp.

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