



Soil health

The foundation
of sustainable
agriculture

*Proceedings of a workshop on
the importance of soil health in agriculture*

WOLLONGBAR AGRICULTURAL INSTITUTE
20-21 JUNE 2001





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Editor: Rebecca Lines-Kelly, NSW Agriculture



Foreword

How do you know if your soil is healthy? What are the characteristics and functions of healthy agricultural soils? These are broad questions that challenged scientists, farmers and consultants at a soil health workshop held over two days in June 2001 at Wollongbar Agricultural Institute. The workshop attracted interest from both farmers and specialists in soil biology, soil chemistry, soil physics, agronomy, horticulture, extension, plant pathology and microbiology. The program was organised into sessions on soil biology, soil chemistry, soil physics, farming systems, and extension. These proceedings collate more information than was possible to present at workshop and should serve as a valuable reference for the whole community.

The workshop aimed to review NSW Agriculture's soil health research and extension activities, identify general soil health issues, identify issues specific to different farming systems that need further attention, and identify strategies to address these issues.

Several key messages emerged from the workshop.

- Healthy agricultural soils are those used within their capability to enhance production without being degraded or degrading their environment.
- The biological, physical and chemical properties of healthy soils enable them to function with resilience to disturbances from agricultural practices and with minimum external inputs.
- To maintain and improve soil health it is necessary to plan for the long term and integrate best practice for erosion control, soil organic matter management, water and nutrient management, and pest and disease management into the production system.
- There needs to be more effective communication of soil health management.

The workshop presentations repeatedly identified that sustainable production systems build and maintain a healthy soil resource. As these proceedings demonstrate, NSW Agriculture has a broad range of expertise and is well positioned to assist agricultural industries and rural communities develop food and fibre production systems that are both economically and environmentally sustainable.

Peter Slavich
Director, Wollongbar Agricultural Institute

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Disclaimer

The information contained in this publication is based on knowledge and understanding at the time of writing, June 2001. However, because of advances in knowledge, users are reminded of the need to ensure that information upon which they rely is up to date and to check currency of the information with the appropriate officer of New South Wales Department of Agriculture or the user's independent adviser.

Cover photo

The soil featured on the front cover is a relatively undisturbed ferrosol (formerly known as krasnozem) derived from basalt. Ferrosols are characterised by high organic matter, high iron content, deep topsoil and very good structure. The profile is located on the NSW north coast's Cudgen plateau, where intensive vegetable production takes advantage of some of Australia's most productive soils. The site was once cultivated but has not been disturbed for many years, and is currently under vegetation. There is a 20 cm A horizon or topsoil over the B horizon or subsoil. While there are few visual indicators of horizon change, laboratory analysis shows marked differences. Topsoil organic carbon is 5.68% compared with 1.96% in the subsoil 65-110 cm below the surface. Topsoil organic matter is 9.4% compared with 3.43% in the subsoil, and cation exchange capacity is 27.8 compared with 6.9 in the subsoil. Topsoil pH_{CaCl2} is 6.1 compared with 4.5 in the subsoil. These analyses, together with the organic litter on the soil surface, the dark soil colour indicating humus, the depth of the soil, and the unobstructed root growth, are indicators of a healthy soil. Photo: David Menard DLWC Altonville.

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Opening address

Helen Scott-Orr
Executive Director, Research Advisory and Education
NSW Agriculture Orange

I am very pleased to be at Wollongbar Agricultural Institute to open this two day workshop focussing on the issue of soil health. This workshop will highlight the fact that soil health is fundamental to productive agriculture. Soils are the basis of agriculture and the basis of our very existence.

NSW Agriculture has substantial investments in soil through specialised soils research and advisory staff as well as our wider agronomic, horticultural, livestock and veterinary staff. Increasingly, our soil chemists and physicists are being joined by scientists developing expertise in soil microbiology and soil entomology.

Many people think of soils as 'just dirt' and cannot imagine that they are interesting. But the study of microorganisms and wildlife in soil is a new frontier. We need someone like David Attenborough to put soils under the fiberoptic camera, and film the dynamic fascination of soil life for the world to see.

To fully understand soils, we need to get a better picture of the complexity of interactions between soil fauna like earthworms and beetles, microorganisms, the soil chemistry and physical attributes. A balanced interaction is the basis of healthy soil life, and therefore the basis of healthy food production.

Aside from highlighting the importance of soil health, this workshop will augment the investment NSW Agriculture and the community has in organic farming. Organic practices have developed from years of empirical observations. A requirement exists, now, to scientifically scrutinise many of these practices in order to verify benefits to soil health. Many of the organic practices are targeted at improving soil health and conventional agriculture can also learn from them.

The outcomes of this workshop will be made available at the Organic Farming Workshop at NSW Agriculture's new Centre for Organic Farming at Bathurst in July 2001.

I would like to welcome everyone here today, congratulate the organisers for developing such a stimulating agenda, and declare this workshop open.

Making soils sexy: discovering the erotics of soils

Rebecca Lines-Kelly
Environmental extension coordinator
NSW Agriculture, Wollongbar

Soil is the connection to ourselves. From soil we come, and to soil we return. If we are disconnected from it we are aliens adrift in a synthetic environment. It is the soil that helps us to understand the self-limitations of life, its cycles of death and rebirth, and the interdependence of all species. To be at home with the soil is truly the only way to be at home with ourselves, and therefore the only way we can be at peace with the environment and all of the earth species that are part of it. It is, literally, the common ground on which we all stand. Frederick Kirschenmann 1997

When I joined NSW Agriculture nine years ago, my job was to communicate soils to farmers. I knew nothing about soils, and was a little daunted to say the least, but I soon realised I had found something I had never found in any of my previous jobs, a willingness to give 150% of my effort. I had fallen in love - with soils! We all know what it's like to fall in love - everything becomes effortless, smooth and glorious. Believe it or not, that's how I found soils communication.

In part it was so effortless because farmers love their soils. Their land is their living, their identity, their kingdom, their passport to independence and wealth. They wanted to hear and see everything that would help them understand and know their soils. I learned so much from my conversations with farmers, whose years of experience give them a close knowledge of soils and soil health. But like most of us, they lack the technical knowledge to articulate what is happening under the soil surface.

In my search for soils knowledge, I have worked closely with soil scientists, and found them to be a breed of scientist whose passion for their subject is quite unheard of in some science quarters. Fanatical is a word that would not be out of place for some of the soil scientists I have worked with over the past decade. They are people we should all value as passionate enquirers, searching for the holy grail of soils knowledge.

It seems to be the case that once you get into soils, they inspire passion and commitment and won't let you go, but for the uninitiated, soils are brown, boring, and beneath notice. They are definitely not sexy. But if soils are the common ground we stand on, why aren't they our common knowledge? What can we do, as farmers and scientists passionate about soils, to make them sexier?

When something is sexy, it attracts our interest and attention. In a government context a sexy issue is a hot issue, able to attract funding for research and

management changes. Water reform is a good example, as is salinity. Millions of dollars are being thrown at these issues in an attempt to remediate the problems we have caused. But if you think about it carefully, these issues are sexy because they have become a problem. They weren't sexy when there was plenty of good quality water flowing in our rivers and salinity was confined to the occasional salt depression. They are only sexy now that water quality and quantity is decreasing, and salinity is taking land out of production, threatening water supplies and town infrastructure. It seems to be that a sexy issue is really a problem that needs fixing urgently. It took the dust storms of the 1930s for the US government to act on soil erosion; will it take desertification of our soils through salinity, acidity, clearing, over-cultivation, erosion and inappropriate drainage to make Australian soils really sexy? I hope not.

What we need to do urgently is celebrate our soils, while they are still productive and relatively healthy, by focusing on the sensuousness and erotics of soils, the really sexy qualities! Science philosopher Nicholas Maxwell says that the first lure of science is not its instrumental power, but its magic, its capacity to kindle awe, wonder and the desire for knowledge, for explanation (Broderick 1993). Frederick Kirschenmann, American farmer, government adviser and something of a poet, takes this concept further and says if we are to inspire everyone with love of the soil we must discover the sensuousness and erotics of soil.

Eroticism ... involves a level of 'seeing' that goes beyond ordinary sight-to penetrate the soul of being. Loving soil involves much the same kind of sight. To love soil requires that we see more than dirt. It requires that we become intimately involved with soil - see its life and beauty, smell its rich aroma, hear its voice. Frederick Kirschenmann 1997

The erotics of soil have long been acknowledged in poetry and literature. Soil is a metaphor for life, belonging, groundedness, richness and productivity. Loving the soil is shorthand for recognising our humanity, our fundamental need of land and our desire to worship where we live. In our attempts to know and understand soils, we have used reductionist science to tear them apart, isolate their elements and learn what they comprise, but in doing this we have ignored the essence of soils as living landscapes, providing the means for new life and productivity. Only now are we acknowledging the integral importance of soil biology in understanding soils. Only now are we looking at soil health as the paradigm for knowing and understanding soils, rather than soil nutrients or soil structure alone. Only now are we beginning to 'see' soils and all that they comprise. As Kirschenmann says 'Now scientists are ready to become lovers of the soil—to know it intimately, to care about it. It is this "inner" seeing that helps us to understand the soil as more than a "medium".'

Soil health is a big picture concept, difficult to quantify and measure, but it offers the key to making soils 'sexy'. Soil health provides us with a sensory picture that can flesh out our primal feelings about soil and help us understand them. Farmers who work with their soil every day are expert at recognising soil health.

Any good farmer knows what soil quality is - the capacity of a soil to take in, hold, and cycle nutrients and water, while also providing a healthy environment for root systems...Quality soils till easier than degraded soils, they smell alive and feel crumbly. They take in water faster and hold it longer. Plants take off faster and grow more vigorously...

Charles Benbrook 1997

Benbrook is right: even though farmers may not have the technical terms, they know what a healthy soil is by looking, smelling and feeling. This engagement of the senses is the key to making soils sexy now, while they are still productive and healthy. Engaging our senses is an activity open to all of us, no matter what level of soils knowledge we have. Even if we need the help of scientists in interpreting what we see, smell and feel, we don't have to wait around until scientists are confident they know everything about soil health.

Sight

While we can see soils at the surface, we do not learn much about them until we examine them deeply and in detail. We need to be able to recognise the surface and subsurface indicators and what they mean. Soil pits are good, but it is also important to know how to dig 'mini-monoliths' that don't require machinery. We need to ensure that visual examinations retain the wonder of discovery and revelation, and don't become ho-hum tools for advisers to display their knowledge.

Surface visual indicator	Indicates
colour	organic matter, drainage
cracks	moisture levels, structure
erosion	structure, organic matter levels
groundcover	organic matter, biological activity
insect activity	organic matter, structure
organic layer	organic matter, biological activity
particle size (dust/clods)	moisture levels, structure
ped formation	biological activity, organic matter, structure
plant growth	nutrient levels, structure, pH

Below surface visual indicator	Indicates
colour	organic matter, moisture
compaction	structure
depth of topsoil	fertility
earthworms	organic matter
holes, tunnels, shells, webs, casts	biological activity, porosity
insect activity	organic matter
root channels	porosity
root mass	structure, nutrients

Visual tool	Indicates
dispersion test	sodicity
infiltration test	porosity
monoliths	subsurface appearance
pH test	acidity/alkalinity
slaking test	structure
soil shaken in water	composition

Touch

Touch is a very sensuous tool to use in soils. The erotics of soil is perhaps best experienced by running healthy, friable, living soil through your hands, but there are many other touch and feel tests available.

Activity	Indicates
kicking the dirt	friability, structure, moisture
ribboning soil	clay levels
rubbing between your fingers	dominant soil composition-sand, silt or clay
rubbing between your palms	soil moisture
running hands through soil	friability and health

Smell

Smell is not something we normally associate with soil, but as we learn more about organic matter and soil biology we are realising it is an important indicator of soil life. It too is very sensuous but it is important not to breathe too closely or to deeply around soil, particularly rich organic soil as you may inhale pathogenic bacteria.

Smell	Indicates
earthy smell	presence of actinomycetes (bacteria spp)
rain on dry earth	activation of bacteria spores in the soil
sharp sewagey smell	lack of oxygen and anaerobic bacteria

Soils are only going to be sexy if we become impassioned about them, and engage our hearts as well as our minds in learning about them. We need to inspire everyone, not just farmers and scientists, with an understanding of their fundamental importance to our existence. We can do this by using tools that harness our sensory understanding of our soils- particularly tools based on sight, touch and smell, backed up by good quality scientific knowledge to make sense of that sensory input. We need to acknowledge the complexity and interconnectedness of soil systems, and not look at isolated aspects of soil management on their own. If we do this we will all learn what a healthy, living soil is so that we become more in tune with what our soils need. As a result we will be less inclined to ride roughshod over soils, showing our supposed scientific mastery. Unless we become truly involved with soils, and make them sexy and erotic not only to ourselves but to everyone around us by our passion and commitment, we run the risk of destroying

what feeds us physically and spiritually, and in so doing, destroying ourselves. As a Native American aphorism says: 'If men spit upon the ground they spit upon themselves.'

I'd like to finish with this wonderful quote by US writer Marjorie Harris, who obviously finds soils very sexy.

Project your imagination into the soil below you...Think with compassion of the life that exists there. Think, the drama, the sexuality, the harvesting, the work that carries on ceaselessly. Think about the meaning of being a steward of the earth.

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Appendix 1 Some good websites about soil health

Australian sites

Soilhealth.com

<http://www.soilhealth.com>

This excellent website is run by the Soil Biology Research Group in the Faculty of Agriculture at the University of Western Australia. It aims to answer common questions regarding soil biological processes, organic matter, soil organisms, and the soil management practices that affect these, and provide background information relevant to soil health and sustainable use of land.

Monitoring soil quality in grazed pastures

<http://www.nre.vic.gov.au/agvic/ellinbank/SOILS-12.htm>

Dept of Natural Resources and Environment, Victoria

This site describes a Victorian research project to help dairy farmers assess soil quality and includes the quality indicators used.

Land Management Society soil courses

<http://www.lmsinfo.com/training.htm#ON-FARM-TRAINING-2000>

This site describes the soil quality monitoring courses run by WA's Land Management Society.

Soils zoo

<http://www.waite.adelaide.edu.au/school/Soil/zoo.html>

This site has good quality photographs of different soil organisms.

US sites

Soil quality test kit guide (1999)

United States Dept of Agriculture

<http://www.statlab.iastate.edu/survey/SQL/Attach/KitGuideComplete.pdf>

This is an 80 page book which describes 12 different tests used in assessment of soil quality, together with back-up technical information and interpretations for individual tests.

Soil quality card design guide (1999)

<http://www.statlab.iastate.edu/survey/SQL/cardguide.html>

United States Dept of Agriculture

This site has links to several different soil quality cards designed for on farm use.

Soil quality information sheets (1996)

<http://www.statlab.iastate.edu/survey/SQL/sqiinfo.html>

This site offers a series of information sheets on different aspects of soil quality.

Assessing the pasture soil resource

<http://www.attra.org/attra-pub/pastsoil.html>

This site, run by ATTRIA, Appropriate Technology Transfer for Rural Areas, describes a number of soil assessment techniques.

Soil biology information resources

<http://www.statlab.iastate.edu/survey/SQL/pdf/info.pdf>

This site lists a range of information sources on soil biology.

Soil biology primer

<http://www.statlab.iastate.edu/survey/SQL/SoilBiologyPrimer/index.htm>

This site is an online book on soil biology, providing an overview about the soil foodweb and the different types of soil animals.

Sustainable Farming Connection soil health menu

<http://www.ibiblio.org/farming-connection/soilhlth/home.htm>

This site accesses a range of interesting articles and publications on soil health, even online copies of complete soil classics such as Cyril Hopkins' *The Story of the Soil (1911)*.

Holistic agriculture library

<http://www.soilandhealth.org/01aglibrary/01aglibwelcome.html>

This website has complete online texts of most of the well known pre-industrial agriculture publications on soil health.

On becoming lovers of the soil

<http://www.igc.org/wsaala/lovers.html>

This excellent article by US organic farmer and philosopher Frederick Kirschenmann encourages the concepts of love and eros in soil management.

The roots of soil quality

<http://www.pmac.net/roots.htm>

This article by Charles Benbrook is written for potato farmers and is a good introduction to the concept of soil quality.

Appendix 2

Soil quotes

- A cloak of loose, soft material, held to the earth's hard surface by gravity, is all that lies between life and lifelessness. *Wallace H. Fuller*
- Man, despite his artistic pretensions, his sophistication, and his many accomplishments - owes his existence to a six inch layer of topsoil and the fact that it rains. *Anon*
- We know more about the movement of celestial bodies than about the soil underfoot. *Leonardo da Vinci*
- If we do not permit the earth to produce beauty and joy, it will in the end not produce food either. *Joseph Wood Krutch*
- The earth neither grows old or wears out if it is dunged. *Columella 45AD*
- To forget how to dig the earth and to tend the soil is to forget ourselves. *Mahatma Gandhi*
- A nation that destroys its soils destroys itself. *Franklin Roosevelt*
- Most of all, one discovers that the soil does not stay the same but, like anything alive, is always changing and telling its own story. Soil is the substance of transformation. *Carol Williams*
- Only rarely have we stood back and celebrated our soils as something beautiful, and perhaps even mysterious. For what other natural body, worldwide in its distribution, has so many interesting secrets to reveal to the patient observer? *Les Mollay*
- The earth is the very quintessence of the human condition. *Hannah Arendt*
- The word humility, also human, is derived from the Latin *humus*, meaning the soil. Perhaps this is not simply because it entails stooping and returning to earthly origins but also because, as we are rooted in this earth of everyday life, we find in it all the vitality and fertility unnoticed by people who merely tramp on across the surface, drawn by distant landscapes. *Piero Ferrucci*
- Soil is a resource, a living, breathing entity that, if treated properly, will maintain itself. It's our lifeline for survival. When it has finally been depleted, the human population will disappear. Project your imagination into the soil below you...Think with compassion of the life that exists there. Think, the drama, the sexuality, the harvesting, the work that carries on ceaselessly. Think about the meaning of being a steward for the earth. *Marjorie Harris*

- If a healthy soil is full of death, it is also full of life: worms, fungi, microorganisms of all kinds...Given only the health of the soil, nothing that dies is dead for very long. *Wendell Berry*
- When Hun Attila's Asian warriors moved westward, he cowed his enemies by threatening to throw salt on their lands. *Hans Jenny*
- I find that a real gardener is not a man who cultivates flowers; he is a man who cultivates the soil. He is a creature who digs himself into the earth and leaves the sight of what is on it to us gaping good for nothings. He lives buried in the ground. He builds his monument in a heap of compost. If he came into the Garden of Eden he would sniff excitedly and say: Good Lord, what humus! *Karel Capek*
- We have all come out of the earth, and are its children. The earth has always nurtured us, despite our scornful abuse, and we can no longer continue to behave as its ungrateful offspring. It is time for us, as *Homo sapiens curans*, to nurture the earth in return. *Daniel Hillel*
- You must teach your children that the ground beneath their feet is the ashes of your grandfathers. So that they will respect the land, tell your children that the earth is rich with the lives of our kin. Teach your children what we have taught our children, that the earth is our mother. Whatever befalls the earth befalls the sons of the earth. If men spit upon the ground they spit upon themselves. *Native American wisdom*
- The old people came literally to love the soil and they sat or reclined on the ground with a feeling of being close to a mothering power. It was good for the skin to touch the earth and the old people liked to remove their moccasins and walk with bare feet on the sacred earth. Their tipis were built upon the earth and their altars were made of earth. The birds that flew into the air came to rest upon the earth and it was the final abiding place of all things that lived and grew. The soil was soothing, strengthening, cleansing and healing. *Chief Luther Standing Bear*
- There is nothing in the whole of nature which is more important than or deserves as much attention as the soil. Truly it is the soil which makes the world a friendly environment for mankind. It is the soil which nourishes and provides for the whole of nature; the whole of creation depends upon the soil which is the ultimate foundation of our existence. *Friedrich Albert Fallou*
- The soil is the well of agriculture. In many places, the soil is crying out for a lighter touch and a little help from its friends. But too often the response by farmers to productivity problems linked to the soil is to do more, or apply more of the very things that systematically destroy soil quality. *Charles Benbrook*

- Treat the earth well: it was not given to you by your parents, it was loaned to you by your children. We do not inherit the earth from our ancestors, we borrow it from our children. *Ancient Indian proverb*
- When free of man's interference, most of the earth's soils are clothed with a vigorous system of vegetation which requires no uniform seed beds...we should look more carefully at the mechanism by which soils and their plant cover interact to provide a tilth in which the seeds are germinated and plants established without any application of applied horsepower. *Sir Charles Pereira*
- The basis of healthy livestock, crops and human beings is a healthy soil, one which through its biological activity and inherent fertility can grow high quality crops and remain productive over long periods of time without the need to rely on large quantities of inputs from outside the system. A starting point in the creation of a healthy soil must be to break away from the idea of the soil as merely a growing medium for crops, a place where crops can anchor their roots and pick up the nutrients they need while being fed from the fertiliser bag. *Nicholas Lamplin*
- Love is a mode of knowledge. We can only love what we know, and we can never know completely what we do not love. *Aldous Huxley*
- What has happened to our modern industrialised society is that we have gone through a divorce. We have become divorced from the soil. And I submit that until we heal that divorce and become lovers of the soil again, many of our social problems will go unsolved - including our food safety and environmental protection problems. *Frederick Kirschenmann*
- The first lure of science is not its instrumental power, its brutal force, but its magic, its capacity to kindle awe, wonder and the desire for knowledge, for explanation. *Nicholas Maxwell*
- A man or woman whose mind reins in the heart when the body sings desperately for connection can only expect more isolation and greater ecological disease. Our lack of intimacy with each other is in direct proportion to our lack of intimacy with the land. We have taken our love inside and abandoned the wild... The land is love. Love is what we fear. To disengage from the earth is our own oppression. *Terry Tempest Williams*
- The ecological discourse about planet earth, global hunger, threats to life, urges us to look down at the soil, humbly, as philosophers. We stand on soil, not on earth. From soil we come, and to soil we bequeath our excrements and remains...our generation has lost its grounding in both soil and virtue. *Ivan Illich*

- Soil is the connection to ourselves. From soil we come, and to soil we return. If we are disconnected from it we are aliens adrift in a synthetic environment. It is the soil that helps us to understand the self-limitations of life, its cycles of death and rebirth, and the interdependence of all species. To be at home with the soil is truly the only way to be at home with ourselves, and therefore the only way we can be at peace with the environment and all of the earth species that are part of it. It is, literally, the common ground on which we all stand.

Frederick Körschenmann

- We would do well to honour the mysteries of trees, animals, water, lichens, rocks, earthworms, bacteria...all of the world which it has been beyond human capability to create. For even if we are able to clone DNA and to combine different species' genes, behind that DNA and those genes still lies a creation not of human hands. We would do well to remember that we were never the beginning and, I suspect, we will not be the ending. *Cherie Staples*

- The land ethic simply enlarges the boundaries of the community to include soils, waters, plants, and animals, or collectively: the land. This sounds simple: do we not already sing our love for and obligation to the land of the free and the home of the brave? Yes, but just what and whom do we love? Certainly not the soil, which we are sending helter-skelter downriver. Certainly not the waters, which we assume have no function except to turn turbines, float barges, and carry off sewage. Certainly not the plants, of which we exterminate whole communities without batting an eye. Certainly not the animals, of which we have already extirpated many of the largest and most beautiful species. A land ethic of course cannot prevent the alteration, management, and use of these 'resources', but it does affirm their right to continued existence and, at least in spots, their continued existence in a natural state.

Aldo Leopold

- It is time for us to take off our masks, to step out from behind our personas - whatever they might be: educators, activists, biologists, geologists, writers, farmers, ranchers, and bureaucrats - and admit we are lovers, engaged in an erotics of place. Loving the land. Honouring its mysteries. Acknowledging, embracing the spirit of place - there is nothing more legitimate and there is nothing more true. I believe that out of an erotics of place, a politics of place is emerging. Not radical, but conservative, a politics rooted in empathy in which we extend our notion of community, as Aldo Leopold has urged, to include all life forms - plants, animals, rivers, and soils. The enterprise of conservation is a revolution, and evolution of the spirit. *Terry Tempest Williams*

Soil health: a systems approach to soils

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Healthy agricultural soils are able to balance a range of functions to meet the needs of both farmers and the community. Healthy soils function to sustain soil biota and plant life, store and cycle water and nutrients, decompose organic matter, inactivate toxic compounds, suppress pathogens and protect water quality. Soil health is a systems concept that implies that the soil functions as a balanced living system. It implies that the interactions among the soil's internal components are optimal and that the interactions of the soil with its external environment and the production system are sustainable. Soil degradation and poor water quality are symptoms of poor soil health. Soil biological activity, surface cover, organic matter content, pH and water availability are highly interactive and hence important soil health properties. This paper describes soil health and how it relates to soil properties and management practices in horticultural, cropping and grazing production systems.

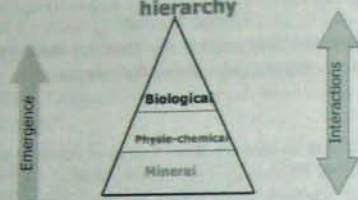
Definition of soil health

Soil health has been defined by Doran and Zeiss (2000) as 'the capacity of soil to function as a vital living system, within ecosystem and landuse boundaries, to sustain plant and animal production, maintain or enhance water and air quality, and promote plant and animal health'. Healthy soil functions optimally through balanced interactions amongst its biological, physio-chemical and mineral components. The mineral component consists of sand, silt and clay particles; the physio-chemical component consists of soil aggregates, pore space, reactive surfaces, and organic and inorganic compounds; and the biological component consists of roots, insects, invertebrates and microorganisms. Healthy soils function to

- sustain biological productivity
- store and cycle water and nutrients
- decompose organic matter
- inactivate toxic compounds
- suppress pathogens
- protect water quality and enhance catchment health.

Hierarchy and emergence are properties of all systems including soils. These properties imply there are higher level components and functions of the system that depend on, and emerge from, lower level components and functions. They enable the whole to be more than the sum of the parts. The biological and organic component and functions of soils depend on, and emerge from, the physio-chemical and mineral components. Hence the abundance, diversity and functioning of these organisms is a key indicator of soil health.

The soil system hierarchy



The main function of soil organisms is to cycle and transform nutrients and energy by decomposing organic matter. This process occurs within a complex food chain and is highly dependent on environmental factors such as moisture content and temperature. Soils are part of the life cycles of many types of organisms including insects, earthworms, mites, springtails, bacteria, algae, blue-green algae, fungi, protozoa and nematodes. The microbial population of fertile grassland exceeds 3×10^{11} cells per square metre whilst the moist biomass may exceed 7 t/ha (Richards 1974). Earthworm biomass may exceed 900 kg/ha and produce more than 25 t/ha of worm casts (Russell 1973).

Soil degradation and soil health

Many agricultural practices increase the soil's vulnerability to degradation processes such as erosion, acidification, salinisation, soil structure decline and contamination. These degradation processes reduce the functional capacity of soils and, at a catchment level, can reduce the quality of water draining to streams and rivers. Hence soil and water quality degradation can be thought of as symptoms of poor soil health. The challenge for management of agricultural soils is to develop production systems that not only prevent soil degradation but also enhance soil health. The biological component of the soil system has a high dependence on the chemical and physical soil components and hence tends to be a sensitive indicator to disturbance or degradation processes.

There is a need for measurable indicators to evaluate the sustainability of resource use by particular management systems. Ecosystem functions can be characterised in terms of their *resistance* to change by an imposed disturbance and their *resilience*, or potential to recover following disturbance/degradation (Pimm 1984). These concepts are equally valid for assessing the sustainability of agricultural production systems (Herrick 2000). Useful indicators to evaluate the sustainability of different management practices may be the amount and rate of change in soil biological functions, and the amount and rate of recovery. The most sustainable practices will be those which cause little or no negative change in functional capacity and/or which enable rapid recovery.

Some soil properties and functions undergo changes when disturbed that are effectively irreversible within management time scales. Examples include the impacts of extreme erosion or the oxidation of acid sulfate soil. The costs and benefits of practices which cause such changes need to be very carefully evaluated if we are to achieve a 'no regrets' approach to agricultural developments.

Properties of healthy soils

Soil health integrates all components of the soil system and is assessed by indicators that describe or quantify biological, chemical and physical properties. Soil characteristics that contribute to a healthy soil include

- protected soil surface and low erosion rates
- high soil organic matter
- high biological activity and biological diversity
- high available moisture storage capacity
- favourable soil pH
- deep root zone
- balanced stores of available nutrients
- resilient and stable soil structure
- adequate internal drainage
- favourable soil strength and aeration
- favourable soil temperature
- low levels of soil born pathogens
- low levels of toxic substances.

Measurement procedures and guideline optimum ranges for soil chemical, physical and biological properties are available (USDA 1999). However, agricultural productivity is determined by a large number of direct and indirect interactions between plant and animal characteristics, climatic conditions, soil properties, pest conditions and management practices. Satisfactory crop production may still occur if soil properties are outside guideline ranges because of plant tolerance, compensatory climatic conditions, or compensatory management practices. Hence it is usually not possible to predict animal or crop production from soil properties alone. This limits the value of generalised soil quality guidelines.

There is a need to develop tools that can assist interpretation of soil data in relation to crop/pasture type, stage of development, climatic & irrigation data, incidence of soil borne diseases, plant nutrient status, and rotation practices. Many types of information need to be combined to enable prediction of a desired outcome, eg response to an added amendment, or runoff water quality. A data analysis tool that could help achieve this is a neural network. Neural networks are a computer-based classification/prediction tools being used increasingly for agriculture and resource management (Shearer et al 1999). They are built using data sets with known properties and are an excellent device for capturing complex interactions and combining diverse information sources. There is potential to build neural networks which are trained to predict soil function, agricultural productivity or environmental indicators from a comprehensive knowledge base. These tools could

be used help farmers identify the most critical limiting soil factors in relation to their soil condition, plant type, climate and management practices.

The cost of fully characterising all soil properties that contribute to soil health is potentially very high. Given that soil-plant processes are complex, a reasonable strategy is to characterise the most interactive soil properties and/or biological properties that have a high level of dependence on physical and chemical properties. For example, soil water directly affects soil biological activity and indirectly affects a range of physical properties (mechanical resistance, soil oxygen, bulk density, thermal capacity, leaching rate) and chemical properties (salinity, ion speciation, breakdown pathways). Letey (1985) proposed the concept of the non-limiting water range (NLWR) to characterise the interactions between soil water content and soil physical properties. This concept identifies the range of soil water contents that limit plant growth. In wet soil, water content limits growth mainly by inadequate soil aeration, whereas in dry soils the main limiting factor is excessively high mechanical resistance to root growth. There is potential to expand the NLWR concept to include interactions between soil water and soil chemical and biological limitations to productivity. Other highly interactive soil properties are soil organic matter content and soil pH.

Integrated soil health research and extension strategy

It is important to distinguish soil health issues generic to all agricultural industries and production systems from those that are more specific to particular industries, regions, climates or farming systems. Sound management of soil erosion and organic matter is fundamental to the sustainability of all agricultural production systems. High levels of soil organic matter enable soils to supply water and nutrients to plants for longer, reduce the risk of soil loss via erosion, and provide the primary food source for soil biota. Management practices that enhance plant productivity generally sustain or enhance soil organic matter, provided cultivation is minimised. Effective methods of characterising soil biological functions such as organic matter decomposition rates, soil mixing by organisms, and nutrient release are also needed for all farming systems.

The potential to apply practices to enhance soil health varies with the type of production system (eg grazing, cropping, horticulture), local climate, landform and soil type, and socio-economic factors such as economic returns, attitude, education level. Practices that improve soil health within grazing systems include establishing deep-rooted perennial pasture species, applying adequate nutrients, liming regularly to manage acidification, adjusting stocking rates to prevent bare soil exposure, and introducing legumes and dung beetles. Management practices used in broadacre cropping systems to improve soil health include minimum cultivation, direct sowing, crop rotations, stubble retention, traffic lanes, soil conservation earth works, water and nutrient management plans. In horticultural production systems there is a growing interest in the use of ground covers, mulches, composts, biological fertilisers and biological inoculants to enhance and manipulate soil ecological processes.

The use of recycled organic materials is a key element of a sustainable agricultural systems and strongly promoted in 'alternative' agricultural production systems (eg organic agriculture, pesticide-free products, naturally grown products). This interest is driven by a combination of factors, including community concern about soil degradation and food safety, loss of confidence in 'conventional' farming practices, ready availability of recyclable organic materials and a desire to supply growing markets for organic produce.

These practices can have significant effects on the physical, chemical and biological properties of the soil. Ground covers and mulches reduce soil loss by protecting the surface from rainfall impact and decreasing the velocity of overland water flow. Increasing soil organic matter content favours soil structural stability and can increase the numbers and diversity of soil biota (bacteria, fungi, nematodes, protozoa, arthropods, microinvertebrates).

The interaction of soil biological processes and fertilisers can have significant management implications. Microbial activity during organic matter decomposition can either release nutrients (mineralisation) for uptake by plants or decrease soil nutrient availability to plants through competition (immobilisation). Soil nitrogen immobilisation is common when organic materials with high carbon to nitrogen ratios are incorporated into soils. These processes may affect the most appropriate time to incorporate organic materials and timings to apply supplementary fertiliser. Microbial activity in the rhizosphere can also affect nutrient availability to the plant through a complex of interactions. For example many rhizosphere bacteria produce chelating agents such as ketogluconic acid which can make phosphates soluble (Richards, 1974). This process could be affected indirectly by the form of nitrogen available for uptake as this is known to affect rhizosphere pH which in turn may affect the microbial activity. The effects of microbial interactions on nutrient availability should have practical implications for improving the efficiency of use of fertilisers, but these are not well developed.

To maximise the soil health benefits through use of specific management practices (eg groundcovers, mulches, organic amendments, fertiliser strategies) there is a need to systematically evaluate and demonstrate their use across a range of production systems and climates. This can only be achieved through an integrated research and extension strategy that brings together the necessary disciplines, programs, organisations, and partnerships. This strategy needs to identify both generic and farming system specific issues and to establish linked project teams to address these issues. It is the intention of this workshop to develop and gain support for a strategically integrated approach to soil health management.

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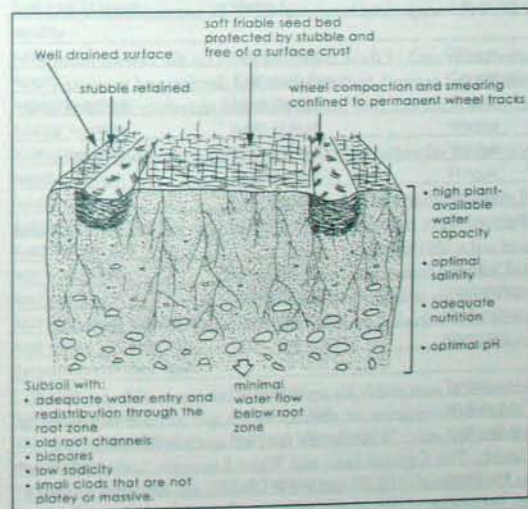
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Soil health and NSW Agriculture's soil management strategy

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The overall goal of NSW Agriculture's soil management strategy is to develop, promote and increase adoption of management practices that maintain or improve soil quality within profitable farming systems in NSW. The department's focus has been on soil quality rather than soil health. Soil quality is 'the fitness of a specific kind of soil to function within its surroundings, support plant and animal productivity, maintain or enhance water and air quality and support human health and habitation' (Rosewell 1999). A high quality soil is a healthy soil fit for its purpose. The ideal soil for farming is a quality soil for farming. The department's soil management manual series, SOILpak, defines an ideal, quality, healthy soil as having high plant available water, optimal salinity, nutrition, pH and structure including biopores (Anderson et al 1999). The purpose of the soil does not have to be agricultural; a desert soil or an acid sulfate wetland soil may be a healthy soil that supports appropriate vegetation and wildlife communities.

Figure 1. The ideal soil for dryland farming.



Some protagonists argue that soil health includes issues and concepts that soil quality does not. At the very least, a healthy soil gives the impression that the soil is a living vibrant community where micro and macro flora and fauna actively drive chemical and physical processes. At the strategic planning level, the terms soil quality and soil health can be used synonymously.

The department's soil management strategy has focussed for more than a decade on maintaining high quality healthy soils by preventing land degradation and remediating land where it has become degraded. This can appear a negative approach, but efforts to revise the strategy have always been dominated by the exploitative nature of agricultural production on NSW's essentially poor quality soils. Without preventative measures, soils used for agricultural production tend to acidify, degrade structurally, decline in nutrient status and in some instances become more saline. In more intensive agricultural farming systems, overuse of chemicals and fertilisers can impact on soil and water health. Offsite impacts of agricultural soil management have grown in importance over the last decade. The management of soil water to reduce drainage to groundwater is crucial for the management of land and water salinity.

The strategy has six key objectives:

- soil structural degradation diagnosed and managed in NSW farming systems
- soil salinity diagnosed and managed in NSW farming systems
- soil acidity diagnosed and managed in NSW farming systems
- acid sulfate soils diagnosed and managed in coastal farming systems
- soil nutrient decline and loss diagnosed and managed in NSW farming systems
- integration of key soil management issues within NSW farming systems.

The specific activities under each of these objectives focus on the development of techniques to recognise and research the processes, and develop and promote management practices that prevent land degradation and remediate degraded land.

The strategy is focussed on achieving the following soil quality and soil health outcomes:

- improved soil organic carbon and soil structure
- minimised groundwater recharge and slowed trends in soil and river salinities
- reduced rates of soil acidification
- minimised acid leaching from coastal acid sulfate soils
- balanced use of nutrients with minimal nutrient decline and loss
- soil management recommendations integrated into an economic, social and biophysical framework.

Increasingly government is responsible for reporting of outcomes of its programs. Soil quality and soil health outcomes are often nebulous and difficult to measure in an unbiased way across the state. What can be used are some indicators of soil quality and soil health. The National Land and Water Resources Audit and other initiatives such as the National (ASRIS) and NSW (SALIS) soil databases provide a useful benchmark for a range of parameters such as soil carbon, salinity, sodicity,

pH, and nutrient levels for the major elements of nitrogen, phosphorus, potassium and sulfur. Where SOILpak scores are used over time they can be a useful indicator of structural health. Sales figures for lime, gypsum, perennial pasture and grain legume seed, and the area planted to farm forestry, can all be used as indicators of the adoption of appropriate land management techniques. Surveys of farmers' adoption rate of conservation farming techniques and their use of split applications of fertilisers and precision farming are also useful indicators. Water quality in our major rivers and the number of fish kills in coastal rivers give an indication of the level of offsite impacts from land management practices. It is important that all activities that aim to improve soil health have systems in place to monitor the outcomes.

It is clear from the range of speakers in this workshop and the strategic plans of the department's Organic Waste and Recycling Unit and its production programs such as Pastures and Rangelands, Cereal Products and Horticulture, that soil health is a major focus for NSW Agriculture. The challenge is to coordinate and communicate between agricultural industries and departmental programs on soil health issues. This workshop is a useful contribution to this process, a process that has been evolving over the last decade in NSW Agriculture.

At the risk of missing out on the activity of some people I would like to highlight some of NSW Agriculture's activities in developing and promoting healthy soils.

Table 1. Some key soil health practitioners in NSW Agriculture

Soil health issue	Name	Location
Acidity		
Acidity	Greg Fenton	Wagga
Acidity	Catherine Evans	Condobolin
Acidity/ nutrition	Mark Conyers	Wagga
Acidity/ nutrition	Keith Helyar	Wagga
Acidity/ nutrition	Guangdi Li	Wagga
Acidity/ nutrition	Brandan Scott	Wagga
Acidity extension	Mick Duncan	Armidale
Acidity extension	Bill Schumann	Queanbeyan
Acid sulfate soil		
Acid sulfate soil	David McCoy	Taree
Acid sulfate soil	Peter Slavich	Wollongbar
Acid sulfate soil extension	Christina Collins	Wollongbar
Acid sulfate soil extension	Scott Henderson	Kempsey
Extension/communication		
Extension	Hugh Allan	Tamworth
Soil health extension	Abigail Jenkins	Wollongbar
Soil health communication	Rebecca Lines-Kelly	Wollongbar
Horticulture		
Horticultural soil health	Neil Treverrow	Alstonville
Vegetable farming systems	Tony Wells	Gosford

Soil health under citrus	Nerada Donovan	Menangle
Irrigation		
Irrigated soil health	Geoff Beecher	Yanco
Irrigated soil health	John Thompson	Deniliquin
Irrigated soil health extension	Lindsay Evans	Deniliquin
Nutrients		
Nutrient extension	Brett Butler	Cowra
Nutrient movement	Warwick Dougherty	Richmond
Nutrient movement	Roy Lawrie	Richmond
Nutrient movement	Paul Milham	Orange
Nutrients/microbiology	David Herridge	Tamworth
Nutrients/structure	William Manning	Tamworth
Potassium nutrition	Ian Collett	Tamworth
Heavy metal impacts	Mark Whatmuff	Richmond
Organic farming		
Organic cereals	Latarnie McDonald	Wagga
Organic cereals/microbiology	Jeff Evans	Wagga
Organic farming	Robyn Neeson	Yanco
Organic horticulture	Gus Campbell	Bathurst
Organic horticulture	Roy Menzies	Bathurst
Organic horticulture	Karen O'Malley	Bathurst
Organic matter		
Soil microbiology	Percy Wong	Richmond
Soil carbon	Graham Schwenke	Tamworth
Genetic markers	Tony Vancov	Wollongbar
Conservation farming	Emma Wilson	Moree
Chemical residue impacts	Lukas Van Zwieten	Wollongbar
Salinity		
Salinity	Grant Fraser	Tamworth
Salinity	Peter Milthorpe	Condobolin
Salinity	Rick Young	Tamworth
Salinity education	Paul Robey	Yanco
Salinity extension	Nicole Gammie	Condobolin
Salinity extension	April Gee	Dareton
Salinity extension	Fiona Leech	Yass
Salinity extension	Katrine O'Flaherty	Forbes
Salinity extension	John White	Deniliquin
Soil structure		
Soil physics	Gunnar Kirchhof	Tamworth
Structure/microbiology	Yin Chan	Wagga
Pedology/structure	Ian Daniells	Tamworth
Structure/nutrients	Graeme Sanderson	Dareton
Structure/carbon	Neil Fettell	Condobolin
Structure/carbon	Damien Heenan	Wagga
Structure/salinity	John Friend	Trangie
Water quality impacts on soil	Hamum Gill	Yanco

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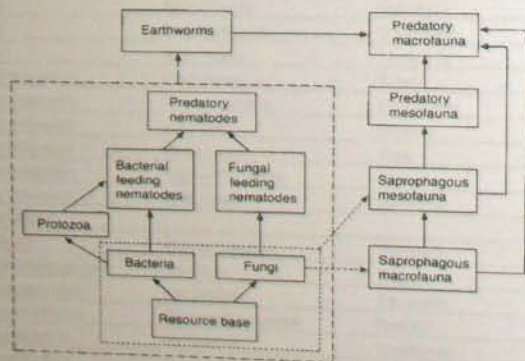
Soil biology and its importance in soil health

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Soil is taken for granted by many horticulturalists, who often think of it as an inert support for plants. In reality, it is a dynamic, living resource whose condition is vital for food production and for the function of the ecosystem as a whole. The physical and chemical components of soil are important, but the organisms that live in the soil ensure that it remains fertile and productive in the long term.

The biological component of soil (Figure 1) is concentrated mainly in the topsoil, occupying only a tiny fraction (<0.5%) of the total soil volume and making up less than 10% of total soil organic matter. A small part of this living component of soil consists of plant roots, with microorganisms and soil animals forming the bulk of the biomass. The soil biota are therefore much more important than is usually recognised, and this paper provides an overview of their function in soil and the role they play in maintaining soil health.

Figure 1. Simplified functional food web for detritus-based systems in soil. Organisms in the dotted and dashed boxes may be consumed by organisms that utilise substrates from more than one trophic level. From Wardle (1995).



Soil microorganisms

Bacteria, fungi, protozoa and algae (mostly blue green algae or cyanobacteria) form the major part of the soil biomass. There is an enormous number of species in each of these groups, but our knowledge of each of them is limited because many species have not been described taxonomically and most have not been cultured.

Bacteria

Typically, there are between 10^6 and 10^9 bacteria per gram of soil. Bacteria play an important role in soil because their diverse metabolic capabilities enable them to exploit many sources of energy and carbon in soil. They are the principal agents for the global cycling of inorganic compounds such as nitrogen, sulfur and phosphorus.

Fungi and actinomycetes

About 70% of soil microbial biomass is contributed by fungi, whose numbers vary typically from 10^4 to 10^6 per gram of soil. Fungi may be free-living or have a mutually beneficial or parasitic relationship with plant roots. They exploit a diversity of substrates because of their filamentous nature and are decomposers of large molecules such as cellulose and lignins produced by plants. Other microorganisms such as bacteria then utilise the resulting smaller molecules. Mycorrhizal fungi are involved in a mutually beneficial association with plant roots. They derive nutrients from roots and in turn aid the plant in the uptake of relatively immobile nutrients such as phosphorus and zinc. By acting as agents of nutrient transport, they form a vital link between plants and soil and therefore play an important role in soil fertility.

Actinomycetes are filamentous bacteria that are found in soil at populations of 10^5 to 10^8 per gram of soil. They are involved in the decomposition of organic compounds including cellulose, chitin and recalcitrant substances such as humic acids.

Nitrogen fixing bacteria and actinomycetes

Biological fixation of nitrogen occurs predominantly but not exclusively in symbiotic associations between plant roots and bacteria. The symbiotic bacterial genera most commonly involved are *Rhizobium* and *Bradyrhizobium*, which specifically infect leguminous plant roots. Actinomycetes in the genus *Frankia* are also symbionts but have a much wider host range that includes several non-legume plant groups. However, our knowledge of these organisms is still limited (compared to *Rhizobium* and *Bradyrhizobium*) because they are difficult to culture. Among the free-living bacteria, *Azotobacter*, *Azospirillum* and *Bacillus* may also contribute relatively small amounts of nitrogen to soils.

Algae

Estimates show that populations of algae in soil vary between 10 and 10^6 per gram of soil. Valuable nitrogen inputs to soil are made by the blue green algae due to their capacity to fix nitrogen. Because of their photosynthetic capacity, they contribute to the organic carbon input of soil, and also produce extracellular polymers that may help to conserve soil structure.

Soil microfauna

The main components of the soil microfauna are the protozoa and nematodes, the largest members of the soil microbiota. They feed on bacteria and fungi (the primary decomposers) and are involved in nutrient recycling in soil.

Protozoa

Protozoa are water-dependent, unicellular organisms possessing a nucleus, and are classified as ciliates, flagellates and naked amoebae. They feed on soil bacteria and fungi and their populations range from 10^4 to 10^6 per gram of soil. Although protozoa constitute only a small proportion ($\sim 5\%$) of soil microbial biomass, they are important ecologically because of their rapid turnover rates and the large grazing pressure they exert on the microflora. This grazing pressure maintains microbial populations that are physiologically young and in a high state of metabolic activity. Thus microbial turnover is stimulated, resulting in increased rates of nutrient mineralisation, especially nitrogen and phosphorus.

Nematodes

Nematodes are ubiquitous in soil and are among the most abundant soil microfauna. Some species are parasites of plants and animals but the majority are beneficial, playing an important role in nutrient cycling processes. This latter group of nematodes, commonly known as 'free-living nematodes', feed on bacteria or fungi and/or prey on various soil microfauna. They therefore obtain their nourishment from organisms that are associated with decaying organic matter. Thus free-living nematodes are part of the natural food web of organisms, the protozoans, earthworms, mites, insects, fungi and bacteria that reduce the organic remains of animals and plants to their primary constituents.

Soil mesofauna

The soil mesofauna comprise mites, collembola (springtails), enchytraeids (small worms from 1 mm to 5 cm in length), tardigrades (water bears) and small insects. They are a diverse group with a wide range of feeding habits, but collectively they play a role in regulating microbial populations and disseminating microbial propagules. They also accelerate decomposition of plant residues by fragmenting large pieces of organic matter and reworking the faeces of larger fauna. Microarthropods (mainly collembola and mites) are usually the most obvious of the mesofauna. Population densities vary from 10^4 to 10^7 per square metre of soil. Populations are generally highest in the top 5 cm of soil and decline with increasing depth. Apart from fragmentation of residues, enchytraeids also affect soil porosity through their burrowing activities and influence soil aggregation via production of faecal pellets.

Soil macrofauna

These are the most conspicuous of the soil animals and, because of their size, have the greatest potential for direct effects on soil functional properties. Members of this group include ants, termites, millipedes, adult and larval insects, earthworms, snails and slugs. Through their feeding habits and their movement through soil, they help to comminute and redistribute organic residues in the soil profile. This activity results in an increase in the surface area of organic substrates available

for microbial activity. Certain groups, especially ants, termites, and earthworms, can greatly modify soil structure through the formation of macropores and aggregates. These effects may influence water infiltration and solute leaching through soil and hence the soil's capacity to function as an environmental buffer.

How soil biota contribute to soil health

Maintenance of soil structure

The binding substances that hold soil particles together have both mineral and organic origins. Some of the organic 'binding agents' are contributed by soil biota. Fungal hyphae, along with fibrous roots from plants, bind soil particles and small aggregates together into larger units. Polysaccharides produced by microorganisms (eg many commonly occurring soil bacteria such as *Bacillus*, *Pseudomonas*, *Agrobacterium*, *Azotobacter* and *Rhizobium*) act as the gums that bind and stabilise aggregates. Plant residues are also broken down by soil biota to create soil aggregates. Mycorrhizal fungi (VAM) contribute significantly to soil aggregate formation and soil stability at both micro and macro levels by enmeshing mineral and organic debris in a network of external hyphae.

Nutrient cycling

Most of the nutrients contained in soil organic matter are in complex organic forms that have to be mineralised to an inorganic form before they can be used by plants. Soil microorganisms play a dominant role in the decomposition of organic materials such as cellulose, hemicellulose, polysaccharides, hydrocarbons, lignins, proteins and amino acids, and are also responsible for nearly all nitrogen and carbon transformations in soil. They are also important in transforming nutrients such as phosphorus, sulfur, iron, potassium, calcium, magnesium, manganese, aluminium and zinc into forms that can be used by plants. Soil microorganisms therefore have a beneficial impact on plant health by releasing nutrients that would otherwise be 'locked away' in dead plant and animal tissue.

The decomposition of organic matter is brought about by a succession of microbial communities. For instance, the sugar fungi (*Mucor* spp) are the primary colonisers and the cellulose and lignin degraders then follow them. Different nutrients are cycled at different rates by soil biota. Thus amino acids and various oligosaccharides turn over rapidly and form a fast/active nutrient pool whereas humified soil organic matter forms a slow/passive pool that may take several decades to be degraded. The fast/active pool, which cycles 8-10 times per year, has the greatest impact on plant growth.

Nutrient cycling involves a complex array of interactions between soil organisms that are often referred to as the detritus food web. In agricultural soils, the way these food webs operate depend on the type of farming system. When plant residues are incorporated into soil by cultivation, bacteria start the decomposition process. This immediately results in an increase in protozoa and bacterial feeding nematodes and nutrient cycling proceeds rapidly. On the other hand, when plant residues remain on the surface of the soil (eg minimum tillage), a fungal flora

develops and populations of fungal feeding organisms increase in the surface layers. In this case mineralisation of nutrients proceeds much more slowly.

Suppression of plant pathogens

Soil-borne disease problems are common in soils that have been intensively cropped for decades. Such soils are said to be 'conductive' to disease. They have lost much of their microbial diversity and biological buffering capacity, so many competitors of fungal pathogens and root-feeding nematodes have disappeared. In contrast, a 'disease suppressive soil' has a full complement of beneficial organisms, and the pathogens that cause disease are unable to increase to levels that will cause damage.

The organisms involved in disease suppression act in many different ways. Fungi and bacteria are able to displace each other from specific ecological niches in soil by competing for nutrients. A group of bacteria known as the fluorescent pseudomonads (*Pseudomonas* spp), for example, inhibit the growth of pathogens by limiting their access to soluble ferric iron. Other bacteria (eg *Bacillus* spp, and some actinomycetes) produce antibiotics that are detrimental to pathogens. Fungi such as *Trichoderma* and *Gliocladium* are able to parasitise fungal pathogens and are therefore useful biological control agents. Other fungi can parasitise or prey on nematodes. The 'nematode trapping fungi', for example, are able to capture nematodes by producing unique trapping structures in which nematodes become ensnared. Some small arthropods (eg mites and collembola) consume fungal spores or feed on parasitic nematodes.

Conclusions

The interactions that occur between soil organisms and their relationships with the soil environment are so complex that they will never be fully understood. Nevertheless, our current knowledge shows unequivocally that the soil biota play an important role in nutrient cycling and in improving soil structure. Some components are detrimental to plants but, from a horticultural perspective, there are other components that provide an active form of defence against these pests and pathogens. Thus the soil biota play a vital role in sustaining a healthy, productive soil capable of supporting a level of plant growth that is appropriate for a particular soil and climate.

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Soil fauna and the sustainability of arable soils: the earthworm viewpoint

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The topic of the role of soil fauna in agricultural soils encompasses an extensive range of information for a large number of groups of organisms from mites to earthworms. While biological studies of soil fauna are in themselves of great interest and relevance, discussion in more recent years has emphasised the notion that soil organisms provide valuable information to land managers on two rather elusive concepts: soil health and sustainable production. Lobry de Bruyn (1997) provides an excellent overview of soil fauna, while the potential role of each of the major groups of soil organisms is given thorough review by Pankhurst et al (1994) and Pankhurst et al (1997). Useful entry points into the literature pertaining to specific groups of soil fauna are provided by Lee (1985) and Temple-Smith and Pinkard (1996) for earthworms, and by Lobry de Bruyn and Conacher (1990) for termites and ants. The current paper does not attempt to cover the breadth of territory reviewed in these works. Rather, the purpose is to demonstrate that soil fauna, particularly earthworms, have an impact on soil physical, chemical and microbiological properties; that agricultural practices have impacts on soil fauna; and that soil faunal abundances have implications for the long term biological sustainability of agricultural systems.

1. Interaction between soil fauna and agricultural management

Complexity of soil biota

Biological activity in soils is complex. The taxonomic diversity is immense and each species has its own complex requirements and influences according to its taxonomy, size, biology and lifestyle. In order for each to survive and reproduce, environmental conditions and dietary requirements within the soil must remain supportive throughout each season and through each successive intervention by land managers. Individuals of each species or group of species have the potential to interact in a number of possible ways with every other species at the same site. Such interactions may be direct, for example predation and parasitism, or indirect, including the construction of burrows by one and the use of them by another, or the provision by one of smaller fragments of organic matter for consumption by another. In restricting the focus to the soil fauna we need to treat the remainder of the soil biota, including the bacteria, protozoa, fungi and plant roots, together with the physical and chemical properties of the soil, as the total environment in which soil fauna operate. The number and species composition of the soil fauna present at a site will be affected by these environmental factors, by microclimatic conditions, and by the general climate as determined by latitude and altitude. Each of these

levels of complexity holds implications for land managers each time an operational change is effected.

Soil fauna and the functioning of terrestrial ecosystems

All plant matter eventually dies and decomposes, releasing its constituent nutrients for re-use. An entire 'trophic level' of biological organisms of diverse taxonomy and form has evolved to take advantage of what is, for them, a resource. Associations of such organisms, centred on the soil, have developed into highly complex communities with great interdependence between members. Changes in the soil physical and chemical environment brought about by soil fauna, including 'improved soil structure' and the release of nitrogen-rich excreta, contribute to increased plant growth, which in turn improves the reliability of the supply of the very energy source that 'runs' the soil faunal community. Such a system depends only on sunlight, rainfall and gases, mainly carbon dioxide and oxygen, as external inputs. As long as these resources remain available and in balance the system is 'sustainable'. Such systems are the norm in undisturbed vegetation, so we can deduce that the presence of such decomposer communities is a desirable component of sustainable agronomic systems.

Soil fauna and plant growth

Studies of soil fauna, notably earthworms, in arable soils over the past 40 years have shown that the presence of fauna leads to increased growth rates by a variety of plant types, including pasture grasses, field crops and orchard trees (reviewed by Lee 1985). Many other studies have looked more closely at soil physical, chemical or biological changes that result from the presence of soil fauna, but these studies have been mostly short-term and narrowly focussed, making it difficult to extrapolate implications for either productivity or sustainability of production in the longer term.

Soil formation

Bioturbation or soil mixing by soil fauna over long periods of time is one of the major processes by which soil profiles develop (Chittleborough 1992). Soil fauna may continue to have a defining influence on soil texture profile even in well-developed soils either through the sorting of particles by both ants and termites (Lobry de Bruyn, Conacher 1990) or by mixing, as by earthworms (Laffan, Kingston 1997). The power of soil fauna to construct soils over geological time highlights the vital importance of minimising our degrading activities, especially as we have not yet devised economically viable means to artificially create productive soils in bulk.

Soil structure

Soil fauna has a major influence on soil structure by selective movement of particles of a certain size, mass movement during burrowing by larger species, and mineralisation and incorporation of organic matter. The influence of soil fauna on the structure of soils may be local, such as within an ant nest or termite mound, or extensive, as by earthworms. Many soils under rainforest and wet sclerophyll forest in Tasmania, for example, have been found to consist entirely of earthworm casts and burrows (Laffan, Kingston 1997). The earthworm species *Ponotocoles coarctatus*,

when studied in pots at Kingaroy in Queensland, brought about decreases in bulk density and penetration resistance over a three month period (Zund et al 1995). Subsequent image analysis revealed an abundance of burrows and fine pores associated with the lowest bulk densities. Many soils under dairy pasture and macadamias within the NSW northern rivers region have subsoils comprised entirely of open and in-filled earthworm burrows (Kingston, in prep). Experimental work elsewhere has demonstrated that ingress by both air and water into soils with earthworm burrows is more rapid than into soils without such channels. Where the burrows are both deep and interconnected they aid soil drainage and affect nutrient leaching and rainfall run off. At a finer scale earthworms increase the aggregate stability or 'crumb' structure of some soils. This is believed to be a consequence of colloids that coat soil particles during their passage through the earthworm gut, and fungal hyphae which preferentially expand into and around particles and crumbs, binding them together.

Soil pathogens

There is some evidence that earthworms can influence the pathology of agents causing root diseases, and the efficacy of beneficial soil organisms. The presence of the earthworm *Aporrectodea trapezoides* has been shown to reduce the severity of the potentially destructive fungal disease *Gaeumannomyces graminis* or 'Take-all' in wheat (Stephens, Davoren 1996), and the fungal pathogen *Rhizoctonia solani* on wheat (Stephens et al 1994) and subterranean clover and perennial ryegrass (Stephens, Davoren 1997). The latter study showed greater growth of both roots and shoots in the presence of earthworms. Earthworms also appear to allow greater dispersal of soil microorganisms used as agents in the control of pathogens, as shown for *Pseudomonas corrugata* when used against Take-all in wheat (Ryder et al 1993). More such studies are required for a greater range of crops and diseases and under a wider range of management regimes.

Impacts of agriculture on soil fauna

There are now several published studies of the impact of specific farm management alternatives on soil fauna, especially earthworms. Some practices have been shown to be deleterious, either because they directly damage individual animals, disturb their habitat or because they disrupt essential physiological processes. Other practices may be beneficial because they render the physical or chemical environment more conducive to soil fauna survival or because they supplement the organic food supply. Even if impacts are not detected immediately their effects may be delayed or only become apparent after some years, perhaps in a year of extreme climate. Alternatively the impact may be masked by the complexity of the system or the variability in the results of research. In reality, all changes in management practices are likely to affect faunal groups differentially and result in a shift in the balance of component groups. Some years of consistent management may be required before a new balance is achieved. If the result is undesirable it could take even longer to reverse. In theory at least, greatest notice should be given to studies that continue observations over a long time period and employ maximum taxonomic separation of the soil fauna. Such studies are rare, one good model being that of Longstaff et al (1999) undertaken at Cowra and Harden in New South

Wales over a three-year period. This project recommended further work in two specific areas, 'DNA probes' for soil biological assessment and the production of user-friendly, computer based keys for identifying soil fauna. Regrettably, the CSIRO soil biology group responsible for the study was instead disbanded soon after (B Longstaff, pers.comm).

Effect of lime

In several countries the addition of lime or dolomite to acidic soils to raise soil pH has increased populations of earthworms. Most recently, the addition of lime to highly acidic pasture soils in a high rainfall zone in South Australia increased earthworm numbers from 85 to 250/m² over four years (White et al 2000).

Cultivation and crop residue management

There is now a large body of research showing that cultivation reduces earthworm numbers and that the greater the energy used, the greater the population decline. The use of rotary hoes has been found to be especially deleterious whereas mouldboard ploughs have much less impact. Results of a study from tropical Queensland, in which earthworms were sampled at four localities between 1987 and 1992, support this pattern (Robertson et al 1994). At each site, wheat or grain sorghum was grown over a range of tillage intensities, including zero till, reduced till and conventional cultivation. The abundance and biomass of one introduced and one native species were greatest under zero tillage cropping with retention of stubble. The presence of the introduced species increased the rate of water infiltration by a factor of three in zero tillage compared with conventionally cultivated soils. Longstaff et al (1999) examined 20 groups of soil fauna under conventional cultivation, direct drilling and stubble incorporation at two NSW sites. In all cases stubble incorporation and direct drilling supported more soil fauna than conventional cultivation. Mite and springtail populations shifted in favour of fungus-feeding species. Near Casino, in northern NSW, laser levelling of a paddock resulted in moribund earthworms with empty intestines. The scraping of the soil surface had either closed the earthworm burrows and cut off the air supply and access to food, or had removed the topsoil and food supply altogether (Kingston, personal observation, March 2001).

Irrigation

Irrigation has been found to increase earthworm numbers in areas of summer drought, for example in New South Wales (Noble, Mills 1974) and in Victoria (Tisdall 1985). The water appears to extend the earthworm feeding period into summer and reduces mortality from desiccation. In Tasmania however, irrigation applied to a krasnozom soil, immediately followed by grazing by dairy cattle, altered earthworm species composition dramatically. The mobile, surface-feeding species *Lumbricus rubellus* increased in abundance while the topsoil species *Aporrectodea caliginosa* was seriously depleted. Earthworm mortality occurred as a direct result of physical damage to the soil and increased exposure of earthworms during the summer to a seasonally active parasitic fly (Kingston 1989). In a follow-up study the interactions between irrigation, grazing, soil structure and earthworms were explored in both experimental plots and by farm survey (Lobry de Bruyn, Kingston 1997). Summer irrigation at the trial site led to a decline in soil structure: but areas

protected from trampling were found to have higher infiltration rates and lower bulk densities than trampled areas. The same shift in earthworm species as found in the preliminary study was duplicated on these study plots.

Biocides and metals

The use of herbicides in Australian agriculture as a 'chemical plough' has increased greatly as an alternative to cultivation in the control of unwanted plant growth in both field crops and orchards. Fungicides are used with great regularity in some subtropical fruit orchards and insecticides are called upon when necessary. Consideration of the impact of these biocides on soil fauna in the field is thus of great relevance, but published field studies are few. Dalby et al (1995) tested a single application of the broad spectrum herbicide glyphosate, the broadleaf herbicide 2,4-DB and the insecticide dimethoate for impact on earthworms in a pasture soil. None of these biocides reduced earthworm numbers by more than 10%. A study of post-emergent herbicides (Mele, Carter 1999) found that applications in two consecutive years resulted in significant increases in earthworms in the soil below. These results, supported by many other informal observations, suggest that an indirect effect of herbicides, the provision of freshly dead plant matter, is more significant to earthworms than any harm from the chemical itself. However a cautious approach should be taken in generalising this to all earthworm species, let alone to all groups of soil fauna or to the longer term.

In a study of four insecticides, Choo et al (1998) found significant mortality in the earthworm *Aporectodea trapezoides* when exposed to endosulfan and fenamiphos on filter paper. When applied to soil in pots the only effect was a loss of weight in earthworms over a five week period with fenamiphos. Two other chemicals, methiocarb and ridomil, caused neither mortality nor loss of weight. In an overseas study of a semi-arid tropical soil (Reddy et al 1995) the biomass of three species of earthworms was reduced drastically by applications of carbofuran and herbicides. The extent of the impact varied significantly according to soil management.

A fungicide study carried out in orchards in Italy has particular relevance to orchards elsewhere. The study focussed on the effects of copper sulfate on earthworm communities in a variety of settings including vineyards and apple, peach and kiwifruit orchards (Paoletti et al 1998). Both abundance and biomass of the earthworm *Aporectodea caliginosa* were severely reduced by copper spray and by soil tillage. Another study of fungicide use in orchards (Heijne, Anbergen 1998) provides evidence of the potential complexity and disguising of impacts. The rapid removal of fallen leaves from the soil surface in an orchard by earthworms was found to have a significant role in the suppression of fungal diseases. While some short-term disease control could also be achieved by the use of either copper or benzimidazole, these chemicals also reduced earthworms, thus creating a greater dependency on chemicals for disease control. This is an excellent example of the kind of impact that soil biologists intuitively fear, but that is difficult to demonstrate.

Another important aspect of the interaction between soil fauna and chemical contaminants of soil is the demonstrated ability of earthworms to bioaccumulate

organochlorines and heavy metals. Given the place of earthworms at the base of food chains involving all the major groups of vertebrates: birds, mammals, frogs, lizards and fish, the entry of the contaminants into food chains is of concern. Vorobeichik (1998) looked at the effects on earthworms of the contamination of soils by copper, lead and cadmium. When levels of these metals were up to 2.5 times higher than in control soils, earthworm populations were reduced; at up to 4.5 times higher, earthworms were absent. In the Tasmanian Midlands, earthworms were collected from trial plots to which superphosphate had been applied at rates of up to 250 kg per annum over nine years and their tissue analysed for cadmium, a known impurity of superphosphate fertiliser. Levels in earthworms from the 250 kg/ha plots contained cadmium at 8.7 ppm compared with 3.4 ppm on the control plots (Kingston, unpublished data).

There is cause for concern about the use of copper sprays in subtropical orchards, particularly avocados, in northern NSW. Observations made during joint soils research by Tuckombil Landcare and NSW Agriculture suggest that fallen leaves under avocado trees are slow to decompose, that there is poor mixing of organic matter into the mineral soil and that earthworm populations are low. Soil analyses have revealed greatly elevated levels of both copper (834 ppm) and cadmium (10 ppm) from within an avocado orchard (Lukas Van Zwieten, pers. comm). The link, if any, between these observations is the subject of ongoing investigations.

II. The earthworm resource in Australia's arable soils

Earthworms are widespread, diverse and frequently abundant in Australian soils under both natural vegetation and agricultural production, as well as in gardens and compost. The major geographic limitation to their distribution appears to be low rainfall, few specimens having been collected in areas with an annual rainfall of less than 400 mm (Abbott 1994).

Surveys of earthworms of both arable and naturally vegetated areas have been undertaken in West Australia (Abbott, Parker 1980; Abbott 1985; McKenzie, Dyne 1991), South Australia (Baker 1992; Baker et al 1992), Victoria (Baker et al 1992; Mele 1991), and Tasmania (Kingston, Temple-Smith 1989; Garnsey 1994; Kingston 2000). One innovative community-based survey, the 'Earthworms Downunder' project (Baker et al 1997) was Australia-wide in its coverage. The project asked members of the CSIRO Double Helix Club to collect earthworms from gardens and farms near their homes and submit specimens to the CSIRO for identification. Other taxonomic and ecological studies of Australian earthworms have contributed many additional records to species' distribution maps.

Earthworms found in Australia belong to either native or introduced species. The introduced ones have been inadvertently imported from overseas during the past 200 years. Earthworm surveys in areas of native vegetation generally find native species, while those carried out in areas cleared for agriculture, at least in southern Australia, have found predominantly introduced species. In more tropical parts of Australia fewer surveys have been conducted but it appears that inter-mixing of native and introduced species is more common, at least under agricultural soils (Baker et al 1997; Kingston, unpublished data collected in March 2001).

Australian native earthworms

The native earthworms of Australia are poorly known because, in general, surveys have been conducted in a patchy and low intensity manner relative to the small natural ranges occupied by the great majority of species. Perhaps 500 species have now been described but many more are known to exist in museum collections, their number being enlarged by each new survey undertaken. Kingston and Dyne (1994) suggested that eventually more than 1000 species will be described for the continent. Since then a number of publications have brought the total number of described species to around 700. These results now enable a revised minimum estimate of 1500 Australian species.

Very few large geographical areas under native vegetation have been comprehensively surveyed for earthworms, and the collections fully documented, as has been done by the author and his colleagues at the Queen Victoria Museum, Launceston, for the whole of Tasmania (Kingston 2000). In this survey 400 sites were sampled between 1990 and 1994, almost 8000 specimens were collected, preserved and sorted to about 220 native species. No more than 30 of these were previously known. Other more localised or lower intensity surveys outside areas of human activity have been reported for Mt Kosciuszko in New South Wales (Wood 1974), for Tasmania (Laffan, Kingston 1997) and Western Australia (Abbott 1985 and McKenzie, Dyne 1991). Some additional studies of earthworms in agriculture, conducted at a limited number of sites only, have reported the presence of native species in significant numbers: for example at one of three sites assessed in the Mount Lofty Ranges in South Australia (Baker et al 1993), at a single site in western Australia (Abbott et al 1985) and at 19 of 50 sites within a radius of 100 km from Alstonville in the NSW northern rivers region (Kingston, in preparation). The site with both the heaviest mean earthworm weight (1.4 grams) and the greatest biomass of earthworms (171 grams/m²) (weight of earthworms preserved in alcohol) was a dairy pasture near Kyogle. The population comprised a single native species. Not only was it one of the largest species encountered but it was also found to be living more deeply in the soil (Plate 1) than introduced species in the district. Species having this deep-burrowing characteristic are considered especially desirable under agriculture (Baker 1996). The reasons for the appalling state of knowledge of Australian native earthworms include such factors as the difficulty of collecting, the rapid deterioration of unpreserved specimens, the specialised knowledge required in their identification and the chronic shortage of specialists performing the overdue taxonomic work required.

'Introduced' earthworms in Australia

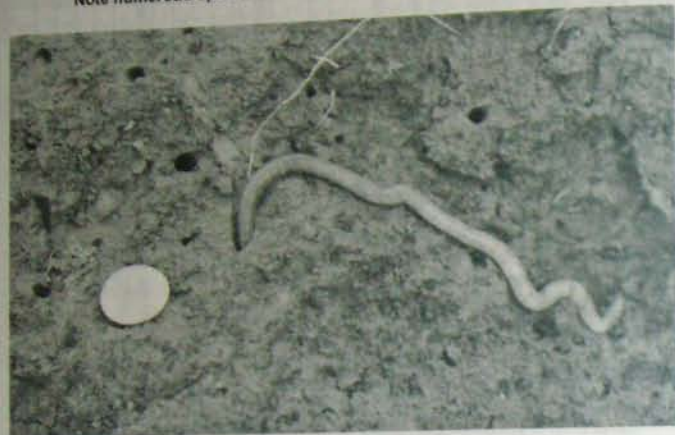
The most up-to-date list of introduced earthworms in Australia (Blakemore 2000) includes 63 species in eight families but many of the species listed have been rarely recorded and may be considered to be of academic interest only. In surveys of soils under agriculture in WA (Abbott, Parker 1980, Abbott 1985), South Australia (Baker 1992, Baker et al 1992), Victoria (Baker et al 1992, Mele 1991) and Tasmania (Kingston, Temple-Smith 1989, Garnsey 1994), the great majority of which have been carried out in the southern half of Australia, the most commonly encountered earthworms belong to a very small group of introduced species (Table 1).

Table 1. Frequently encountered introduced earthworm species.

FAMILY/SPECIES LUMBRICIDAE	DISTRIBUTION	WEIGHT	NOTES
Aporrectodea caliginosa	WA, SA, VIC, TAS, NSW, QLD	1.2 gm	One of the six most common species in Australia-wide survey ¹ . Widespread southern Australia, rare in tropical areas, most frequent species in urban and orchard habitats ² . Dominant species in northern Tasmanian pastures ³ .
Aporrectodea longa	WA, SA, VIC, TAS, NSW, QLD	5 gm	Northern European origin. Only in Tasmania ⁴ . Locally distributed species in northern Tasmanian pastures, usually with <i>A. caliginosa</i> ¹ . Described as 'deep burrowing' but in Tasmania is found near the surface when active ⁵ .
Aporrectodea rosea	WA, SA, VIC, TAS, NSW, QLD	0.4 gm	One of the six most common species in Australia-wide survey ¹ . Equal dominant (with <i>A. trapezoides</i>) in croplands ² . Occasional species in northern Tasmanian pasture, often with <i>A. caliginosa</i> ³ .
Aporrectodea trapezoides	WA, SA, VIC, TAS, NSW, QLD	1.5 gm	Mediterranean origin in Europe. One of the six most common species in Australia-wide survey, especially in Mediterranean climate ² . Most common species in pastures and (with <i>A. rosea</i>) in cropland ³ . Most common species in permanent pasture near Adelaide ⁴ . Most common species in pasture - cereal rotations in South Australia and western Victoria ⁴ . Most common species in Tasmanian Midlands, replaces <i>A. caliginosa</i> in lower rainfall areas becoming dominant below 800 mm ⁵ .
Dendrodrillus rubridus	WA, SA, TAS, NSW, QLD		
Eisenia fetida Tiger Worm	WA, SA, VIC, TAS, NSW, QLD, NT	1 gm	
Lumbricus rubellus 'Red Worm', 'Dung Worm'	WA, SA, VIC, TAS, NSW	2 gm	Northern European origin. One of the six most common species in Australia-wide survey ¹ .
Octolasion cyaneum	WA, SA, VIC, TAS, NSW, QLD	2.5 gm	
GLOSSOCOLECIDAE			
Pontoscolex corethrurus	WA, NSW, QLD, NT	1 gm	Only recorded coastally from northern New South Wales, Queensland and NT ² .
ACANTHODRILLIDAE			
Microscolex dubius	WA, SA, VIC, TAS, NSW, QLD		Mediterranean origin in Europe. One of the six most common species in Australia-wide survey, especially in Mediterranean climate ² . Most common species in Perth ³ .
Microscolex phosphoreus	WA, SA, VIC, TAS, NSW, QLD		
MEGASCOLECIDAE			
Perionyx excavatus	SA, VIC, TAS, NSW, QLD		
Amythas corticis	WA, SA, VIC, TAS, NSW, QLD		
Amythas rodeniensis	WA, VIC, NSW, QLD		One of the six most common species in Australia-wide survey, most abundant coastally in New South Wales and Queensland ² . Most common species in Sydney

1. Kingston, Temple-Smith 1989; 2. Baker et al 1997; 3. Garnsey 1994; 4. Baker et al 1996; 5. Baker et al 1992.

Plate 1 Native earthworm and soil block from 30 cm depth below pasture, Casino.
Note numerous open and in-filled burrows



Introduced species fall into two subgroups according to their place of origin and climatic zone of their distribution within Australia. Their origin is, to a large degree, reflected in their taxonomy with members of the first subgroup, belonging to the family Lumbricidae, having their origin in eastern and Mediterranean Europe. Within Australia they are concentrated in regions of temperate and mediterranean climate; in the east of the continent they are rarely found north of the New South Wales - Queensland border. The second subgroup is a more heterogeneous mixture derived from several families and contains species from widely separated locations including South America and Asia. The species predominate in Australia's tropical north, extending as far south as northern New South Wales. Many members of the group belong to the same family as the majority of Australian native species: the Megascolecidae. This family is endemic to an area from eastern Russia, through Asia, Malaysia, Indonesia, New Guinea, Australia and New Zealand, and contains perhaps 2000 species. The overlay of introduced over native members of the same family, within Australia, has caused unresolved difficulties in determining the true origin of some species.

From the distributions of these two groups of introduced earthworm species it is apparent that there is a broad transition zone within which the species dominant under arable soils shift from predominantly European to predominantly tropical ones. The zone stretches from south of Sydney to the Queensland border. Distribution maps of species (Baker et al 1997) show that some species within each group traverse this entire zone, rather than there being a sequence of species replacing each other across the zone. Some species are apparently able to tolerate a wide range of maximum and minimum temperatures and rainfall. Within this extensive area it is presumed that microclimatic conditions, notably soil temperature and moisture, as mediated by altitude, aspect and distance from the

ocean, combined with local soil conditions, determine the presence or absence of a species. Considerably more earthworm survey is required, particularly in the north and west of the continent, in order to reveal the key factors that determine the distributions of the two subgroups.

Interactions between native and introduced species

Within southern Australia at least there appears to be an incompatibility between native earthworms and the changes made to soils in the process of preparing them for agriculture. Whether any particular change, such as soil disturbance *per se*, removal of native plants or alteration of pH and/or fertility is a key factor is unknown. The equivalent picture for tropical and especially subtropical Australia is only now emerging and is still based on very inadequate surveys. Published results for the region come only from the 'Worms Downunder' project (Baker et al 1997) but because of a lack of consistency and rigour in the collecting, and taxonomic difficulties in separating some of the introduced, as well as most of the native species, little information on interrelationships between the two groups can be deduced. However, an as yet unpublished survey in northern NSW in recent months by the author does have the potential to do so. In a preliminary survey of earthworms at 50 sites under a variety of orchard crops, sugar cane and pasture, within about 100 km of Alstonville on the NSW north coast, Kingston (in prep.) found that lumbricids, 'tropical' exotics and native species were found at seven, 41, and 19 sites. Lumbricids and tropical exotic species were not mutually exclusive, tropical species being present at six of the seven sites occupied by lumbricids. Of the 19 sites at which native species were found, exotics were also found at 14. This level of intermixing of native species with both groups of exotic species at the same sites has not previously been reported.

Conclusions

The current state of knowledge of the major groups of soil fauna is extremely poor, whether it be taxonomy, biology, ecology, distributions, or their inter-relationship with other groups or with agricultural management. This statement applies generally for Australia but is especially true of the northern half of NSW. There are some useful data sets for earthworms but they come mostly from uncoordinated studies in temperate and mediterranean regions and largely relate to species introduced from Europe. Next to nothing is known about more tropical exotics and rather less about native species. Considering the demonstrated benefits available from soil fauna, the ease with which populations can be depleted by unsympathetic management practices, and their potential use as indicators of soil conditions, this lack of knowledge is surprising. The onfarm consequence of this data deficit is that land managers are unable to realistically take account of the welfare of their underground 'stock' in the way they are used to doing for their more traditional above-ground plants and animals.

As farmers increasingly move towards ecologically-based management they will be rewarded with soil conditions compatible with increased abundance and diversity of soil fauna, including species exterminated during times of harsher practices. If remnant soil fauna populations have survived locally along fence lines, creeks or

small patches of remnant bush then they are likely to recolonise without intervention. If no such reserves exist, then experimental reintroductions from further afield or of proven overseas species may be required. There are obvious advantages in using native soil faunal species that have evolved under local conditions.

Taking into account the recent confirmation of widespread, diverse and locally abundant populations of native and introduced earthworms persisting under agricultural soils in subtropical NSW, and the fact that some of these species clearly possess the desirable qualities of large size and deep-burrowing habits, the potential benefits to be derived from earthworms in the region is as high as for any other region of Australia. With such potential from the native species it no longer makes sense to focus our efforts on seeking additional overseas species for active introduction, as proposed by Baker (1996), a mindset perhaps overly influenced by the success of the dung beetle story.

While much more needs to be known about almost all aspects, review of the current literature has strongly endorsed the soil biologist's perspective that greater combined abundance and diversity of soil fauna (and one lacking in bioaccumulated chemicals), both supports and reflects 'biologically sustainable' agricultural systems and soils that a majority of observers would describe as 'healthy'. It needs to be appreciated that these latter terms are by no means synonymous with 'most productive'. Indeed, taking care of soil fauna and attaining biological sustainability are likely to come at a cost to production. On marginally productive properties this cost may well be the 'final straw' that breaks the back of economic sustainability. Socio-economic considerations must then be invoked in the formation of a new paradigm for the use and management of the land, one that may involve continuing the operation with an organic matter 'subsidy' or alternatively, a move to a lower intensity usage encouraged and supported by financial incentives.

Recommendations

There is a dire need for a significantly increased effort, in both research and education, on all aspects of soil fauna throughout Australia, but the need is greatest in tropical and subtropical regions. Examples of the kind of research required under a variety of climate and crops include:

- surveys of earthworms and other soil fauna in soils under both agricultural management and bushland remnants
- studies of the impact on soil fauna, over a minimum of three years, of frequently employed management practices including irrigation (including with dairy effluent), drainage, cultivation, land levelling, mulches, herbicides, insecticides and fungicides
- studies of the life cycle of representatives of the major groups of soil fauna, particularly of native earthworms
- screening of native soil fauna to test their capacity for reintroduction into soils under agricultural management

- studies of the introduction of both native and exotic earthworms, alone and in combination, into study plots and the monitoring of their populations over a period of 5-10 years
- revision of economic models of analysis of agricultural operations to account for the declining 'ecological capital' of depleted soil organic matter and soil biota.

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Role of organic amendments in disease control

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In agriculture and horticulture, organic amendments such as composts and green manures have long been valued as good sources of organic matter and slow-release fertilisers. Organic matter is important for improving soil structure and ensuring a microbiological balance that is vital to the health of the soil and the plants it sustains. However, the quality of the incorporated organic amendments determines the eventual microbial composition and diversity developing in the soil, which then impact on the interactions between beneficial microorganisms and plant pathogens. Some crop residues have also been found to be superior to others. For example, brassica crops have been used in many countries for crop rotation and as green manures. The seed meal, following the extraction of oil, has a high protein content and has served as an important agricultural fertiliser in China and the Indian sub-continent. The fortuitous disease-suppressive effects of the seed meal and crop residue amendments were probably not fully realised in the past but contributed to the production of healthy crops and sustainable systems of agriculture, which have lasted for thousands of years in those countries. In the last few decades, increasing scientific research has been carried out to explain the disease-suppressive effects of composts and brassica amendments. This paper will explore some of this research.

Mechanisms of pathogen suppression

Certain types of composts have been shown to suppress a range of plant pathogens and pathogenic nematodes. The diverse antagonistic microflora present in these composts are thought to mediate this suppression. The beneficial microorganisms achieve this through the production of antibiotics that suppress the pathogen either in the resting stage or when the pathogen is at the infection site. Other microorganisms parasitise the resting bodies or actively growing stages of the pathogens. There is also evidence that some microorganisms present in the roots of plants can induce localised or systemic resistance in plants and thereby ward off infection either in below-ground parts or in the foliage. For example, the suppression of the take-all pathogen of wheat by closely related non-pathogenic fungi is due to induced localised resistance. There is no evidence of antibiosis, parasitism or the production of phytoalexins (Deverall et al 1978) and the presence of the non-pathogenic fungi in the wheat root cortex induces greater lignification (strengthening) of the vascular tissues directly below the colonised cortex (Speakman, Lewis 1978). As this is a localised response, a large proportion of the root system would have to be colonised in order to provide adequate protection. Therefore, competition for root cortical tissues is critical. This was confirmed when a dose response in disease control was obtained by the application of increasing rates of the non-pathogenic fungi in field experiments (Wong et al 1996).

There are increasing examples of compost microorganisms inducing systemic resistance, that is, their activities in the root systems can cause aerial plant parts to become resistant to such diseases as anthracnose and grey mould (Wei et al 1991, Zhang et al 1996, De Meyer et al 1998). This phenomenon may account for numerous observations that plants are more resistant to diseases when grown in compost or green manure amended soils. Scientists are hopeful that it may be possible to isolate microorganisms that are responsible for inducing systemic resistance and apply them to the soil under the right environmental conditions to obtain effective disease control.

Biofumigation

Biofumigation is a term used to describe the suppression of soil-borne pests and pathogens by *Brassica* crops (Angus et al 1994). There is considerable interest in biofumigation as an alternative to synthetic soil fumigants in horticulture and for the control of intractable soil-borne pathogens in broadacre agriculture. It may also become a cheap replacement for the common chemical fumigant, methyl bromide, which will soon be banned. The main mechanism of suppression of plant pathogens and pests by brassica amendments is through the production of a range of toxic gases called isothiocyanates, released when the brassica residues decompose in soil. These compounds are selectively biocidal, being more effective against some pathogens and pests than others. The superior growth and yield of wheat following brassica crops such as canola (*B. napus*) and Indian mustard (*B. juncea*) has been attributed to the suppression of soil-borne fungal pathogens by the gases released from the crop residues (Kirkegaard et al 1996).

Apart from the direct biocidal effects of the toxic gases on fungal pathogens, the brassica amendments appear to enhance the populations of antagonistic microflora such as bacteria, actinomycetes and fungi (Ramirez-Villapudua, Munnecke 1987). Sharma and Trivedi (1987) found that a parasite of nematodes, *Paecilomyces lilacinus*, was unaffected by mustard meal and proliferated in a medium of rice husks and oilseed meals. My preliminary studies also show a succession of fungi following the incorporation of mustard meal into soil, beginning with growth of tolerant fungi such as *Rhizopus* and *Mucor* species, followed several days to a week later by a flush of *Trichoderma* species and actinomycetes (Wong, unpublished). The overall increase in biological activity and, in particular, the increase in antagonistic microflora would serve the useful role of 'mopping up' the pathogenic fungi which may have escaped the toxic effects of the gases. The duration of this suppression is not known but is expected to last several weeks, if not months. Therefore, the application of these amendments on a regular basis could ensure that disease and pest pressures do not become high enough for chemical pesticides to be required. Research is in progress to investigate the types of brassica residues to use, the brassica species that release the most toxic isothiocyanates for targeted pathogens, and the methods and rates of application for optimal efficacy without phytotoxic effects on crops.

Disease-suppressive composts

The nature of the disease-suppressiveness of composts is not fully understood but it appears that composts that have been matured for a long time (more than six months) tend to be highly disease-suppressive (Hoitink, Boehm 1999). These composts contain large and diverse populations of mesophilic microflora that usually grow at temperatures of 20-35°C and include large proportions of microbial antagonists of plant pathogens. However, mature composts are not all equally disease-suppressive (Chen et al 1988, Inbar et al 1991). In attempts to produce highly suppressive composts consistently, various microbial antagonists such as *Trichoderma*, *Flavobacterium* and *Enterobacter* species, have been added to the composts at the last stages of composting so that these mesophilic antagonists would predominate (Hoitink, Fahy 1986). It has now been confirmed that these added antagonists significantly increase the suppressiveness of well-matured and stabilised composts (Hoitink, Boehm 1999). It may be possible in the future to tailor-make composts for various glasshouse or field situations.

Some factors affecting pathogen suppression

Temperature

Most of the serious pathogens of economically important crops are mesophiles, active at temperatures of 20-35°C. However, the temperature range for growth and infection of these pathogens can extend to lower temperatures, eg *Botrytis cinerea* (16°-21°C), *Pythium* species (7°-30°C), *Phytophthora infestans* (5°-30°C), *Rhizoctonia solani* (10°-32°C) and *Sclerotinia sclerotiorum* (4°-26°C). Therefore, for microbial antagonists present in organic amendments to be effective in the field, they have to be active throughout the whole temperature range or at those ranges that favour infection. In attempts to select specific biocontrol agents for disease control, potential agents screened at 25°C in the laboratory failed when tested at soil temperatures of 10-15°C in field experiments because they were not cold tolerant (Wong et al 1996). The greater diversity of microbial antagonists in organic amendments would improve the chances of successful disease control.

Moisture

Pathogens such as *Pythium* and *Phytophthora* species flourish in wet soil conditions, so the microbial antagonists required to combat these pathogens would need to grow in the same conditions. Bacteria and protozoa are most active in very moist to wet soils and would, therefore, be more effective against these pathogens than fungi and actinomycetes, which generally require drier soil conditions. It is unlikely then that one biocontrol agent will be suitable for the control of a number of plant pathogens, especially when the environmental conditions for their pathogenic activities are dissimilar. As such, the great diversity of antagonistic microflora in mature composts could account for the control of a broader spectrum of pathogens.

pH

Some *Trichoderma* species have been commercialised as biocontrol agents for several crop diseases (Fravel 1999). However, the various species of this fungus tend to be active only under acid soil conditions of pH 5-6. Their efficacy is reduced or non-existent at higher pH of 7-8. As such, other groups of fungi or bacteria will

have to be selected for alkaline soils. Again, the microbial diversity in mature composts would overcome this deficiency in a single biocontrol agent.

Substrate quality

The maturity of composts and the freshness of incorporated green manures can affect the behaviour of plant pathogens. Hoitink and Grebus (1994) found that immature composts provide a food source for plant pathogens such as *Pythium* species and *R. solani*, and exacerbate disease severity. This would also be the case for freshly incorporated green manures. However, excessively stabilised compost did not support the activities of the antagonistic microflora and also resulted in more disease. Therefore, the age and quality of organic amendments are of the utmost importance. In addition, Erhart and Burian (1997) show that the degree of suppression of *Pythium* damping-off disease is related to the organic matter content of the compost.

Management of organic amendments

Traditionally, large annual incorporations of more than 50 tonnes/ha of green manures and composts have been considered necessary for disease control and fertility. However, in the turf industry, Nelson and Craft (1992) have shown that monthly applications of relatively small amounts of suppressive composts, around 500 kg/ha, have suppressed turf diseases such as dollar spot (*Sclerotinia homoeocarpa*), brown patch (*Rhizoctonia solani*) and *Pythium* root rot (*Pythium* species). Moreover, the application of regular top-dressings and root-zone amendments of suppressive composts were as effective as chemical fungicides in suppressing *Pythium* root rot in established turfgrasses (Nelson et al 1994). As such, regular or strategic applications of highly suppressive composts may provide a way to control some notably intractable soil-borne diseases. This is encouraging for broadacre agriculture and may also explain the success of the organic farming practice of the regular use of side-dressings of composts as fertiliser and for disease control.

Conclusions

The control of plant diseases by organic amendments is founded on the encouragement of large, diverse populations of antagonistic microorganisms that reduce the activities of pathogens in crops and fallow, when the resting stages of the pathogens may be attacked. The amendments have to be suitably aged or mature before cropping as the quality of the substrates may alter the population dynamics of the pathogen-antagonist relationship and, therefore, the expression of disease. A good knowledge of the ecology of the pathogens and microbial antagonists may also assist in the provision of the most suitable environmental conditions for pathogen suppression.

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Molecular techniques for measuring soil microbial diversity

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More than one million bacterial species exist on this planet, yet fewer than 4500 have been described (Heywood 1995). Despite the importance of microbial activity in the health of soil, the diversity of microbial species and the circumstances that govern their activities have not been explored in depth. These have been treated as a 'black box', an approach that ignores possible controls of processes by species or community interactions.

The inability, however, to identify greater than 90% of community members through cultivation makes this job intimidating (Hugenholz et al 1998). The technical difficulties associated with defining species in soil have led to a number of culture-independent approaches that measure biodiversity of microbial communities. These procedures are either process-orientated, such as carbon utilisation profiles appraised via BIOLOG plates (Heuer, Smalla 1997), or census-based approaches such as comparative analysis of ester-linked fatty acids (Cavigelli et al 1995), or single or multiple genetic markers.

This paper focuses on the genetic marker approach. The intention is not to appraise the various techniques but to provide an overview of current molecular approaches in exposing microbial diversity.

Measuring biodiversity

Techniques that do not rely on culturing, such as molecular biology, have become a powerful means to describe microbial diversity and potentially unearth its role in ecosystem maintenance. There are three distinct phases in the application of molecular methods in soil microbiology. The first phase is characterised by the development of methods to isolate and amplify nucleic acid molecules from soil in the presence of inhibitors. The second phase reflects microbial evolutionary relationships, where microbes are grouped according to similarities in genes fundamental to all life forms (eg rDNA genes) or unique to certain physiologies (eg nitrogen fixation). The third and arguably the most central phase is combining the molecular information with soil process measurements to provide an understanding of what constitutes a healthy soil (O'Donnell, Gorres 1999).

Isolation of microbial nucleic acid

There are a number of reports in the literature describing methods for isolating microbial community DNA from several different environments. The reader is referred to Trevors 1992, and Coutinho et al 1999 for detailed reviews. Generally,

DNA isolation methodologies derive from two approaches, *in situ* lysis and DNA recovery, whereby the microorganisms are lysed in the soil matrices and the DNA is subsequently isolated and purified (More et al 1994, Zhou et al 1996, Cullen, Hirsch 1998). The alternative approach is microbial fractionation which relies on removing microorganisms from soil before cell lysis and DNA retrieval (Hopkins et al 1991). This method is seldom used today largely due to inefficient recoveries.

Most molecular microbiologists favour the direct isolation procedure because yields are higher, which consequently increases the sensitivity of the measurement. *In situ* nucleic acid extraction procedures also offer quicker turn around times and lower cost per unit extraction, not to mention the convenience associated with using commercially available kits. As with most methods, problems do arise, particularly when dealing with soils high in organic matter. Soluble humic acids and other organic compounds tend to be co-extracted with the DNA, thereby inhibiting subsequent molecular analyses. For the additional cost of a cafe latte, soil DNA can be promptly decontaminated using a range of commercially available purification kits.

16S rRNA genes

One of the most powerful ways to explore microbial diversity in nature is to analyse DNA sequences that encode the bacterial 16S ribosomal RNA (rRNA) molecule. This molecule is found in all life forms and is essential for translating genes into functional proteins. Since certain structural features of the 16S rRNA molecule must be preserved for its function, it follows that 16S rRNA gene sequences are highly conserved. Indeed, within the bacterial kingdom, this is what one finds. Structural constraints ensure against mutational changes that may compromise the functional integrity of the 16S rRNA molecule. However, throughout the course of hundreds of millions of years of evolution, non-deleterious mutations have slowly accumulated in segments of the 16S rRNA gene known as divergent regions (Woese 1987). Sequencing these divergent regions in the 16S rRNA genes and then comparing the sequences to a database of known 16S rRNA sequences can lead to the rapid identification of bacterial isolates.

This pattern of gene conservation has been exploited in determining microbial diversity through amplification of these regions via polymerase chain reaction (PCR), cloning the products and subsequently sequencing the library clones. The power of this technique rests in its ability to reveal uncultivable bacteria and measure the diversity of the soil community. A number of researchers have isolated from total DNA soil libraries rDNA sequences that have not been found in cultured bacteria (Stackebrandt et al 1993, Rheims et al 1996, Chandler et al 1997, Felske et al 1997, Kuske et al 1997).

As a result of the widespread adoption of the 16S rDNA approach, the size of ribosomal DNA sequence databases has increased. Besides resolving phylogenetic issues, expansions in the field of comparative genomics (bioinformatics) have facilitated the isolation of novel organisms for the biotechnology industry, and advanced the development and application of DNA hybridisation and rapid genetic fingerprinting techniques to dissect microbial soil communities and study

successional changes. Comparative genomics imparts an indispensable insight towards the designing of PCR amplification primers and hybridisation probes. Prior to the dawn of the PCR age, these sequence collections were primarily used to devise rRNA-targeting oligonucleotide probes. These probes could target signature sites of the rRNA molecule characteristic for defining phylogenetic entities such as species, genera, families, orders and even domains. Indeed, within the context of microbial ecology, one of the earliest exploits of such gene probes was the identification of ruminant bacteria using phylogenetic targeting rRNA probes (Stahl et al 1988). Identification of individual microbial cells has greatly profited by advancements made in fluorescent chemistry, particularly the ability to fluorescently tag probe molecules. This gave rise to a new visual technique, namely fluorescence *in situ* hybridisation (FISH) analysis. The technique consists of fixing the sample material onto a microscope slide and hybridising with a fluorescently labelled probe. The probe traverses through the cell wall and membrane, and binds to the complementary region within the 16S ribosomal RNA molecule (DeLong et al 1989). With the aid of an epifluorescent microscope, fluorescent emissions corresponding to microbial cells are visualised and counted. Given that ribosome numbers are proportionally related to protein synthesis (actively growing cells contain between 1000-10,000 ribosomes), the strength of the fluorescent signal may also be correlated with recent microbial activity (Wallner et al 1993).

DNA fingerprinting techniques

Several fingerprinting techniques have been developed with a view to providing comparative microbial community profiles of different environments and or to follow the behaviour of one population over time. These have been reviewed recently (Coutinho et al 1999, Marsh 1999, Muyzer 1999, Theron, Cloete 2000). The general strategy for genetic fingerprinting of microbial communities consists of isolating the nucleic acid, amplifying the target gene, and finally separating/analysing the PCR products on the basis of their composition (DGGE/TGGE) or size (T-RFLP).

Denatured gradient gel electrophoresis (DGGE) and its close cousin temperature gradient gel electrophoresis (TGGE) are capable of detecting sequence polymorphism by separating the PCR amplified DNA fragments based on their melting behaviour (Myers et al 1987). When subjected to double stranded DNA (dsDNA) to an increasing denaturing gradient, the double strands do not melt in a uniform fashion but in discrete units called melting domains. The PCR amplified products possess two domains: an artificially created high melting region, introduced via the PCR amplification primers (a GC clamp at the 5' termini) and the lower melting domain which comprises the region of interest (up to 450bps). When the melting temperature of the lowest melting region is reached, the double strand of this domain becomes partially melted, creating branched molecules, which effectively stops further migration through the gel. The position in the gel at which melting takes place, therefore, depends on base pair composition and sequence of the lower melting domain. Provided they melt at different denaturing conditions, the respective positions of equally sized dsDNA molecules on the gel should differ. For a more detailed account the reader is referred to Muyzer and Smalla (1998).

A method currently gaining wide acceptance for separating PCR amplified sequences is terminal restriction fragment length polymorphism (T-RFLP) analysis. As the name implies, T-RFLP analysis measures the size polymorphism of terminal restriction fragments from PCR amplified products (Liu et al 1997, Marsh 1999). In essence, the soil DNA is amplified from a high background of sample DNA and subsequently digested with judiciously selected restriction endonucleases. The choice of enzymes to be used in differentiating sequence variants of the target gene depends on the level of discrimination required. The resulting digests produce appropriately sized terminal fragments, which are resolved by automated sequencing or capillary electrophoresis systems that provide digital output. The use of fluorescently tagged primers limits the analysis to only the terminal fragments of the digestion. Because size markers bearing different fluorophore from the samples can be included in every lane, the sizing is extremely accurate (± 1 base). One sequence variant therefore corresponds to a single T-RFLP fragment. Comparison with terminal fragment sizes derived from RDP (Ribosome Database Project [Maidak et al 2000]) sequence entries allow for phylogenetic inferences to be made about the sequence variants within the T-RFLP profiles of mixed community PCR products.

Besides assessing amplification product diversity within a community, genetic fingerprinting techniques have been used to study specific microbial activities by targeting functional genes, and comparatively measuring microbial distribution across communities. A summary outlining the types of measurements, the entities under study (specific microbial activities/groups and changes brought about by management practices), and the molecular techniques employed, is presented in Table 1.

Conclusion

Molecular techniques in their current format have undoubtedly contributed to our awareness of the extent of microbial diversity in soils and to the largely untapped microbial resource. The long-term goals of using such approaches is to increase our understanding of important microbial processes, characterising the cues to which they respond and the mechanisms by which they are regulated, for the express purpose of diagnosing the health of soils and intervening when required. Realising these goals will require additional technology, extensive data collection, sophisticated computational tools, and efforts to discern cause and effect.

Table 1. List of molecular techniques used to measure microbial/gene diversity.

Measurements	Microbial community or genes under study or management practice	Techniques	References	
Microbial diversity		16S rDNA sequencing	Borneman et al 1996 Borneman, Triplett 1997 Dunbar et al 1999	
		DGGE/TGGE	Muyzer et al 1993 Felske et al 1996 Smialla K et al 1996 Heuer et al 1999 Smit et al 1999	
		T-RFLP	Liu et al 1997 Dunbar et al 2000 Osborn et al 2000 Derakshani et al 2001	
Functional microbial diversity	Actinomycetes	DGGE/TGGE	Heuer et al 1997	
	Ammonia-oxidising bacteria	FISH DGGE/TGGE T-RFLP	Juretschko et al 1998 Brunns et al 1999 Kowalchuk et al 1999 Horz et al 2000	
	Denitrifiers	T-RFLP	Braker et al 2001	
	Coryneform bacteria	DGGE/TGGE	Felske et al 1999	
	Cellulolytic bacteria	16S rDNA sequencing	Ulrich, Wirth 1999	
	Methanotrophs	DGGE/TGGE	Jensen et al 1998 Hanckel et al 2000	
	Plant rhizosphere microbes	DGGE/TGGE	Duineveld et al 1999 Smit et al 1999 Methling et al 2000 Yang et al 2001	
	Soil disease suppressiveness / conductiveness	16S rDNA sequencing DGGE	Shiomi et al 1999 Yang et al 2001	
	Changes in community diversity	Crop rotations	ERIC-PCR	Achouak et al 2000
		Composting	DGGE	Kowalchuk et al 1999
Flooding		T-RFLP	Lueders & Friedrich 2000	
Heavy metal contamination, pollution and soil bioremediation		TGGE/DGGE	Torsvik et al 1998 Brim et al 1999 MacNaughton et al 1999 Rasmussen, Soransen 2001	
Nitrogen fertiliser and tilling		DGGE, Group specific 16S rDNA PCR and sequencing	Ceccherini MT et al 1998 Brunns et al 1999 McCaig et al 1999 Phillips et al 2000	
Spatial and temporal and oxygen effects		16S rDNA sequencing, FISH and T-RFLP	Chin et al 1999a Chin et al 1999b Fey, Conrad 2000 Ludemann et al 2000 Lukowil et al 2000	
Pesticides		TGGE	Engelen et al 1998 el Fantrousai et al 1999	
Waste water		T-RFLP	Kerkhof et al 2000	
Functional gene diversity		amoA and amoB	DNA hybridisation PCR T-RFLP	Brunns et al 1998 Hastings et al 1998 Horz et al 2000
		dsz	DGGE	Duarte et al 2001
	mcrA/mrtA	T-RFLP	Lueders et al 2001	
	nifH	DGGE RFLP	Rosado et al 1998 Widmar et al 1999	
	[NiFe] hydrogenase	DGGE	Wawer et al 1997	

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Biologically active soils help suppress nematode pests

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Most of the horticultural crops grown in subtropical and tropical regions of north-eastern Australia are attacked by plant-parasitic nematodes (Table 1). In many of these industries, nematodes are serious pests, and nematicides and soil fumigants are used routinely to achieve control.

Table 1. Major nematode pests of horticultural crops in tropical and sub-tropical regions of north-eastern Australia.

Crop	Nematodes	Pest status
tomato, potato, sweet potato, capsicum, zucchini, rockmelon	root-knot nematode (<i>Meloidogyne</i> spp.)	A serious pest in most vegetable crops grown in sandy or well-structured clay loam soils. Of major importance in Bundaberg and other coastal regions of Queensland and NSW.
pineapple	root-knot nematode (<i>Meloidogyne javanica</i> .)	A major limiting factor on about 25% of pineapple farms.
banana	burrowing nematode (<i>Radopholus similis</i>) and lesion nematodes (predominantly <i>Pratylenchus goodeyi</i>)	Serious pests in both tropical and sub-tropical regions.
apple	lesion nematodes (<i>Pratylenchus penetrans</i> and <i>P. jordanensis</i>)	One of the factors causing apple replant problems in the Granite Belt, Queensland.
citrus	citrus nematode (<i>Tylenchulus semipenetrans</i>)	Occurs on many farms in the Burnett region of Queensland. The importance of the nematode is underestimated by industry.
grape	root-knot nematodes (<i>Meloidogyne</i> spp.)	Widespread on wine grapes in the Granite Belt. Commonly found on table grapes in Queensland and the Northern Territory.
strawberry	root-knot nematodes (<i>Meloidogyne</i> spp.) and lesion nematode (<i>Pratylenchus vulnus</i>)	An occasional problem because of the widespread use of soil fumigation.
ginger	root-knot nematodes (<i>Meloidogyne</i> spp.)	Important on many farms, particularly in late-harvested crops and market ginger.
turf	many species	Common on turf and an important component of the root disease complex.
ornamentals	root-knot nematode (<i>Meloidogyne</i> spp.)	A serious problem on some crops (e.g. riceflower).

Health and environmental effects of nematicides

Several soil fumigants have been removed from the market in the last 25 years (eg DD, DBCP and EDB) and many of the remaining chemicals used against nematodes are detrimental to human health and the environment. All nematicides and soil fumigants are relatively mobile in soil and therefore have the potential to contaminate groundwater (Thomson 1987). Atmospheric pollution is an ongoing problem with the fumigants because they are extremely volatile materials. Methyl bromide is being phased from use because of its ozone-depleting properties while its potential replacements (metham sodium, chloropicrin and 1,3 D) will readily drift off-site if fumigated soil is not sealed adequately. The non-volatile organophosphate and carbamate nematicides have the highest mammalian toxicity of all the chemicals currently used in horticulture. Another problem from a grower's perspective is that the usefulness of nematicides is threatened by enhanced microbial degradation. Microorganisms capable of degrading fenamiphos (Nemacur®) are already widely distributed in Australia (Stirling et al 1992), while enhanced degradation of metham sodium has recently been reported from Western Australia (Warton et al 2001). The above problems will almost certainly result in a continuing decline in the number of chemicals available for use against nematodes.

IPM as it applies to nematodes

As the number of registered nematicides and soil fumigants declines, growers will have little choice but to start using integrated pest management (IPM) to achieve nematode control. The appeal of IPM is that it provides acceptable procedures for managing pests in sustainable agricultural systems. In the case of nematodes, population densities are measured and control tactics are implemented only when infestation levels are above the economic threshold. When measures are required to reduce nematode populations, the economic and environmental impacts of possible control options are considered and the safest and most effective tactics are chosen. These tactics include crop rotation, fallowing, resistant varieties, various cultural and biological controls, and the strategic use of nematicides.

In north-eastern Australia, the IPM systems currently used against nematodes are in their infancy. The banana and pineapple industries have taken their first tentative steps towards adopting IPM by establishing monitoring programs that determine whether nematode population densities in particular fields have reached damaging levels. Control is still achieved mainly with nematicides, but monitoring is enabling growers to use them strategically rather than routinely. In the vegetable industry, an increasing number of growers collect samples from fields before planting and have them analysed for nematodes. Non-chemical management strategies are also being used more frequently. Some vegetable growers reduce nematode and soil-borne disease problems by rotating with sugarcane or nematode-resistant green manure crops such as forage sorghum. Others prepare beds for planting and then use appropriate fallowing, solarisation and irrigation techniques to reduce nematode populations to acceptable levels by the time the crop is planted.

Biological control of nematodes

Biological control is a vital component of IPM programs for some insect pests, but there are no examples anywhere in the world of the successful use of introduced

natural enemies to control plant-parasitic nematodes. Many bacteria, fungi and other soil organisms parasitise or prey on nematodes, but many of these organisms cannot be grown in culture, are difficult to mass-produce or cannot be formulated in a commercially acceptable manner. However, the main limiting factor with laboratory-cultured natural enemies is that they often fail to establish or are relatively ineffective when they are introduced into soil (Stirling 1991). The reason for this is that the introduced organism must compete with the multitude of other organisms already established in the soil environment. Progress has been made with some fungi in recent years (Stirling et al 1998a, 1998b; Stirling, Smith 1998), but biocontrol systems based on one or a few mass-produced organisms have never been consistently successful. Some Australian companies have experimented with or marketed products based on egg-parasitic fungi (eg *Paeclomyces lilacinus* and *Verticillium chlamydosporium*) or nematode-trapping fungi (eg *Arthrobotrys* species), but these products have never been registered in Australia and there is no experimental evidence that they are effective. Thus the most practical way to use biological control is to conserve and enhance the activity of the natural enemies of nematodes that occur naturally in all horticultural soils.

Nematode-suppressive soils

Fungi that produce specialised trapping structures to capture nematodes are present in most Australian soils (McCulloch 1977), while fungal parasites of nematode eggs and the bacterial parasite *Pasteuria penetrans* are also commonly found (Stirling, White 1982, Stirling, West 1991). However, survey data indicate that these indigenous natural enemies of nematodes tend to have their greatest impact as biological control agents in perennial rather than annual cropping systems (Stirling, White 1982, Mertens, Stirling 1993). The reasons for this are not known, but one possibility is that perennial crops are subject to minimal disturbance (Stirling 1999). Specialised parasites of nematodes occupy the same ecological niche as their nematode hosts and cultivation tends to destroy the intimate relationship that develops between host and parasite. Thus circumstantial evidence suggests that the activity of indigenous natural enemies of nematodes will be enhanced if cultivation is minimised.

Another way of manipulating the environment to favour the natural enemies of nematodes is by adding crop residues, animal manures, composts and other organic materials to soil. Organic inputs induce a succession of microbiological changes in soil and as decomposition proceeds, populations of various parasites and predators of nematodes increase and biological control activity is enhanced. Mechanisms other than parasitism and predation are probably also involved (Stirling 1991). For example, some of the chemicals released from organic materials during the decomposition process (eg ammonia, nitrites and various organic acids) are toxic to nematodes. Plants also tend to become more resistant to attack by nematodes following the addition of organic matter to soil, possibly because microorganisms in the rhizosphere activate natural nematode-resistance mechanisms in the plant. The detrimental effects of nitrogenous amendments on plant-parasitic nematodes have been known for many years (Rodriguez-Kabana 1986). Proteinaceous materials, poultry manure, residues from leguminous crops and other nitrogenous waste materials produce ammonia when they decompose in soil, and ammonia is

nematicidal at concentrations in excess of 300 mg/kg soil. Since the amount of ammonia produced varies with the level of nitrogen in the amendment, the effectiveness of nitrogenous amendments against nematodes will increase as the nitrogen content increases. The usefulness of high-nitrogen containing materials such as poultry manure has been demonstrated in Australia (Stirling, Nikulin 1998), while Lazarovits et al (2001) have shown that soybean meal and meat and bone meal are useful in field trials in Canada. However, to be effective, such materials must be added to soil at relatively high application rates (at least 2% of soil mass or more than 40 tonnes of dry matter/ha). Since high concentrations of nitrogen in soil can cause phytotoxicity, planting may need to be delayed when nitrogenous amendments are applied. Plant-back periods can be reduced by adding a source of carbon, as this balances the carbon nitrogen ratio and allows soil microorganisms to more effectively convert the excess nitrogen into proteins and other less toxic compounds.

Although there has been less experimental work with high-carbon amendments, results of recent studies suggest that they can also be used to suppress nematodes. Pine bark was effective against root-knot nematodes in glasshouse experiments in the USA (Kokalis-Burelle, Rodriguez-Kabana 1994), while sawdust and molasses reduced galling caused by root-knot nematodes in a field trial on tomatoes at Bundaberg (Vawdrey, Stirling 1997). The mechanism of action of high-carbon materials is not known, but fungi are mainly responsible for their decomposition, and it is thought that some of these fungi may also be antagonistic to plant-parasitic nematodes. Pine bark and some wood products are also rich in phenolic compounds that may be directly toxic to nematodes. The main problem in using such amendments is that the nitrogen status of soil must be managed carefully so that nitrogen drawdown does not become a problem.

Despite the fact that scientists continue to demonstrate the benefits of using organic matter for nematode control, the practice of adding organic amendments to soil is still not widely accepted in horticulture. One of the main reasons for this is that the effectiveness of amendments depends on their chemical composition and application rate, and there are currently no guidelines on how locally-available organic materials can be prepared and used for nematode control. It is clear from studies of fungal pathogens such as *Pythium* (see review by Hoitink, Boehm 1999) that the concentration and availability of nutrients in soil organic matter regulates the activity of disease-suppressive microbial communities. Sustained biological control of certain soil-borne fungal pathogens is achievable, but a minimum threshold level of microbial activity must be maintained. The situation with nematodes is likely to be similar. The critical question is what type and amount of organic matter must be added to soil to maintain a biological community capable of providing a consistent and useful level of nematode suppression.

Current research

Currently, I am trying to determine the level of biological activity that is required to reduce populations of root-knot nematodes to densities that are not economically important. Plots that have received different organic inputs have been established in two different soils in Bundaberg and changes in various biological parameters are

being measured over time. Initial results from one trial (Table 2) clearly show that total numbers of free-living nematodes and microbial activity increase as increasing amounts of organic carbon are added to soil. Populations of root-knot nematodes were reduced and tomato plants had fewer galls in soils receiving carbon inputs of more than 23 t/ha. These inputs were achieved by adding sugarcane trash and growing a green manure crop of forage sorghum and lab lab.

Table 2. Biological status of organically amended soils at Bundaberg, and the effects of various organic inputs on root-knot nematodes.

C applied (t/ha)	No. of free-living nematodes/200 ml soil	Microbial activity ($\mu\text{g FDA/g/min}$)	No. of root-knot nematodes/200 ml soil	Root gall rating on tomato
0	1320 d	0.145 d	977 a	7.83 a
10	3160 c	0.197 d	417 b	7.00 ab
17	3890 bc	0.202 cd	331 bc	7.00 ab
23	4790 bc	0.262 bc	407 b	6.50 b
33	5750 ab	0.323 ab	282 c	5.33 bc
43	5250 a	0.370 a	245 c	5.00 c

Within each column, numbers followed by the same letter are not significantly different ($P=0.05$)

Conclusions

A trend towards monoculture, excessive use of the rotary hoe and other tillage implements, lack of replenishment of organic matter, widespread use of plastic 'mulches', and over-dependence on herbicides and chemical fertilisers have reduced the fertility of many soils used for horticulture. These soils are susceptible to erosion, poorly drained, inadequately aerated, and have limited biological activity and therefore provide an environment that is ideal for the development of chronic nematode and root disease problems. There is experimental evidence to show that increasing the amounts of labile organic carbon in soil will increase microbial activity, reduce nematode problems and have many other positive effects on soil health. However, the changes in soil biology that are required to improve degraded soils cannot be achieved quickly or with limited organic inputs. Organic amendments can help in the fight against nematodes but they may not provide the level of nematode control that is achievable with nematicides. Thus they should always be used as a component of an IPM program for nematodes rather than as a stand-alone control procedure.

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The good, the bad and the ugly: copper and arsenic in soils.

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Soil contamination is an emotive and potentially contentious subject area, particularly if the land also happens to be used for the growing of food crops. The use of chemicals to control diseases, weeds and pests is often necessary and unavoidable in profitable agricultural production systems. However, in some situations the long-term build up of residues in soils from the extensive use of agricultural chemicals may have potentially detrimental and far-reaching consequences.

This paper discusses the behaviour of arsenic and copper in soils associated with the long-term or excessive usage of agricultural chemicals containing these elements. It also aims to demonstrate the importance of being able to ascertain what concentrations of these elements are potentially detrimental or toxic, how these effects may be manifested and what can be done about it. This final objective builds on collaborative work currently being performed by NSW Agriculture and Adelaide University.

Background

The use of copper and arsenic to control agricultural and horticultural weeds, pests and diseases has a very long history. Indeed, fungicidal sprays such as Bordeaux mixture, copper oxychloride and lead arsenate have been used in Australia for over 100 years and elsewhere, in the case of Bordeaux mixture, for over 1000 years. The use of arsenic-based insecticides and herbicides has greatly diminished in the last 30 years with organic chemical alternatives and environmental safety concerns restricting their continued application. However, copper fungicides are still widely used, and in Australasia over 7500 tonnes of copper fungicides are applied every year, representing 13% of the global total (Lepp, Dickinson 1994).

The two elements differ widely in their chemistry and potential toxicity, but both tend to accumulate in the surface horizons of soils. Copper is an essential trace element, being required by all living organisms in small quantities for the completion of life cycles and function. Arsenic is a non-essential element, in that it has no known beneficial biological function. Both elements occur naturally in soils, primarily originating from parent materials and rocks underlying the soil surface. The typical range of concentrations in soils from a range of sites are shown in Table 1.

Table 1. Typical background or 'natural' copper and arsenic 'total' concentrations in a range of world soils (mg kg⁻¹ or parts per million).

Location	arsenic (mg kg ⁻¹)	copper (mg kg ⁻¹)
Australia	1-20	0.4-200
UK	10-51	1.2-1508
USA	5.2	0.6-495

*Total concentrations are considered to be those obtained through strong mineral acid digestion.

Anthropogenic or human-induced enrichment of soil concentrations of copper and arsenic may occur through many sources such as mine wastes, combustion of fossil fuels, smelting, and of course through the deliberate application (or indirect application) of agricultural treatments such as pesticides, fungicides and herbicides. Copper and arsenic may also be present in animal foodstuffs, and therefore often present in animal wastes and manures. Table 2 shows the range of total soil concentrations of arsenic and copper from a range of sources with different histories of application and contamination.

Table 2. 'Total' concentrations of arsenic and copper in soils contaminated from a variety of sources.

Source of contamination	Arsenic (mg kg ⁻¹)	Source of contamination	Copper (mg kg ⁻¹)
Lead arsenate, apple and pear orchards ¹	3-24	Copper fungicide, citrus plantation ¹	84-98
Lead arsenate, apple orchard ²	209	Copper fungicide, apple orchard ²	1108
Arsenicals, apple orchard ³	9.8-124	Copper fungicide, citrus grove ³	100-380
Arsenic, cattle dip sites ⁴	0-3000	Copper fungicide, vineyard ⁴	200-500
Arsenic, mine tailings ⁵	120-14800	Copper smelter ⁵	11-1890
Arsenic, potato crop ⁶	6-26	Copper fungicide, hop field ⁶	>150

- | | |
|--------------------------|------------------------|
| 1. Merry et al 1983 | 1. Graham et al 1986 |
| 2. Aoyama, Nagumo 1996 | 2. Aoyama, Nagumo 1996 |
| 3. Bishop, Chisholm 1962 | 3. Alva et al 2000 |
| 4. Smith et al 1998 | 4. Brun et al 1998 |
| 5. Stavrakis et al 1994 | 5. Dudka et al 1995 |
| | 6. Filser et al 1995 |

Importantly, both elements tend to accumulate in soils, because their depletion and removal from the soil via plant uptake, leaching, erosion and methylation (in the case of arsenic) occurs only very slowly (Smith et al 1998). Estimates have suggested that concentrations of both elements may persist for well over 120 years, before a return to background or natural levels is observed (Merry et al 1986). In the case of arsenic, the greatest levels of accumulation have been reported for soils that have

received treatments of arsenic-based insecticides rather than arsenic-based herbicides, probably because herbicides tend to be applied at lower rates (Smith et al 1998). The greatest levels of copper accumulation occur in those vineyards, plantations and orchards with the longest history of application and in the wettest regions because conditions favour fungal outbreaks (Brun et al 1998).

How much is too much?

Clearly, the presence of either of these elements in soils is not enough to infer potential toxicity or elucidate some detrimental effect upon a soil process or growing plant. A further potentially complicating issue is that it is well known that the 'total' concentrations of metals in soils have very little bearing on potential toxicological effects. This holds true for both arsenic and copper, and it is the speciation or form of each element in the soil which determines the potential environmental impact.

Figure 1. Examples of metal-soil associations and their interrelationships.

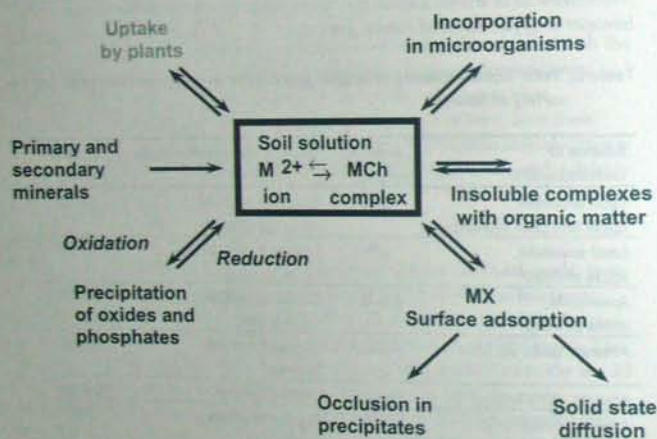


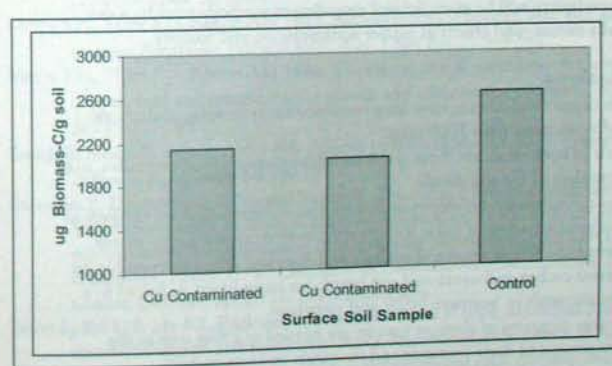
Figure 1, above, shows some of the associations of metals in soils. The soil solution box in the centre of the diagram is often considered to be of immediate importance to plant and microbial uptake of that element. Furthermore, regulations and guidelines relating to metal contaminants in soils are often based on the effects on human health as an endpoint. But both arsenic and copper may have toxic effects on plants and soil biota, such as earthworms and soil fungi, at concentrations below those that affect animal or human health (Smith et al 1998). Therefore, suitable measures of potential soil toxicity are required.

In copper's case, this is compounded by the unreliable nature of traditional plant tissue analysis and soil tests in recognising incipient copper toxicity. The leaf tissue of many crops does not closely reflect 'available' copper concentrations in the soil,

as copper tends to be strongly absorbed by plant roots and is not readily translocated through the plant (McBride 2001). The accumulation of copper in plant roots may lead to the inhibition of fine root development and also reduced trace element uptake (especially iron, but actually also copper!). A similar pattern may also occur for arsenic in most plants and therefore phytotoxic symptoms may rarely ever develop (Smith et al 1998).

In addition different organisms may have different sensitivities to copper, which may again be altered with changing soil texture, pH and soil organic matter content and form. Studies have shown that concentrations of copper as low as 15 mg kg⁻¹ can adversely effect earthworms (Helling et al 2000), mycorrhizal fungi (Graham et al 1986), microbial biomass (Zelles et al 1994) and biodiversity of soil fauna (Filsler et al 1995). These organisms are crucial for the healthy functioning of soil, and essential for the cycling of nutrient elements and the suppression of plant and root disease as well as the maintenance of soil fertility and sustainable agricultural systems. The potentially detrimental effect of long-term use of copper fungicide is shown below in Figure 2 derived from data obtained from the current collaboration between NSW Agriculture and Adelaide University. This graph shows the amount of biomass present in the surface horizons at three locations, two in northern NSW avocado orchards, the other a non-copper treated soil. The reduced biomass compared to the control may be considered as evidence of the potentially detrimental effects of copper accumulation and potential toxicity.

Figure 2. Biomass in surface soil samples from two sites within an avocado orchard in northern NSW and a control non-copper contaminated soil.



It is clear that useful, practical measures of potential arsenic and copper toxicity in soils are required. This is the first step in the management of soils that have received inputs from these pesticide sources, and in many situations are still receiving copper inputs.

Measurement and management of copper

A universally applicable measure of copper toxicity in soil is probably not available, but it has been suggested that free Cu^{2+} ion in solution (see central box in Figure 1) is the most toxic form or species under a range of environmental conditions (McBride 2001). Therefore, factors that reduce the formation of this form or species in soil may also be thought of as reducing the potentially damaging effects of copper. Although copper fungicides are effective in controlling the fungal diseases that afflict many of the crops grown in the tropics and sub-tropics, they have potentially damaging side effects and there are currently few alternatives to their use on the market.

Practical methods for removing copper from agricultural soils are presently not cost-effective and removing the soil is not a feasible option. Therefore, *in-situ* soil amendments offer a potential option for the reduction of copper toxicity as well as enhancing the soil processes which have been detrimentally affected. Such amendments may include organic materials like vermicomposts and green wastes or inorganic treatments like agricultural lime. The testing of these amendments and assessment of their potential is currently being undertaken in a collaborative project between NSW Agriculture and Adelaide University. Soil health and fertility equates very strongly to long-term agricultural and horticultural sustainability. The reduction of copper toxicity in plantation and orchard soils through the use of soil amendments will ensure sustainable management and production of plantation crops that require continued use of copper-based fungicides. The ultimate aim of the current research is to provide guidance to horticultural grower groups and plantation holders in the form of research extension material, within which recommendations will be given for soil amendment methods to reduce the potentially detrimental effects of copper accumulation and toxicity.

Conclusions

- Both copper and arsenic have long residence times in soils, under some conditions more than 1000 years.
- Levels of both elements, from previous or continued use of pesticides, may accumulate in the soil profile.
- Potentially detrimental effects of this gradual accumulation are unlikely to manifest themselves as foliar toxicity symptoms in growing crop plants.
- Detrimental effects upon soil animals and flora and fauna responsible for nutrient cycling and continued soil health are more likely, as found in a scientific study in northern NSW and elsewhere.
- Suitable measures of element toxicity are needed as a first step in the management of these pesticide and fungicide residues in soils.
- Potential solutions including the use of soil amendments need to be fully tested under field conditions. A collaborative research partnership between Adelaide University and NSW Agriculture is currently attempting to tackle this issue.

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Metal contaminant bioavailability in Australian soils

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The concept of bioavailability is intimately linked with soil health. For plant uptake, an element is bioavailable if it is present in a form that can readily be adsorbed by a plant and which can then affect the life cycle of that plant, all within a relevant time frame (Heil, Sposito 1997). The term bioavailability can also be extended to include assimilation of elements by other soil and aquatic organisms, as well as adsorption and assimilation of an element from the digestive system of animals. Under certain circumstances, a bioavailable element may also be quite mobile in the soil system and may therefore be transferred off site or downwards through the soil profile.

Concern about the accumulation of heavy metals and metalloids in Australian soils is increasing because of their potential threat to food production and environmental health (McLaughlin et al 2000). Our agricultural exports are increasingly being marketed as clean and green, and strict food standards are in place to regulate the maximum allowable concentration (MPC) of contaminants in food (ANZFA 1996). Metal inputs into our soils have come from the use of agricultural fertilisers and soil amendments, pest control, human and animal wastes, urban solid wastes, mining and smelter activities and atmospheric deposition (Chaney, Oliver 1996). Many of the above practices are necessary for the continued economic viability of many of our farming systems. Unfortunately, unlike many organic chemicals (eg organic pesticides), these metal contaminants will persist indefinitely in the soil and wider environment. Removal of metal contaminants from the soil by natural processes is often undesirable as this may lead to negative offsite effects. Dedicated remediation is often impractical because of the high cost or the lack of availability of suitable technologies. Of far more promise are methodologies that reduce the bioavailability of these metals in the soil, thereby removing their impact on organisms associated with the soil system (Tiller 1996).

This paper gives a brief outline of the implications of the bioavailability of cadmium and zinc for both plant uptake and off site transfer. Some options for reducing metal bioavailability are also discussed.

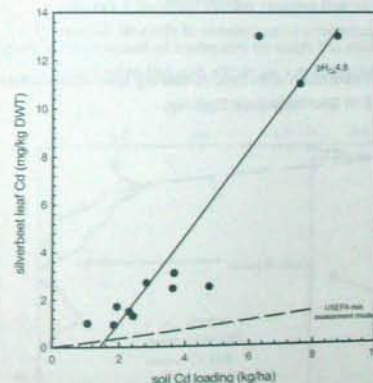
Implications of metal contamination in Australian soils

Many Australian soils are old and highly weathered (McLaughlin 2000). Several features distinguish them from the bulk of soils found in Europe and North America, including low cation exchange capacity, low organic matter, high sodium content, high soil salinity and low soil pH. Together, these features mean many of our soils are less able to immobilise metal contaminants than soils found overseas (Whatmuff, Osborne 1992). Of the metal contaminants commonly found to have

accumulated to excessive levels in agricultural soils, cadmium and zinc are seen to pose the greatest threat to soil, plant, animal and human health. Cadmium readily accumulates in plant tissue to levels that exceed food standards without affecting plant growth, and may also accumulate in significant levels in some animal products. Zinc may accumulate in plant tissues to high levels which can reduce plant growth and may also affect the function of soil microorganisms.

In a study using silverbeet grown on acid soils of pH <5 (measured in CaCl₂) amended with biosolids, the bioavailability of cadmium was up to 10 times greater than US guideline data (Figure 1). Zinc bioavailability under the same conditions was up to 20 times greater (Whatmuff 2001). A study at the same site found that zinc uptake following heavy biosolids applications resulted in zinc phytotoxicity and yield reductions in leafy and root vegetables, where levels of soil zinc exceeded 200-250 mg zinc /kg soil. This experimental threshold for zinc phytotoxicity was almost eight times lower than the maximum allowable soil zinc concentration in United States biosolids regulations.

Figure 1. Comparison of cadmium uptake by silverbeet grown on biosolids amended soils at pH<4.8 (●), with the cadmium uptake response for leafy vegetables used by USEPA in their risk assessment methodology.



Changes in metal bioavailability

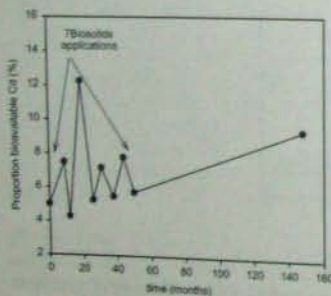
As stated earlier, once in the soil, metal contaminants are likely to persist indefinitely. There is conflicting evidence in the literature on the effect of time of contact between soil and cadmium on cadmium bioavailability (McBride 1995). This contrasts with zinc which has been shown to be more strongly bound to the soil (less bioavailable) with time. There is now a growing body of evidence to suggest that this decrease in bioavailability does not occur with cadmium, especially under acidic soil conditions (Sparrow et al 1993, McLaughlin et al 1994). Using radioisotopes, Hamon et al (1998) studied cadmium inputs at a long-term

phosphorus fertiliser trial and found that only 1-1.5% of the total cadmium added with the fertiliser each year was being fixed by the soil.

It has been suggested in some of the overseas literature that organic amendments such as biosolids provide their own capacity to immobilise heavy metal contaminants through the large organic matter and inorganic oxide components that go to make up the biosolids. This is said to produce a 'plateau' effect in metal uptake by plants (Chaney, Ryan 1994, Chaney, Oliver 1996). The validity of the plateau effect has been questioned by some sections of the scientific community (McBride 1995, Harrison et al 1999), and recently Hamon et al (1999) have shown that plant physiology is more likely to be responsible. No evidence of a plateau effect was seen in the plant uptake of biosolids cadmium and zinc for a range of food crops grown on acidic soils near Sydney (Whatmuff 1997a, 1997b), and metal availability did not decrease when biosolids were composted with other organic materials (Michalk et al 1999).

In a study of the uptake of metal uptake by leafy vegetables in a long-term biosolids trial, it was found that the proportion of both cadmium and zinc in the soil that was available for plant uptake has persisted (or in some cases increased) for some time following biosolids application (Figure 2) (Whatmuff 1999). Further investigation of the soil chemistry at the site has shown that the sustained availability of these metals has been accompanied by a decrease in soil organic matter without a parallel increase in metal adsorption by the inorganic components of the soil (Figure 3).

Figure 2. Increasing bioavailability of cadmium with time following final application of biosolids to an acidic soil at Glenfield near Sydney.



In a series of field-based experiments aimed at assessing the risk of biosolids metal movement into groundwater, it was found that when cadmium was added to the soil as a soluble salt solution, all of the cadmium was retained in the topsoil (0-5 cm). However when a liquid biosolids solution was added to the same soil, it was found that the cadmium from this solution moved well beyond this depth and percolated into the clayey subsoil (Figure 4). Similar results were obtained for a range of soils tested under laboratory conditions. It was concluded that the

cadmium from the biosolids solution was bound to small organic particles from the biosolids and these were unreactive in the soil, while the cadmium added as a soluble salt quickly reacted with the soil matrix.

Figure 3. Changes in soil organic matter levels (%) with time following final application of biosolids to an acidic soil at Glenfield near Sydney.

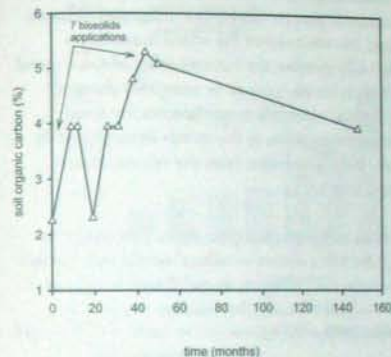
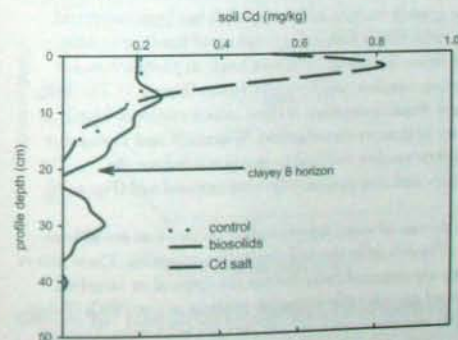


Figure 4. Movement of cadmium through the soil profile, where cadmium was applied to the soil either as a soluble metal salt or in a biosolids solution.



Some options for the remediation of metal contaminated soils

There is a range of management options to minimise the impact of metal contaminants in Australian soils. These include the use of non-accumulating crop species and cultivars, site selection, and reduction in metal contaminant inputs (eg reduced metal levels in fertilisers) (Grant et al 1999). Technologies for the remediation of metal contamination *in situ* by reducing metal bioavailability are gaining support in scientific and environmental communities and are currently the subject of considerable research both in Australia and overseas (McLaughlin et al

1998). These include the alteration of soil pH, the addition of organic and inorganic materials to increase the soil's metal adsorption capacity and the use of hyperaccumulator plants, or phytoremediation.

It is well recognised that increasing soil pH reduces the bioavailability of most heavy metal ions in soil, except in the presence of soil salinity (high chloride) (McLaughlin et al 1994), and as such is the most commonly used method of *in situ* remediation for metal contaminants. However, it should also be viewed as a temporary measure given that lime must be reapplied once the reactivity of the added limestone is exhausted. Increasing soil pH may actually increase the bioavailability of some metal ion species such as molybdenum, which is usually present as negatively charged (anions) in soil. Likewise, the use of organic materials as ameliorants for metal contamination should be viewed with some caution, as the metals immobilised by these materials may be re-released into the soil solution once the organic matter becomes broken down by soil microorganisms.

The use of inorganic materials with high metal binding capacity such as zeolite or aluminium/iron oxides/hydroxides have been shown to reduce metal uptake in pot studies (Mench et al 1994). More recently, the cadmium immobilisation capacity of a range of industrial by-products such as coal-washing clays, smelter by-products, zeolite and biosolids was assessed (McLaughlin 1998).

The application of incinerated biosolids (sewage-ash) has been shown to reduce cadmium uptake by pasture grown on soils contaminated with fertiliser cadmium (Whatmuff, Simpson 2000). As this material has been heated at very high temperatures (>800°C), the organic fraction of the biosolids has been destroyed, leaving only the inorganic oxides which have substantial metal binding capacity. Increasing rates of ash application decreased cadmium levels in pasture herbage compared with superphosphate fertiliser and lime treatments (Figure 5). The long-term changes in the cadmium binding capacity of these soils is currently being investigated. In a preliminary laboratory investigation, Whatmuff and Dougherty (2001) used recycled aluminium smelter residual to drastically reduce the bioavailability of soil cadmium and zinc in a heavily contaminated soil (Figure 6).

Phytoremediation involves the use of metal tolerant plant species that are able to accumulate large amounts of metals from the soil (hyperaccumulators). These plants are harvested and the metals are removed from the site for disposal or recycling. Initially this technology gained considerable attention overseas in the 1990s (Baker et al 1994, Brown et al 1995) and some work on this area has been carried out in Australia (McLaughlin et al 1998). Currently there are limits to the effectiveness of such technology, caused in part by the limited size or biomass produced by such plants (Grant et al 1999). Phytoremediation should be viewed as a means of reducing soil contaminant levels to below relevant environmental thresholds rather than as a means of removing contaminants from the soil completely. Future breeding programs aimed at increasing the size of these hyperaccumulators may improve the effectiveness of such technologies.

Figure 5. The effectiveness of biosolids ash at reducing pasture herbage cadmium concentrations in soils with a history of phosphate fertiliser usage.

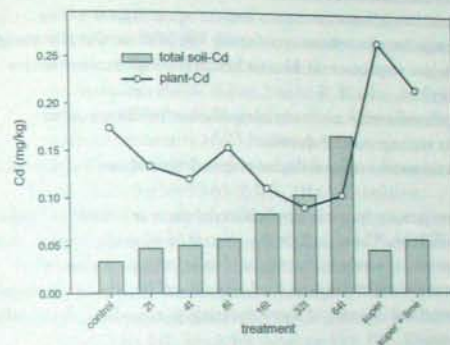
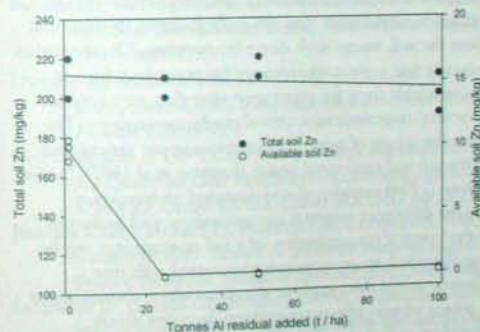


Figure 6. The effect of increasing rates of aluminium smelter residual on both total and available soil zinc.



Centre for Recycled Organics in Agriculture (CROA)

Inappropriate management of waste materials and by-products in past years has led to the pollution and contamination of aquatic and terrestrial environments. The need for responsible management of these materials is recognised through the development of environmental strategies at both state and national levels. Environmental legislation in place aims to reduce the amount of waste currently being disposed to landfill and to reward producers who seek to beneficially use their waste materials. Unfortunately, unlike sewage biosolids, regulations governing the beneficial use of these other organic and inorganic materials do not have a sound scientific basis.

Recently, NSW Agriculture's Organic Waste Recycling Unit has been granted funding for the establishment of a dedicated, long-term research and education centre (CROA) to identify and promote the resource value of recycled organic and inorganic materials for the benefit of catchment quality and agricultural sustainability. Key issues to be addressed by CROA include;

- land rehabilitation and remediation
- improvement in the regulatory environment for the use of these waste materials
- development of strategies to protect catchment health through more effective runoff and erosion control
- promoting the resource value of such materials to the community and to agricultural and waste management industries
- improving the environmental sustainability of targeted agricultural industries.

Unresolved research issues arising from the application of these materials to land will also be addressed by CROA. These include the impact of oil and grease in food wastes; rates of mineralisation of nitrogen, particularly from organic wastes; the impact of these materials on microbial ecology and general soil health; heavy metal bioavailability; and the potential of some of these materials to remediate chemically and physically degraded soils.

Conclusions

To some degree, inputs of metal contaminants into our farming systems are unavoidable. It has been shown that this trend is continuing, with evidence that contaminants are being added at rates higher than the soil's ability to fix them and are not being removed from the soil, except with direct intervention. Characteristics unique to our soils have meant that some contaminants, for example cadmium, continue to remain in a bioavailable form for many years after they were applied, and this has impacted on several important agricultural production systems. The challenge is how we balance the inputs of metal contaminants to our agricultural and natural ecosystems with soil and catchment health (Rapport et al 1997). Davies (1992) and Chaney and Ryan (1994) introduced and discussed an important perspective in this debate; the difference between 'contamination' and 'pollution'. These authors point out that, even if contamination of a soil or ecosystem can be measured, this does not indicate risk to any organisms associated with that ecosystem. The term pollution would then apply to situations where contaminants have reached levels that, where adverse effects are evident, decisions about remediation should be based on pollution rather than contamination.

Methods to remediate areas of metal contamination where the bioavailability of the contaminant is reduced *in situ* show great promise, although these are not currently recognised by regulators. It has been strongly argued that there is little scientific evidence to exclude the use of bioavailability in determining soil clean-up or remediation targets used in environmental regulations (Tiller 1996, McLaughlin et al 2000). Current German national standards for soil clean-up are based on a bioavailability index (Prüß 1997) and similar schemes are being considered in other European countries (McLaughlin 2000). NSW Agriculture is currently developing a dedicated research and demonstration resource that will allow us to

investigate sustainability and remediation issues for metal and other contaminants in our farming systems.

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Nutrient management for healthy soils

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Australian soils are generally of low fertility. The key agricultural nutrients of nitrogen and phosphorus are generally low because of the great age of our soils. Improving the levels of these nutrients in soils has been a key objective of soil management and has formed the basis of most soil nutritional research over the last 50 years.

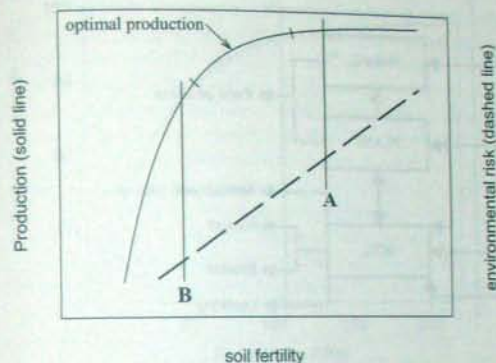
Australian farmers use approximately 1 million tonnes of nitrogen and 430 000 tonnes of phosphorus each year (source: Fertiliser Industry Federation Australia), at a cost of \$1 billion and \$1.3 billion respectively. Until relatively recently, the management of nutrients in agriculture and soil focussed primarily on the optimisation of production, but there is now a growing awareness of the potentially adverse effects of poor nutrient management in agriculture. These effects are already well recognised in Europe and the United States. The problems of nutrients and water quality management in Australia have been demonstrated spectacularly in numerous algal blooms on the Darling River, Gippsland Lakes, Peel Harvey Estuary and the Hawkesbury River. Although nutrients such as nitrogen and phosphorus are not the only factors in stimulating algal blooms, they undoubtedly play a major role. Groundwater contamination with nitrates is also an issue in numerous areas such as the Somersby plateau, north of Sydney, where nitrate levels can restrict the use of the water for human and livestock consumption.

One of the challenges to achieving soil health is to design nutrient management systems that balance the need for economically viable production of food and fibre with protection of the environment.

Soil health conflicts

Managing agricultural nutrients to protect soil and catchment health has been little considered in Australia. Nutrient management can result in a conflict between the economic and environmental objectives of soil health (Rappport et al 1997). As we raise soil fertility to make production economically viable, we generally increase the 'leakage' of nutrients to the external environment. When these leaks affect the environment adversely, the economic and environmental objectives of soil health conflict. Resolving this conflict without compromises may be difficult. The situation is summarised in Figure 1.

Figure 1. Schematic diagram illustrating the balances between production and environmental risk (adapted from Sharpley, 1999).



In the past, it has generally been regarded that critical environmental risk occurs at levels greater than those critical to optimal crop production (A on Figure 1), so there is no conflict. However, in some instances, sustainable environmental levels may be below optimal production levels (B on Figure 1). If this is the case, how do we reconcile the two without adversely limiting production goals and economic viability of farms? There are opportunities available to manage nutrients to reduce these conflicts and increase the profitability of production.

Nutrient cycling

The cycling of nutrients within soils, farming systems and landscapes is extremely complex. A generalised outline of the cycle is shown in Figure 2. The importance of various components of the cycle varies with the nutrient in question, soil and climate, production enterprise and management, and the ecosystem and its sensitivity.

Soils and their accompanying vegetation communities in their natural state have evolved over long periods to a point of equilibrium where they have a high capacity to buffer nutrients or contain them within the system. When we boost productivity with nutrient inputs and change the structure of the system by planting different species, we alter the system so that the soil system operates at a higher fertility level. Unless the ability of the system to hold and recycle nutrients is also increased, the system slips back towards a more stable equilibrium, losing nutrients as it goes. We then have to add more nutrients to maintain levels of production. For instance, when we add phosphorus to grazed pastures, the soil fertility is boosted (reflected in higher levels of available phosphorus) which leads to higher production. However, at the same time the leakage of nutrients as evidenced by phosphorus concentrations in runoff is also increased (see Figure 3).

Figure 2. Simplistic diagram of cycle of nutrients in soil/catchment system (after Williams and Hook, 1991).

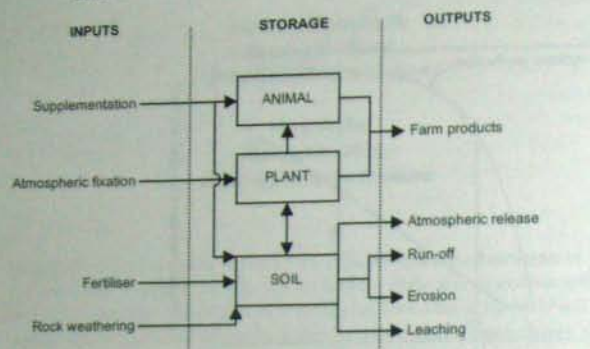
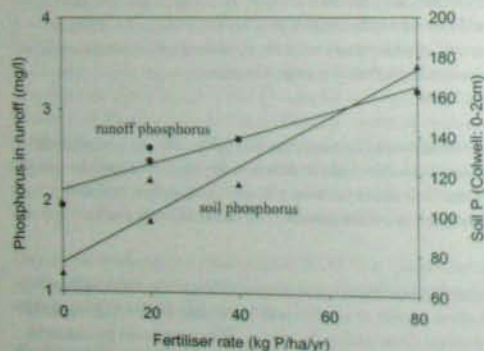
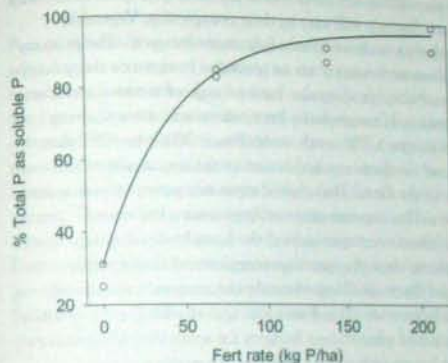


Figure 3. Effect of increased inputs of phosphorus in soil phosphorus levels and runoff phosphorus.



Changes in the cycling of nutrients can also make remedial strategies more difficult to implement. Research on losses of phosphorus in runoff from pastures has shown that as the level of fertiliser applied is increased, not only do we increase the amount of phosphorus lost in runoff but the proportion moving in highly environmentally significant forms is also increased (see Figure 4). These forms are then also more difficult to control.

Figure 4. The effect of changing inputs of fertiliser phosphorus on forms of phosphorus contained in runoff.



In the case of vegetable farming, balancing production and environmental objectives is difficult. The efficiency of nutrient management is low because the soil is regularly bare, vegetable crops are shallow-rooted and their residues tend to break down rapidly. Additionally, the soil's ability to store and re-cycle nutrients through organic matter pools and the activities of microorganisms can be reduced by frequent tillage, erosion and the use of pesticides.

Nitrogen inputs to agricultural systems are particularly difficult to manage because of the mobility of the nitrate (NO_3) form of nitrogen. Leaching of nitrate below the root zone of vegetables on permeable sandy soils can be very high because the inputs are often very high, crop use is relatively low, nitrate is mobile and the soil cannot hold this form of nitrogen until plants are ready to use it. The results of a leaching study on vegetable farming systems conducted at NSW Agriculture's Somersby Research Station, show that up to half the applied nitrogen is leached from the systems (Table 1). Monitoring on clay soils with much lower permeability under similar management revealed far lower leaching losses (Dougherty, 1999).

Table 1. Major nitrogen pathways under various vegetable farming systems (Dougherty and Wells, 1998).

System	Nitrogen inputs (kg/ha)	Nitrogen removed in harvested product (kg/ha)	Nitrogen lost in leaching (kg/ha)
District practice	948	127	633
Best practice	164	83	110
Organic	181	15	115

Managing nutrients to reduce conflict

Management of nutrients for improved environmental outcomes and increased profitability does not have to be complex or difficult. Whole farm nutrient budgeting can be useful in identifying key areas where excessive phosphorus is being brought into the farm system. Systems will vary in their complexity. Vegetable production systems are relatively simple in terms of the nutrient cycle. The primary input of nutrients is in fertiliser and outputs are in produce. In contrast dairy farms not only have these inputs and outputs, they also have a range of internal transfers associated with the redistribution of nutrients by livestock in manure and urine. Examination of a dairy farm on the NSW south coast (Finch 2000) revealed that nutrient redistribution around the farm was important in the accumulation of phosphorus in various parts of the farm. These areas represent potential risk areas for environmental impact as well as representing inefficient use of nutrients. Changing the distribution of these nutrients around the farm by developing effluent and manure reuse plans, changing grazing strategies and making more strategic use of phosphorus fertiliser could significantly reduce accumulation of phosphorus in the soil. This in turn would reduce costs and environmental risks. Withers and Peel (1998) examined phosphorus budgets for a number of dairy farming systems with varying inputs of feed and fertiliser. They showed that improved management of phosphorus inputs in feed and fertiliser resulted in a reduction from 23.3 to 2.7 kg P/ha excess with no reduction in milk yield.

Similarly, reducing nitrogen and phosphorus inputs to vegetable farming systems can also significantly reduce nutrient leakage. The results of the Somersby vegetable experiment (Tables 1 and 2) show this clearly (Wells 2000). However, the lowest erosion and nutrient leakage in the experiment occurred on two systems that had raised organic matter levels as a result of compost additions and regular cover cropping. This supports the idea that improving overall soil health, and thus increasing the soil's ability to hold and cycle nutrients, is a powerful way to reduce nutrient leakage. Unfortunately these more 'organic' systems generally had lower yields than the more conventional systems. This does not seem to support the idea of using nutrient cycling as a means of resolving the conflict between production and environmental objectives. Yet even if environmentally sound systems will always have lower productivity it does not necessarily entail lower profitability. If growers who are willing to invest in the health of their soils were rewarded for the environmental benefits they provide, then it may be possible to reconcile economic and environmental objectives.

The 'best practice' vegetable production system appears to achieve some sort of compromise between production and environmental protection. Inputs of nitrogen are relatively low compared to the 'district practice', yet yields are acceptable and the risk of environmental impact from nitrate leaching is dramatically reduced. Adoption of these changes to 'district practice' has the potential to dramatically improve soil health.

Indicators of soil health

The management of nutrients involves not only the needs of producers, but also requires consideration of the objectives of the wider community. These objectives

are generally poorly defined, both spatially and temporally. Where do we want particular goals to be met: at the paddock, farm or catchment scale? How do we know who is contributing what to the catchment? How often do we want the goals met? Is 95% of the time adequate?

Part of the challenge of managing nutrient dynamics is the difficulty of knowing what impact the system is having on both productivity and the environment. Soil measures are often used as 'indices' of soil health. However, they may be relatively poor predictors of off-site environmental impact. For instance, total nitrogen and mineralisable nitrogen measured on three of the vegetable systems at Somersby showed that the organic system had higher nitrogen stored in the surface soil but lower concentrations of nitrate NO₃ below the root-zone than the conventional system. The nitrate concentrations were determined far more by the inputs of nitrogen than the measured levels of nitrogen in the topsoil (Table 2). Concentrations of nitrate in water draining below the root-zone, and therefore potentially reaching groundwater, was regularly much higher than the acceptable limit of 10 mg/l. The best practice and organic treatments resulted in much lower concentrations of nitrate.

Table 2. Nitrogen cycling under various vegetable farming systems (adapted from Wells et al 2000 and Dougherty, Wells 1998).

System	Nitrogen inputs (kg/ha) (removal in product)	Total nitrogen (g/kg)	Mineralisable nitrogen (mg/kg)	Average nitrate nitrogen in soil water at 90cm (mg/l)
District practice	948 (127)	1.15	19.4	72
Best practice	164 (83)	1.03	19.7	16
Organic	181 (15)	1.33	22.5	22

Similarly, soil phosphorus measurements can be poor predictors of nutrient lost in runoff, although they may be useful as relative indicators within a particular system. Research on two soils used for dairying showed that a highly productive alluvial soil had higher losses of phosphorus in runoff than the lower productivity podsollic soil (Dougherty, unpublished results). This was despite similar available phosphorus levels and an apparently higher capacity of the alluvial soil to fix phosphorus. It may be that the higher nutrient mineralisation rate on the alluvial soil resulted in a greater pool of phosphorus readily available to be lost in the runoff.

As well as managing nutrients to reduce environmental impact, we can also implement measures to stop transfer of nutrients to sensitive environments. However, identifying appropriate management practices can be difficult. Often these management practices can be complex and for this reason it can be difficult for land managers to implement them effectively. For example, buffer strips as a nutrient control tool have been widely promoted. However, landscape, climate and the composition and forms of the nutrients that are moving all significantly affect the capacity of buffer strips to remove nutrients. The use of buffer strips in the case of the dairy runoff phosphorus discussed previously would be questionable because buffer strips are primarily designed to trap sediment, and sediment movement is

not a significant mechanism of nutrient transport in pastures. However, in the vegetable production systems discussed previously, sediment movement is significant, so buffer strips are likely to be highly effective in reducing nutrient transport. If the tools being used to reduce nutrient movement are in fact ineffective, then the only outcome is a waste of farmers' money. Understanding the system and getting the management right is the key to minimising nutrient losses.

Conclusions

Nutrient cycling for soil health needs to consider both the management of nutrients to improve agricultural production and the protection of off-site air and water quality. Poorly managed agricultural systems have significant potential to adversely affect the wider environment. However, a thorough understanding of the management/cycling of nutrients and primary risk pathways for off-site impacts can lead to significant improvements in profit and environmental impact. More efficient management of fertilisers can save significant amounts of dollars and significantly reduce the exports of nutrients to the wider environment.

The goals of nutrient management for soil health need to be clearly defined and targets set. These are likely to be somewhat fluid but need to be carefully agreed upon by farmers, land managers and the community and appropriate frameworks for evaluation established.

Improving the efficiency of nutrient management of soils through better use of decision support systems and tools such as soil testing, nutrient budgeting, minimal tillage and the use of controlled release nutrient sources such as organic matter, promises to be an effective way of reducing nutrient leakage and improving profitability.

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The role of organic carbon in soil chemistry

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Soil chemistry is intimately connected to soil health and productivity. If all aspects of soil chemistry are not balanced and functioning correctly, then plant production suffers.

Organic carbon as a measure of soil organic matter or humus plays a vital role in many of the soil chemical processes and as such is crucial to plant productivity. When we measure the organic matter content of soils we actually measure the organic carbon content and convert this to an estimate of organic matter by multiplying the organic carbon figure by a constant - usually 1.72. Organic carbon content of agricultural soils commonly varies between 3 and 60 g/kg.

Organic matter includes undecomposed plant litter, soil organisms and humus. Litter and organisms are of little importance in soil chemistry, but humus is the most reactive component in soils and plays a vital role in soil health and productivity. It is formed by the actions of soil organisms on plant and animal litter over very long periods. It is extremely fine, highly reactive, exists as coatings on other soil particles and is more resistant to microbial decomposition than the original material from which it was formed. Schematic diagrams showing the components of soil organic matter and the main functions of humus in soils have been developed by Baldock and Skjemstad (1999).

Humus has many effects on soil chemistry. In this paper we will discuss the following topics in relation to humus: pH, phosphorus reactions and availability, cation exchange capacity, aluminium solubility and toxicity, and nutrient reserves and availability

pH

Although one of the simplest measures we can make, pH is one of the most important determinants of soil health through its influence on the solubility of metal ions such as aluminium and manganese, its effect on the supply of basic cations and its influence on both the type of microbes and their activity.

pH is commonly measured in both water and 0.1M CaCl₂. The differences between these measures is a characteristic of different soils and provides a useful indication of salinity and possible aluminium or manganese toxicity

Humus has an important effect on the pH at which productivity is influenced by aluminium toxicity and hence the requirement for lime. In 1982 Jim Bradley and I published an *Agnote* (16/82) highlighting the difference in percent aluminium

saturation of the CEC between coastal and inland cropping soils for the same pH. Inland cropping soils are typically low in humus and have higher levels of aluminium saturation for the same pH than coastal soils under pasture which are high in humus. Response to lime has been shown to occur more frequently in light textured inland soils than in coastal pastures. Because soil acidification from nitrogen use and legumes is an important issue, the rate at which soils will acidify is also important. pH buffer capacity, or the soil's ability to resist changes in pH is increased by humus content.

Phosphorus reactions and availability

Although the chemistry of phosphorus is dominated by its reactivity with compounds of iron and aluminium, humus plays an important role. It acts as a reservoir or sink for phosphorus when microorganisms use mineral phosphorus to form part of their structure. This removes significant amounts from chemical fixation. In addition, humic substances complex metal cations, thereby slowing their ability to react with phosphorus, and form coatings on others, thereby slowing fixation. As we will see later, this phosphorus tied up in organic compounds can be an important source of plant nutrients.

Cation exchange capacity (CEC)

Cation exchange capacity is the ability of a soil to 'hold' negatively charged cations such as calcium, magnesium and potassium by electrical attraction. This positive charge in soils is present in both clays and humus. The contribution of humus to the soil's total CEC and hence ability to hold important plant nutrients is a major contribution to soil health and productivity. Table 1 lists the CEC of some of the common clay minerals and humus.

Table 1. Cation exchange capacity of clays and humus.

Soil type	CEC (cmol (+) /kg)
degraded kaolin	1-5
kaolin	10
illite	25
vermiculite	100-120
humus	100-300

To understand the importance of humus in this important soil property let us look at a practical example. The red krasnozems soils of the north coast have a clay content of around 60%, the clay type being degraded kaolin. This means that with 60% clay content and a CEC of 5 for the clay type, the CEC of the soil would be only 3 cmol (+)/kg. Figure 3 plots the relationship between pH and CEC for local krasnozems soils used for macadamia production and shows that these soils commonly have a CEC of 10-25 (mo (+))/kg, because there is a strong effect of pH on the CEC. (See also soil test 3 in Table 2.) Figure 2 emphasises the importance of humus and pH on CEC for two different soils.

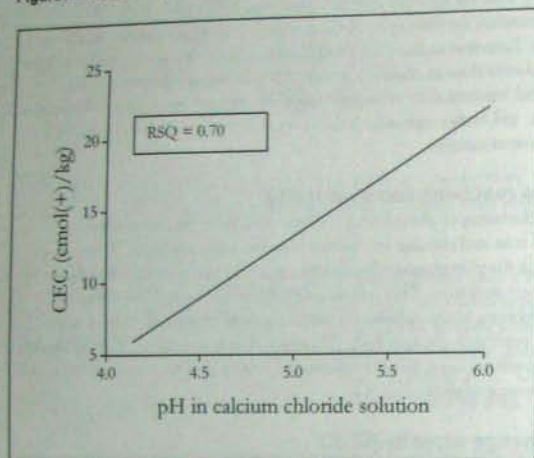
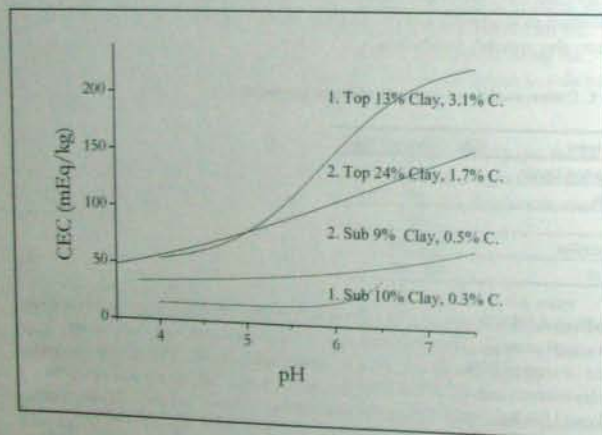
Figure 1. Relationship between pH (CaCl₂) and cation exchange for Richmond area.

Figure 2. Variation of CEC with the content of clay and humus and pH for two soils.



This property of humus to vary its CEC, or the amount of positive charge, with pH is very important. It influences the pH to which soils should be limed in order to optimise plant nutrient availability and plant productivity. So we see that in soils high in clay but with low CEC clay types, and in light textured, sandy soil, humus has a major beneficial role in ensuring good productivity.

Aluminium solubility and toxicity

While aluminium is commonly considered an exchangeable cation, its chemistry is so complex and its effects so important to plant growth in acid soils that its interactions with humus are discussed separately. At soil pH (CaCl₂) below 5 compounds of aluminium become increasingly soluble and aluminium enters the soil solution. The most phytotoxic ions are Al³⁺ and AlOH²⁺. Liming to raise the pH to above 5.5 will remove these ions from solution but in many situations it is uneconomic to lime or it is not practical as in perennial tree crops. There is now considerable data to show that humus and its components have an important role to play in rendering aluminium non phytotoxic and hence improving soil health and productivity without the need for lime.

Humus works in two ways to achieve this beneficial effect. Components of humus form complexes with aluminium ions, rendering them non-toxic in solution; and combine and complex aluminium into their structure rendering it less soluble. In acid soils there are numerous examples of this effect. For example, when first developed, acid sands at Coonabarabran will only grow *Serradella* legumes without liming. After three to four years of pasture improvement with *Serradella*, subclover begins to grow and eventually dominates. Humus formed by the *Serradella* pasture complexed aluminium in these sands. In another example, soil that had been under pasture for long periods on the central tablelands of NSW did not respond to lime despite low pH (4.3) and high aluminium saturation (30%).

Table 2. Soil analyses of three krasnozems soils.

	Soil 1 Kikuyu	Soil 2 Cane/Macadamia	Soil 3 Macadamia
pH (H ₂ O)	4.5	4.8	6.2
pH (CaCl ₂)	4.2	4.3	5.6
phosphorus (Colwell)	22	87	300
exchangeable potassium	.53	.13	.74
exchangeable calcium	1.48	1.0	13.96
exchangeable magnesium	1.33	0.4	2.97
exchangeable aluminium	.60	1.32	0
exchangeable sodium	.06	.08	.05
CEC	4.0	2.9	17.73
Ca/Mg ratio	1.12	2.9	4.69
aluminium saturation	15.0	44.9	0

Table 2 shows the analysis of three krasnozems soils with different histories, showing the effect of humus on aluminium solubility. Soil 1 is from a local soil that has had many years under kikuyu and is very high in humus, and soil 2 is from a macadamia orchard previously used for sugar cane production where humus is very depleted. The table shows that humus clearly has an important role to play in ameliorating aluminium toxicity in conjunction with liming and the consequent beneficial effects on productivity.

Nutrient reserves and availability

There is a close correlation between organic carbon and nitrogen for some important agricultural soils. This is because the microbes that form humus need nitrogen, sulfur, phosphorus and other nutrients in their life cycle and so combine these into humus. Cultivation and consequent oxidation of humus has the potential to release significant amounts of plant nutrients for cropping. This practice has been used for many years on the black soil plains of NSW to obviate the use of fertilisers. This practice is however 'mining' the soil of reserves and fertiliser is now used in many of the black earth soils where humus levels have become depleted.

Humus as a source of nutrients is clearly of great importance to nutrient supply and productivity, and adequate rotations between cropping cycles are required to replenish it. The red krasnozems soils of the north coast appear to contribute significant amounts of nitrogen to fruit orchards, particularly early in the orchard's life.

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Soil structure: the key to sustainable agro-ecosystem management

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Sustainable land use practices are affected by a large number of interlinked factors. Soil structure is an important, yet often misunderstood component of the function and hence dynamics of agro-ecosystems. On a paddock scale, soil structure affects how water infiltrates, drains and moves through the soil and therefore determines how efficiently soil nutrient and pollutants are stored, released and taken up by plants. Within the catchment, structure influences runoff and erosion and is therefore a main factor in the stability of an agro-ecosystem. No single measure can describe soil structure. Further, it is not possible to uniquely assign a quality value to soil structure or exactly quantify its impacts unless it is assessed within a specified context. Because of its nebulous nature and indirect effects, the impact of soil structure on our agro-ecosystem is often masked, as we apply new technology that pretends to overcome soil structural problems *per se*. However, improved technologies may only offer a temporary solution to problems related to soil structure. There are many examples: if soil organic matter decline causes soil nutrient deficits, fertilisers can be applied; if soil is compacted it can be loosened using tillage; if soil is eroded, earthmoving machines can be used to replace the eroded soil. The additional cost to manage structurally degraded soil is good for the national economy as it lifts the gross domestic product; however, this benefit may be short-lived and economic management of structurally degraded soil may no longer be possible. Therefore we must strive to maintain, improve or stabilise soil structure. As a first step we must understand the importance of soil structure. This paper outlines its major functions and how it interacts with our agro-ecosystem.

What is soil structure?

Soil structure has been defined as the arrangement and orientation of soil particles into secondary particles or aggregates, such that the properties are different to a similar mass of unaggregated soil (Taylor, Ashcroft 1972). By definition, soil structure *per se* cannot be measured and can only be assessed or described by measuring appropriate soil properties that are related to soil structure. It can be described qualitatively, based on the appearance, shape and size of aggregates and pores (McDonald et al 1984). It can be assessed quantitatively as the soil pore space (Hamblin 1987), macropore space (Ringrose-Voase 1990) or the permeability of the soil for air and water (Kirby, Blunden 1991). It can be described semi-quantitatively using image analysis techniques or through measurement of the strength of the soil aggregates. The latter is measured using friability tests (Utomo, Dexter 1981) or penetrometer resistance and soil tensile strength (Roloff, Larson 1988). The stability of soil aggregates in the presence of water can be determined as the soil's ability to withstand dispersive forces associated with the presence of water.

Measurements include dispersion tests (Hamblin 1984, So, Cook 1988) or wet sieving analysis (Yoder 1936, Horn et al 1984). The diversity in methods of assessment of soil structure shows that it influences more than a single soil property. The complex interactions between affected soil properties and their influence on soil structure makes it difficult to obtain a clear relationship between soil structure and crop production (Letey 1991).

Organic matter

Soil organic matter strongly affects soil structural stability (Cook, Ellis 1987, Ross 1989, Schnitzer 1991, Chan et al 1992). Soane (1990) lists a number of possible mechanisms by which organic matter may influence soil stability: dilution effect, effect of friction, binding forces between particles and within aggregates, elasticity and the filament effect. The dilution effect is due to the lower absolute density of the organic matter resulting in lower bulk density (Gupta et al 1977). However, the dilution effect may only have a marginal effect on the soil bulk density. Furthermore, bulk density is an insensitive measure of how root growth and the movement of air and water respond to soil structure.

The effect of increased friction is probably associated with an increase in shear resistance. Free et al (1947) reported decreased packing densities with increasing amounts of organic matter. However the type of organic material, not just the amount present in the soil, affects shear resistance. Humified organic matter may increase the surface roughness of the particles, leading to increased shear resistance, but undecomposed organic residue may decrease shear resistance as observed by Oju et al (1985). In this case organic matter may separate soil particles rather than bind them together, and the increased elasticity due to organic matter may result in decreased compactibility rather than decreased shear strength (Soane 1990).

The filament effect is mainly attributed to the increase in true cohesion (Soane 1990) where organic fibres such as roots or fungal hyphae bind particles and aggregates together. It is probably associated with the strong decrease in structural stability observed within the first year after cultivation of a virgin soil (Cook 1988). Soane (1990) summarises and points out that the effect of organic matter on soil stability is largely determined by the type of organic matter present in the soil, and that in turn determines soil structure and soil structural stability.

Mechanical aspects of soil structural stability

The mechanical stability of soil depends on its cohesive and frictional forces activated when the soil is exposed to deforming forces. This is governed by soil texture, cation exchange capacity and type of cations, salt concentration, soil water content, pH and organic matter content (Means, Parcher 1964, Hartge 1978, Zhang, Hartge 1989). Most of these properties are fairly static and cannot easily be altered, except organic matter content. Soil water content is a very dynamic property and has a very strong influence on the stability of soil.

Soil cohesion

Cohesion can be separated into true cohesion and apparent cohesion. True cohesion exists between particles bonded together by cementing agents or

electrostatic and electromagnetic forces of attraction. Apparent cohesion holds particles together through capillary forces and interlocking of rough particle surfaces (Mitchell 1976, Lambe, Whitman 1979). The magnitude of apparent cohesion depends on the interactions between water and soil particles. It is therefore very dynamic and changes with changing soil water contents. However, it is influenced indirectly by static soil properties such as texture and cation exchange capacity and the type of cations on the exchange complex. Sands, for example, have no true cohesion unless they contain organic matter, and only some apparent cohesion due to the water that holds particles together by the formation of menisci (Whitman, Lambe 1979). Apparent cohesion is more pronounced in soil that has a large number of contact points between particles. Menisci can form at these contact points and hold particles closely together and apparent cohesion increases with decreasing water content until the soil is dry. Apparent cohesion generally increases with increasing clay content and is related to cation exchange capacity (Craig 1987).

Effect of cations

The impact of different types of cations on soil structure is related to the size of the hydrated cation as well as to its charge (its position in the lyotropic series). Divalent cations (calcium and magnesium) tend to stabilise soil as colloidal particles flocculate. Due to its larger effective ionic radius, magnesium is less efficient in flocculating clay particles than calcium. Potassium tends to be adsorbed very tightly by many clay minerals and has little known effect on soil structure. Sodium, however, is strongly dispersive due to its low charge and large hydration hull. It is often the primary cause for poor soil structural stability: soils disperse and concomitantly erode easily. Dispersed particles block pores and lead to poor aeration and low permeability for water. However, irrespective of type of cation, high salt concentrations flocculate and hence stabilise soil. Since salt concentration increases as the soil water content decreases, soil with very weak structures when wet can develop very strong structures when dry.

Effect of pH

The effect of pH on cohesion is indirect and is associated with the influence of pH on cation exchange capacity, amount of exchangeable bases and soil organic matter.

Friction

Friction within the soil determines the stability of soil. It is measured as the angle of internal friction, which represents the rate of increase in shear force with increasing normal force. Soil texture, soil water and organic matter largely affect friction. Soil is more resilient to deformation if the angle of internal friction is large. In dry, cohesionless materials, the angle of repose is approximately equal to the angle of internal friction (Lambe, Whitman 1979). These angles tend to be smaller than 40° and decrease with increasing soil water content and approach zero in clay pastes (Kesdi 1974). Organic matter tends to maintain higher angles, particularly if soils are dry. However, soil water content exerts a strong influence on both the soil's cohesion and angle of internal friction.

Agronomic aspects of soil structure

Soil organic matter is often portrayed as the most important factor governing soil structural quality in terms of nitrogen supply and water holding capacity. Its role in nitrogen supply is not disputed, but its impact on soil water relationships is often misunderstood. Pedotransfer functions can be used to assess and quantify the functional relationship between many soil properties. For a wide range of soil types and soil textures, organic carbon tends to increase total plant available water. A 1% increase in soil organic carbon will increase plant available water by 20-30 mm of water per metre of soil (Manrique et al 1991, Kay et al 1997, DaSilva, Kay 1997). To make a significant impact on improvement of plant available water, extremely high increases of organic matter are needed. Most organic matter is located in the top 10 cm of soil. Thus, even an increase as large as 1% organic carbon (1.75 % organic matter) would only increase the amount of plant available water by no more than 3 mm. In some soils such as Vertisols and Ultisols there may be no detectable effect of organic matter on plant available water (Manrique et al 1991). The impact of organic matter on soil water is largely due to its effect on soil water recharge. Organic matter increases the stability of the soil surface, thereby reducing runoff and increasing rates of water movement through the soil's macropore space. It therefore helps soil take up water to its maximum capacity.

Effect of roots

There are two ways that roots proliferate in the soil, and both relate directly to soil structure. Roots explore existing pore space or create new pore space. The former requires that the soil has a continuous macropore system; the latter requires that the soil is soft enough for the roots to penetrate. Penetration resistance of the soil is determined by the soil's cohesion and angle of internal friction. Hence, it is most closely related to soil water potential (within the same soil, the potential is related to soil water content) and loosely related to bulk density. Existing macropores are a prerequisite for root proliferation into well-structured soils with a high penetration resistance.

Management effects on soil structure change

Tillage

Soil tillage is the oldest and still most widely used method to manage soil structure. Although conservation tillage, also known as zero or minimum tillage, is promoted as best management practice, a recent survey showed that two-thirds of farmers in north-western NSW still use conventional tillage practices (Kirchhof et al 2000). An undisputed benefit of conservation tillage is restoration of organic matter. Since definitions or perceptions of soil structure or soil health are organo-centric, one has to ask why more farmers have not taken up conservation farming. There are several reasons. When decline in organic matter causes nutrient depletion, fertiliser application can potentially overcome the problem quickly. On some soil types such as grey clays, conservation tillage may not have a large effect on hydraulic conductivity even though it increases soil organic matter (Kirchhof et al 2000). Benefits of soil structural improvement due to conservation tillage are not immediate; continuous application, possibly for many years, is needed. A yield sacrifice often occurs when conservation tillage is initially adopted.

Sodicity

Sodicity is a soil structural constraint that causes slaking and dispersion when the soil is saturated and excessive hardness when it is dry. Calcium-based amendments are widely used to overcome this constraint, the most common being gypsum. Due to gypsum's relatively good solubility, calcium cations are released into the soil solution. At first the soil's electrolyte concentration increases so that the soil solution becomes saltier and colloidal particles flocculate instead of disperse. Over time the calcium will replace more loosely bound cations from the exchange complex. This affects mostly sodium and results in a decrease in exchangeable sodium. Theoretically this change in exchangeable cations composition should be relatively permanent, but the effects of gypsum application tend to lessen with time and are no longer evident after, say, 10 years. This suggests that the electrolyte effect may be longer acting and more important than the change in exchangeable cation composition. The latter is probably more pronounced if less-soluble calcium salts are used. Solubility of lime is very low and soil structural improvement due to lime application tends to set in very slowly.

Magnesium

The cation magnesium is often flagged as detrimental to soil structure. Like calcium, it is a divalent cation and reduces dispersion. However, it has a lower charge density than calcium and is therefore slightly less effective in flocculating colloidal particles. This means that soils with a given sodium content on the exchange complex are more dispersive if they contain magnesium rather than calcium. Reducing the amount of exchangeable magnesium is extremely difficult and very large amounts of calcium ameliorants are required. In theory, a grey Vertisol with a calcium:magnesium ratio of 0.5 would require 13 t/ha of gypsum to increase the calcium:magnesium ratio to 2 in just 10 cm depth of soil. In practice, very much larger amounts of gypsum would be required because much of the added calcium would leach before replacing exchangeable magnesium.

Soil surface

It is important to realise that soil structural stability and permeability of the very thin surface layer (< 1cm) is the most important factor governing soil water recharge. A soil can be very well drained and have a superior structure immediately below the surface, but a surface seal only a millimetre thick will determine how easily water enters the soil and how readily it runs off. Conservation tillage methods initially influence and change the soil properties very close to the surface, for example through organic matter build-up. This is a catalyst for soil structural improvement over time for the entire soil profile.

Soil biological aspects

Soil meso and micro fauna and flora are often overlooked in their importance for soil structural formation and stabilisation. A separate paper will deal with this issue in detail.

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Soil health in north coast agriculture: assessment and rehabilitation

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At the historic IFOAM (International Federation of Organic Agriculture Movement) meeting in Switzerland in 1977, which placed organic farming under the International spotlight, Lady Eve Balfour discussed works of numerous pioneers in the medical and agricultural field. She applauded their foresight.

They looked at the living world from a new perspective- they also asked new questions. Instead of the contemporary obsession with disease and its causes, they set out to discover the causes of Health.

Since this pioneering review of health, agricultural research has begun to focus on the definition of soil health. Although many prominent research groups have defined soil health (Doran, Zeiss 2000 publish a good example), agriculture in the 21st century is still unable to capitalise on soil biota for economic or environmental sustainability.

In order to achieve sustainable agriculture, Sherwood and Uphoff (2000) argue that efforts are needed to better link multi-disciplinary research with practice and political actions. The achievement of sustainable agriculture was let down in the 20th century because research focused strongly on soil chemical and physical factors, with comparative neglect of biological factors. Concern about soil health is motivated by present and future interest in both agricultural productivity and profitability.

Many factors can have negative impacts upon soil health. These factors include loss of organic carbon (Islam, Weil 2000), compaction (Singleton, Addison 1999), disruption of soil macroaggregates (Islam, Weil 2000), pesticides (Mittra, Raghu 1998, Tu 1991), pesticide breakdown products (Cernakova, Zemanovicova 1998), inorganic pollution arising through fertilisers, fungicides and sludge application (Merry et al 1986, Gong et al 1997), the use of fertilisers (Stamatiadis et al 1999)

and non-pesticide organic pollution including surfactants (Wilke 1997). Other causes of reduced soil health can arise through water and wind erosion (Garcia et al 1997), and loss of organic matter due to fire, deforestation and tillage (Islam, Weil 2000).

The north-eastern corner of New South Wales is an area rich in subtropical agriculture. Principal crops include macadamia, avocado, sugarcane, banana, pasture and other mixed horticulture. The current soil health project being carried out by NSW Agriculture and Tuckombil Landcare group is driven by concerns among growers about the economic and environmental sustainability of horticultural enterprises and the loss of soil health.

The project described in this manuscript has two key objectives: to assess the health of horticultural enterprises in northern NSW, and to develop technologies to rehabilitate soil health where decline is measured.

Farm soils survey

Fifteen farms were selected to cover a range of enterprises in north-eastern NSW. Five industries, including avocado, banana, macadamia, coffee and sugarcane, with some certified and operating as organic farms, were selected for sampling. Each farm had four sampling sites and two control sites. Control sites were areas that comprised a similar soil type and similar microclimate, but were not influenced by recent agricultural practices. Often, control sites consisted of natural vegetation. For orchard crops, two sites were located beneath the trees, and two sites were between rows (interrow space). For crops such as sugarcane, two sites were located on the mounds beneath the plants and two sites were located between the mounds. Each soil core was subdivided into 0-5cm and 5-20cm samples, and each plot had four soil cores taken.

Soil health tests

Many tests exist for the assessment of soil health. Some of the more rudimentary analyses were performed in this survey to enable a large number of sites to be analysed. These tests included microbial activity, pH, bulk density, water holding capacity and moisture. On eight of the 15 farms, microbial biomass carbon was also determined.

Soil pH, moisture, water holding capacity and bulk density were determined using the methods described by Alef and Nannipieri (1998). Soil microbial activity was determined by two methods; hydrolysis of fluorescein diacetate and alkaline phosphatase. Hydrolysis of fluorescein diacetate was assayed using a modified method described by Zelles et al (1991), Fonrvieille et al (1991) and Schnurer and Rosswall (1982). Alkaline phosphatase was based upon the method for assay of acid and alkaline phosphatase in soils described by Tabatabai (1982). Biomass carbon was analysed by methods described by Islam and Weil (1998).

Farm survey results

Comparisons were made between the samples taken from the farm and the control sites. Statistical analysis has shown that on many farms, the level of fluorescein diacetate hydrolysis, alkaline phosphatase activity and microbial biomass were significantly reduced. A summary of these findings is shown in Table 1.

Table 1. Summary of findings from survey of farm soils compared with undisturbed soils

Farm	Interpretation of alkaline phosphatase data	Interpretation of fluorescein diacetate data	Interpretation of biomass carbon data
avocado 1	no differences	no differences	no data
avocado 2	no differences	no differences	no differences
avocado 3	significant increase in surface soil interrow	significant increase in interrow surface soil.	significant decrease in soil in row and in soil at depth interrow
avocado (organic)	significant increase in surface soil in row	no differences	significant decrease in soil at depth
macadamia 1	no differences	no differences	no data
macadamia 2	significant decrease in surface soils	no differences	no data
macadamia 3	significant decrease	significant decrease	significant decrease in soil at depth
macadamia 4	no differences	significant decrease in interrow soil and at depth in row	significant decrease in soil in row
macadamia (organic)	no differences	no differences	significant decrease in surface soil interrow
banana 1	no differences	significant decrease in interrow surface soil.	no data
banana 2	no differences	no differences	significant decrease in surface soil interrow
banana 3	no differences	no differences	no data
sugarcane 1	significant decrease at surface	significant decrease at surface	no data
sugarcane 2	no differences	significant decrease	significant decreases
coffee	no differences	significant increase in depth in row.	no data

The interpretation of the data shows a decline in soil microbial activity and biomass carbon at a number of farms. Assessment of biomass carbon was a more sensitive measure of damage to soil health, as every farm tested had a significant decline. Control sites are the only acceptable reference for comparing farm data in established agricultural enterprises, as they have developed a natural sustainable biological community. Five of the 15 of farms also had statistically significant decreases in the level of fluorescein diacetate hydrolysis, while only two farms showed an increase. A greater level of fluorescein diacetate hydrolysis does not

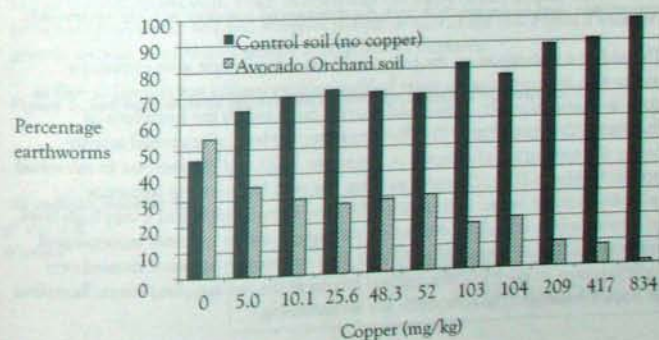
necessarily reflect a greater level of microbial biomass, as activity and total biomass are independent entities. Three of the 15 farms had decreases in alkaline phosphatase activity, while again two showed an increase.

Earthworm tests

During the 15-farm survey, there were suggestions that certain farms had a severely depleted population of earthworms. This information was gathered during the collection of soil samples, as well as from anecdotal evidence from farmers. Further evaluations of earthworm populations (Tim Kingston, pers. comm) have demonstrated significant declines in earthworm populations in orchards with a history of copper use. To determine whether impacts of fungicidal copper on earthworms exist, avoidance trials were set up using methods outlined by Yeardley Jr et al (1996). The basis of these trials is to count the location of adult worms that have the choice to live and feed in either a contaminated soil or a non-contaminated soil with similar properties under controlled environmental conditions.

Multiple replications of the avoidance trials strongly suggest that copper residues have a significant influence on the presence of earthworms in soil. Figure 1 demonstrates that even with concentrations at 10mg/kg, significant avoidance occurs. When copper concentrations reached 200mg/kg, 90% of the worms were avoiding the soil, while at 800mg/kg, almost complete avoidance was found. No other correlations with soil analyses could be found.

Figure 1. Earthworm avoidance of copper contaminated orchard soil.



Rehabilitation trials

Rehabilitation technologies to improve microbial activity and soil health are not new. These may include the addition of manures, fertilisers, lime and gypsum, and organic materials to soil; and the use of crop rotations, green manures and fallows. In fact, most farmers, both organic and conventional are currently practising some form of soil rehabilitation. What is lacking, however, is a thorough understanding

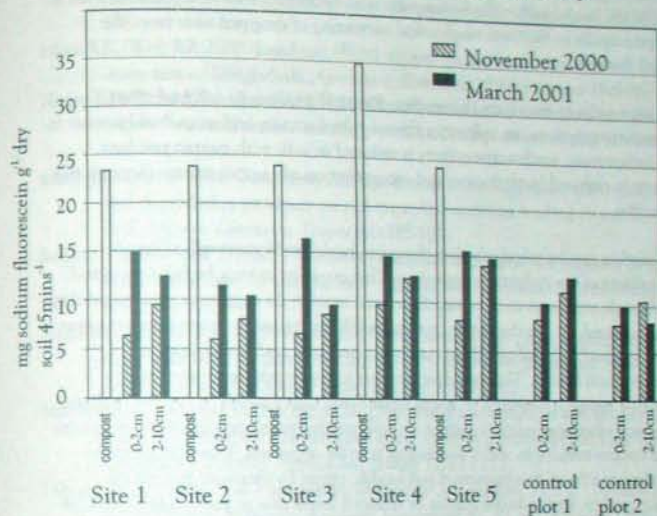
of how these processes benefit the soil biology, to promote soil health. For example, in an Australian vegetable cropping trial which received high inputs of compost, improvements that were observed included higher organic carbon content, greater microbial activity and biomass, greater exchangeable nutrient cations, and greater water holding capacity and aggregate stability (Wells et al 2000).

A composting process was developed at pilot scale to convert farm wastes, including macadamia husk and chicken litter, into a soil conditioner. A pilot system was initially set up according to Van Zwieten et al (1997). Following this, a field scale demonstration was established at a commercial macadamia farm with degraded soil health. The farm had evidence of erosion and decline in soil physical properties, and reductions in biological activity and biomass were measured. Here, 40m³ of chicken litter was composted with 60m³ of macadamia husk. The compost remained thermophilic for more than eight weeks, and the pile was turned three times in this period. Water had to be added to the compost pile, as the moisture level dropped below 50% w/w on a number of occasions. The final compost was spread on an area of the farm which was prone to erosion, and where obvious soil loss had exposed surface roots. The addition of the compost did not affect the farm's standard management practices, as neither sweepers nor nut harvesters were hindered by the presence of the 100mm thick compost layer.

More recently, the composted farm waste described above and commercial compost sourced from Coffs Harbour have also been applied to areas within a three year old macadamia orchard at NSW Agriculture's Tropical Fruit Research Station, Alstonville to further evaluate organic matter addition and improvements in soil health. Some treatments had coconut fibre matting placed on top of them to act as a weed mat, to further reduce the risk of soil erosion. A ground cover (pintoise peanut) was used in conjunction with the commercial compost in some treatments.

The addition of compost on the commercial macadamia farm gave promising results with improvements in water holding capacity (results not shown) as well as quite dramatic increases in microbial activity, measured by the hydrolysis of fluorescein diacetate (Figure 2). The data shows the level of microbial activity before the application of compost in November 2000, and the increase in microbial activity by March 2001. Compost addition was even beginning to influence microbial activity deeper in the soil profile. The compost layer had a very high level of activity, which is likely to decrease as the organic matter becomes incorporated into the soil. Other plots nearby the area with no compost addition showed very little variation in the levels of microbial activity at the two sampling times. Sampling at both this site and the Alstonville site is continuing.

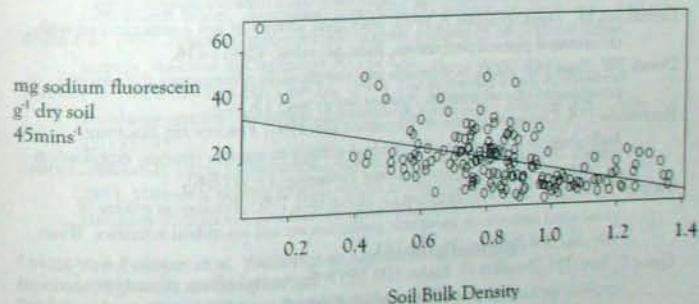
Figure 2. Influence of composted farm waste on soil microbial activity.



North coast soil health

The results of the farm survey show significant decreases in microbial activity in the region's horticultural soils. Trials indicate that the major causes include the presence of copper in soil and increases in bulk density of the soil. Figure 3 shows a general decline in microbial activity as bulk density increases.

Figure 3. Soil bulk density impacts on fluorescein diacetate hydrolysis.



The causes of this increased bulk density include the use of machinery and, in particular, the use of machinery over bare earth, as is common within commercial

macadamia plantations. The bare earth is a result of management practices that promote the use of herbicides to keep the under-tree area free of vegetation. This is done principally to facilitate mechanical harvesting of dropped nuts from the orchard floor.

Research results to date have shown that chemical residues in soil and other management practices can influence the microbial activity and microbial biomass in soil. Furthermore, earthworm activity is reduced in soils with copper residues, resulting in reduced bioturbation and incorporation of organic matter through the soil profile.

The question can be asked whether these soil health indicators will affect the sustainability of the industry in question. This question cannot be fully answered yet, although outcomes such as significant soil erosion do suggest that sustainability is compromised. As for the future, multi-disciplinary research teams need to assess and understand soil biology, along with soil chemistry and soil physics, to understand soil health. This could be the first step towards developing truly sustainable systems. Research in north coast horticulture needs to further evaluate the impacts of copper contamination on soil health, and to develop technologies to reduce copper toxicity in soil if soil health is to be improved. Research needs to prove the benefits of this improved soil health, either by increases in yield or produce quality, and reduced inputs or reduced losses due to pathogenic attack. A more detailed study of organic farming systems and commercial soil amendments is needed to evaluate the benefits of these products or practices, and to gather information that will benefit best practice conventional enterprises.

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Organic agriculture soil health strategies

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Organic farming is agricultural production without the use of synthetic fertilisers, chemicals and growth regulators (USDA 1980). Concerns over the environmental impacts of agriculture, declining terms of trade, reduced market opportunities and human health concerns have increased interest in the adoption of organic farming systems.

Historical development

By the late 1800s the combination of the industrial and scientific revolutions had resulted in undeniable benefits for agriculture and society. The industrial revolution gathered people in larger cities and made greater demands on agriculture for food and fibre, while the scientific revolution saw the development of modern scientific method and the growing importance of technology and engineering. This period (1850-1930) also saw the emergence of the biological, or life, sciences and the earth sciences. While these did not have as visible an effect as chemistry and technology, the findings of individuals such as Darwin (1881), Frank (1885), Rayner (1927), King (1911), Hilgard (1906) and Hopkins (1910), were important for the development of modern organic agriculture.

During the 1930s, agricultural practices came under scrutiny as vast areas of agricultural land in the USA became subject to wind erosion during what became known as the 'dust bowl' period. This led to the establishment of numerous soil conservation projects and agencies. Researchers found correlations between a decrease in soil health and an increase in degenerative diseases, reproductive problems, and a general decline in health among humans and animals (Wrench 1938, USDA 1939, Price 1945).

By the early 1940s there were indications that agriculture was beginning to balance its chemistry with biology, and its technology with ecology. A more holistic approach was permeating the thinking of both farmers and agricultural scientists. Some of the most significant soil researchers of the time included Jacks and Whyte, 1938; Howard, 1943; Cocannouer, 1950 and 1958; Hendricks and Alexander, 1957; Kellog, 1957; Russell, 1973; Albrecht, 1975; and Balfour, 1976. The research of these individuals highlighted the complexity of soils, particularly in the area of soil organisms and their relationships to plant health and growth. Research also investigated the nature and effects of crop rotations on soil fertility (Leighly 1938) and the importance of humus to a healthy soil (Waksman 1936, Howard, 1943).

During the 1950s there was a definite shift back to a predominantly chemical and technological approach. For the next twenty years, holistic and integrative research

declined as scientists lost interest or could not attract research funds. Many attributed this shift to a post World War II surplus of products and technology from petrochemical and munitions industries. It was during this period that the 'organic' versus 'conventional' agriculture debate reached its peak. The publication of Rachel Carson's *Silent Spring* in 1962 saw the debate shift in favour of organic agriculture. Carson's research highlighted the impact of pesticides on the environment and pointed to the inevitable decline in ecosystem health. Carson stressed the interrelatedness of all life on the planet, that each species has its own ties to others, and that all are related to earth.

By 1977, as erosion and declining soil fertility were reappearing as serious problems in agriculture, the United States Senate was preparing to hold hearings on the relationships between diet, disease and health, and researchers began re-visiting agro-ecology. At the farm level, organic agriculture emerged as a movement offering farmers an alternative to expensive biocides and energy intensiveness and which aimed to minimise the impact of agriculture on the environment and work with nature.

Today, as agriculture struggles to find a balance between feeding the world and managing legacies such as salinity, soil acidification, declining bio-diversity, pesticide resistance and human and animal health concerns, a renaissance in integrative thinking is permeating agricultural policy and research. Researchers are beginning to investigate organic farming systems in the hope that they may provide some solutions to improving agricultural sustainability. As consumers begin to demand food that is produced with minimum impact on the environment and with minimum pesticide application, the organic industry is experiencing an annual growth rate of 30%. This expansion far exceeds that of any other agricultural sector.

Soil – the foundation of organic philosophy

Organic farming's basic tenet is the creation of a healthy, fertile soil as the basis of the farm agro-ecosystem. The concepts of the Living Soil and the Law of Return are fundamental principles of organic agriculture.

The 'aliveness' or dynamic nature of soil is intrinsic to organic agriculture. Organic proponents often equate the quality of soil with the level of health of plants and animals, and, in turn, humans living on that soil. Organic farming is primarily a soil building process. Relevant to this is the belief that without an understanding of the soil as a living, dynamic entity, and without an intimate working relationship with the soil, soil building will not occur, and a sustainable self-sufficient agro-ecosystem able to produce basic food requirements will be unattainable.

The Law of Return, in its simplest meaning, says that 'all life forms must return at death what they took from their resources during their life time' (Farmer 1977). This statement recognises the cyclic nature of the earth's natural processes. Refusal to recycle biological wastes back into the soil deprives microbial decomposers of their food supply, which in turn prevents the release of essential nutrients by decomposers. Organic philosophy takes this concept one step further by likening the export of agricultural commodities to irretrievable loss of soil nutrients. Hyams

(1976) and Carter and Dale (1974), note that the continuous export of agricultural products played a definite role in the destruction of the once fertile North African soils. In addition, full compliance with the Law of Return would require a more even distribution and intermingling of urban and agricultural lands and subsequently greater contact between urban and agricultural people. Many advocate that in the long run this would lead to a better balance between agriculture and industry, and build a more humane and holistic society (Merrill 1983).

The organic soil building process

There is worldwide agreement within organic standards that organic farming systems should maintain or increase soil fertility on a long-term basis. Australia's organic standard, The National Standard for Organic & Bio-dynamic Produce (1992, 1998) states that the primary aims of organic agriculture include:

- producing food of high nutritional value
- enhancing biological cycles in farming systems
- maintaining and increasing fertility of soils
- working as far as practicable within a closed system
- avoiding pollution resulting from agriculture
- minimising the use of non-renewable resources
- coexisting with, and protecting the environment.

These aims are achieved through management practices that enhance soil biological activity so that plants are fed through the soil ecosystem and not primarily through soluble fertilisers added to the soil. Organic farming systems rely to the maximum extent feasible upon crop rotations, crop residues, animal manures, legumes, green manures, mechanical cultivation and approved mineral-bearing rocks to maintain soil productivity and till and supply plant nutrients.

Conversion from a conventional fertiliser regime to an organic soil building process involves eliminating the use of artificial chemicals in the farming system. This means that fertilisers such as superphosphate and ammonium nitrate are excluded and replaced by practices which foster the cyclic renewal of nutrients to maintain crop health.

Organic matter content, microbial activity and general soil health are taken as measures of soil fertility. An analysis of organic farming systems in Europe (Stolze et al 2000) has found that organic farming increases microbial activity by 30-100% and microbial biomass by 20-30%. A comparative study of organic, conventional and integrated apple production systems in Washington State from 1994 to 1999 found that organic and integrated systems had higher soil quality and potentially lower negative environmental impact than the conventional system. The data indicated that the organic system ranked first in environmental and economic sustainability, the integrated system second and the conventional system last (Reganold et al 2001).

Research into the sustainability of organic farming systems in Australia has been limited, and has tended to focus on comparative studies in extensive cropping and

livestock systems, systems characterised by their low use of external inputs. Phosphate rock, lime, dolomite, legume rotations, incorporation of green manures and crop refuse, manure application during livestock grazing, and the application of microbial preparations may be used for building soil fertility. Studies by Penfold (1995), Derrick (1996), Derria et al (1996) and Schwarz (1999), suggest a trend towards deficiencies in phosphorus, nitrogen and sometimes sulfur, under current organic management regimes in broadacre (extensive) cropping and livestock systems.

Limited studies of intensive organic farming systems in Australia have generally shown an increase in soil health compared with conventional practice (Wells, Chan 1996, Huxley, Littlejohn 1997, Stevenson, Tabart 1998). This could largely be a reflection of the cost effectiveness of applying larger applications of commercial organic fertilisers, compost and incorporation of green manures to high value crops such as fruit, vegetables, and herbs.

Organic soil building practices

Organic farmers have a range of options to sustain soil health. Applications of these methods are discussed below.

Increasing biological activity

Organic conversion begins with a process that encourages increased microbial and arthropod activity within the soil. The elemental composition, structure, and organic matter content of the soil need to be favourable if soil biological activity is to be enhanced. Biological activity begins with the breakdown of soil organic matter. During the decomposition process, the organic molecules in organic matter are broken down into simpler organic molecules that require further decomposition into mineralised nutrients. Organic farmers supply organic matter through incorporation of green manure crops and crop refuse, and the addition of compost.

The use of bio-indicators is becoming an increasingly important way to assess soil health. Pankhurst et al (1997) review the measurement of soil organisms and biotic processes as indicators of soil health. A range of techniques is available to assess soil biological activity. These include measurement of CO₂ respiration; DNA testing to determine the diversity and abundance of microorganisms present; and measurement of the tensile strength of cotton strips buried in the soil. Commercial laboratories offering soil microbial assessment are now becoming more common in Australia.

Green manuring

Green manure crops are grown specifically to be cultivated back into the soil to build up soil organic matter and nutrients, and to stimulate biological activity. The type of green manure crop and stage at which it is turned in determine the amount of organic matter or nutrients returned to the soil. A lush, actively growing sward of legumes such as vetch, faba beans or lupins contains large amounts of nitrogen (50-140 kg N-gain/ha) that is released to the soil upon cultivation. The same crop, when allowed to mature, contributes more organic matter but less available

nitrogen. If a soil is low in organic matter, then a green manure crop that increases soil organic matter, such as oats, is desirable.

Plate 1. Green manure crops of oats, faba bean and vetch at NSW Agriculture's organic demonstration site at Yanco. Photo: R. Neeson.



Green manures may also act as break crops to reduce the carryover of pests and diseases in subsequent crops in the rotation. Green manure crops are an essential component in intensive organic annual cropping rotations.

Nitrate leaching following the incorporation of a green manure crop may occur when rainfall exceeds evaporation resulting in net drainage. There is some evidence to suggest that nitrate leaching may be less under organic than under conventional systems (Lampkin 1990). Nitrate leached below the root zone is effectively lost from the system. Rotation design within the organic system needs to consider how large nitrogen losses following the ploughing in of the green manure crop can be minimised. Early establishment of a cereal crop immediately following incorporation of green manure has been shown to be the simplest and one of the most effective methods of reducing nitrate leaching.

Undersowing crops

Undersowing of crops is a key practice in organic systems. One example is barley undersown with the grass/clover pasture that will follow in the rotation in the succeeding year. This practice has been shown to have beneficial effects on the diversity and abundance of insect species (Vickermann 1978). Other benefits include the potential for higher protein content in cereals undersown with a legume, due to a small net nitrogen gain, enhanced weed suppression and improved pest and disease control (Lampkin 1990).

Plate 2. Lucerne undersown eight weeks after maize emergence comes away following maize harvest. Yanco organic demonstration site. Photo: R. Neeson.



Growing permanent swards and pastures

In livestock and cropping enterprises, legume-based pastures provide the systems' major nitrogen input. Livestock largely recycle other nutrients. In orchards, permanent swards (sods) are sometimes planted between the rows, and are the preferred method of interrow management because the soil ecosystem remains undisturbed. This favours the development of plant roots, soil microfauna and flora, worms, and mycorrhiza, and helps retain good soil structure.

A mixture of deep-rooted and shallow-rooted species increases the potential for accessing soil nutrients. For example, in organic pastures, herbs such as chicory, plantain, yarrow and caraway are often added. Ideally, an orchard sod consists of a range of perennial plant species. Grasses such as ryegrass or fescue are efficient in obtaining potassium from the soil and able to utilise excess organic nitrogen. Legumes such as clover or lucerne may contribute 40-140 kilograms per hectare per year of nitrogen to the soil reservoir. Herbs such as comfrey and chicory often have a higher mineral content and have deep roots capable of bringing up leached elements that would otherwise be unavailable to the crop.

A study by Evans et al (2000) of organic cropping systems in the Riverina and Central West of NSW will attempt to identify best practice for management of the pasture phase to optimise soil microbial activity and increase soil concentrations of mineralised nutrients. The study aims to quantify soil fertility trends and will introduce a range of innovative pasture management practices to improve yield and cropping frequency.

Plate 3. A range of deep-rooted and shallow-rooted species (oats, faba beans and rape) in green manure crops increases the potential for accessing soil nutrients and improving soil structure. Photo: R. Neeson.



Applying compost

Compost is a primary source of nutrients and organic matter in intensive organic farming systems and an invaluable food source for soil microorganisms. The use of compost in Australian broadacre organic cropping systems is not widely practised, as its application is not cost effective. Animal manures and crop refuse form the major ingredients of compost. Organic standards require that manure intended for application is composted before use.

The major benefits of compost are that it is a more stable form of organic matter than raw waste, and weed seeds and diseases are destroyed during the composting process. When manure is composted, it is easier to spread, and losses to the environment are minimised. Rock dusts and clay, added to compost in small quantities, may help to reduce nitrogen losses from the heap by absorbing ammonia (Lampkin 1990).

There are many recipes and techniques advocated for composting. The Australian Standard for Composts, Soil Conditioners and Mulches (AS 4454:1999) defines composting as 'the process whereby organic materials are pasteurised and microbiologically transformed under aerobic and thermophilic conditions for a period of not less than six weeks'. The pasteurisation process is described as having 'the whole mass of constantly moist material subject to at least three consecutive days at a minimum temperature of 55°C'.

The major aim of composting is to produce a stable humic compound. This is achieved by mixing major ingredients together in quantities that achieve a suitable carbon:nitrogen ratio. The ideal C:N ratio lies between 25 and 35:1 (Lampkin 1990). Moisture content is also important and ideally should be in the order of 55-70%. Compost heaps should be designed to allow for sufficient air access. Microbial

activity quickly raises the temperature of the heap to above 55°C, after which it is turned (ASA standards specify a minimum of three turns) to allow for thorough mixing and a further heating of any undecomposed material.



Plate 4. Compost production at NSW Agriculture organic demonstration site, Yanco. Photo: R. Neeson.

Remineralising the soil

Many Australian soils are leached of elements essential for plant growth. Moreover, many years of farming with emphasis on supplying a nitrogen, phosphorus and potassium fertiliser regime at the expense of minor elements may have resulted in further 'mining' of certain trace elements. This theory has some support, with evidence (McCance, Widdowson 1940-2000) suggesting a gradual decline in the elemental composition of fresh fruit and vegetables since the 1940s.

Soils with higher biological activity play an important role in increasing the availability of micronutrients. Significant research has been undertaken in the symbiotic roles of arbuscular mycorrhiza fungi in increasing phosphorus availability in plants and rhizobium bacteria, and its ability to fix atmospheric nitrogen for plant use. However, little research has been undertaken into the role of other soil microorganisms in improving micronutrient uptake by plants.

The remineralisation of Australian farming soils is a more recent strategy proposed by some soil health practitioners. Various techniques for remineralisation have an increased following amongst farmers, largely based on balancing the CEC of soils and achieving a satisfactory calcium to magnesium ratio (Albrecht 1975). The effectiveness of these techniques is yet to be scientifically evaluated under Australian conditions.

Remineralisation involves the addition of various fertilisers of mineral origin. These are rock-based materials and include rock phosphate, dolomite, limestone and rock dusts from silicate rocks, including basalt and bentonite and some commercial organic blends. Rock dusts may be added directly to the soil or added to compost heaps. Whichever method of application is favoured, release of nutrients from the rock dusts is accelerated by moist conditions, high temperatures and high biological activity, for example, during a green manure stage or composting.

Improving soil structure

Improvements in the biological activity and CEC of soils will generally lead to an improvement in soil structure. However, this needs to be supported by suitable cultural practices. Use of appropriate machinery at correct soil moisture, incorporation of soil organic matter, and improvement of soils utilising different crop root physiology are techniques used by organic farmers to develop soil structure.

Lampkin (1990) describes cultivation practices as having the most significant impact on the soil of any agricultural activity. He summarises the organic approach to soil cultivation as one that seeks to maintain soil structure and allow the soil to have vegetative cover for as long as possible within the rotation. Shallow cultivations, where only surface layers of the soil are mixed, are an important element of this approach. Deep cultivation of dry soil is practised to loosen and aerate soil, avoiding inversion of the lower layers. Green manures or cereal crops are sown as soon as practicable following cultivation, their roots helping to stabilise loosened soil and minimise nitrate leaching.

Organic soil conversion

Organic conversion is not just about replacing a high-input chemical system with a no-input system. I propose that the organic soil building process goes through three critical stages. For the purpose of this paper I will refer to these as the adjustment phase, the comfort phase and the maintenance phase.

Adjustment phase

The adjustment phase involves developing a system that reduces the crop's reliance on artificial chemicals. This could be likened to overcoming 'cold turkey' for those farming systems that are heavily dependent on chemical inputs. During this phase some farmers have observed that crop yields may decline as the system converts from a chemical to a biological one and is starved of its regular 'fix' of readily available, chemical fertilisers.

The length of this preliminary soil building process will depend largely on the soils' pre-existing condition. The adjustment phase involves increasing biological activity by providing optimal soil conditions. The challenge for the organic farmer is to implement a cost-effective strategy that encourages and builds biological processes within the soil while maintaining optimal plant nutrition. Standard organic practices such as planting of legumes and green manures, and applications of compost, rock dusts and commercial organic fertilisers, are combined with foliar

applications of seaweed, fish emulsion, sugar solutions and microbial preparations to stimulate soil biological activity and supplement plant health.

Comfort phase

The comfort phase coincides with an increase in biological activity and a corresponding release of previously 'locked-up' or unavailable nutrients. During this phase optimal crop yields are reached. Organic farmers need to be diligent that over-fertilisation does not occur during the comfort phase. This is more likely to occur in intensive horticulture systems where applications of compost and green manuring are common practice. Evidence of over-fertilisation usually manifests itself through crop physiological problems and increased pest and disease incidence. Organic farmers are encouraged to regularly monitor soil nutrient levels. Soil and plant tissue-testing enables nutrient requirements to be tracked thus avoiding 'overfeeding' the soil system.

Maintenance phase

Research has indicated that some organic systems have, over a longer period of time, undergone a decline in soil nutrient reserves (Small et al 1994; Penfold C et al 1995). This could be attributed to long term drawing down of nutrients during harvesting of crop or livestock products and through natural processes such as leaching. In Australia, this has been particularly evident in broadacre cropping and livestock enterprises where phosphorus deficiency has been found. This has implications for cereal and legume crops. Phosphorus deficiency in legumes will impact on plants' ability to fix atmospheric nitrogen in root nodules. Nitrogen fixed by legume forms is an essential nutrient in subsequent crops in the cropping rotation. Nutrient budgeting by reconciling inputs and outputs to the soil system and correlating these with regular soil tests and crop performance can help organic producers track the performance of the soil nutrient cycle.

Correcting deficiencies

Unseasonal weather conditions, such as a prolonged dry spell or excessive wet, or just a miscalculation of crop nutrient requirements, may result in a deficiency within the crop. If this happens during a critical crop growth period, plant health may decline, predisposing crops to pest and disease attack. A permanent yield depression may result, so it is necessary to correct any deficiency quickly. Leaf analysis is the usual method to detect deficiencies during the crop growing period. Organic farmers make use of foliar sprays such as fish and seaweed extracts, molasses and trace elements to correct temporary deficiencies.

Case study: organic conversion at Yanco

At Yanco in the Murrumbidgee Irrigation Area in southern NSW, NSW Agriculture, in conjunction with the Natural Heritage Trust's National Landcare Program, has established a demonstration site to illustrate the organic conversion process to farmers. Practices demonstrated include:

- increased soil fertility and biological activity by
 - use of legumes, green manure and other crops in appropriate rotations
 - application of composts, special preparations and other organic and mineral fertilisers

- various tillage techniques
- non-chemical methods of pest, disease and weed control
- evaluation of crop varieties for pest and disease susceptibility and adaptability to diverse, low input cropping systems.

Planting on the four hectare site is designed to achieve sustainable production and maintenance of soil health through rotation of cereals, oil seeds, legumes and vegetables. The entire site was sown down initially to green manure crops which were then incorporated in the soil. Two organic soil treatments were then applied. Both treatments comply with organic standards.

Soil treatment A is referred to as 'organic - biodynamic'. In this treatment, crops are fertilised pre-sowing with compost and rock phosphate and foliar applications are applied after six weeks at intervals of eight to ten days, depending on leaf analysis results. The foliar applications consist of biodynamic preparation 500, biodynamic fish emulsion, brown sugar, worm liquid and seaweed liquid.

Plate 5: NSW Agriculture technical officer Tobias Koenig inspects linseed at the Yanco organic demonstration site. Photo: R. Neeson.



Soil treatment B follows a remineralisation strategy that aims to achieve a satisfactory calcium to magnesium ratio. In this treatment the same organic-biodynamic fertilisation program is followed with the addition of small, pre-sowing applications of lime (up to 300 kg/ha) and gypsum (up to 500 kg/ha) as per soil analysis results.

The project, now in its fourth year, has been evaluating soil and crop health in both treatments. A diverse range of crops has been grown, including wheat, oats, sunflowers, linseed, safflower, sweet corn, maize popcorn, soybeans, pumpkins,

melons, tomatoes, lettuce, and green manures. Marketable yields have been achieved for most crops, although in most instances yields are below the district average. Soybeans have been the exception with crop failures due to significant green vegetable bug damage. *Heliothis* spp. has been the other major insect pest, and while some minor crop losses did occur, pest populations were manageable. Disease incidence has been negligible on all crops.

Standard soil analysis has been carried out each year, before and after planting. Soil analysis trends show that organic matter has increased from 1.5% to 3.0%, pH has generally remained unchanged at 7.3, the calcium-magnesium ratio has increased from 1.7 to 2.5, and the cation exchange capacity decreased slightly, due largely, it is believed, to an increase in potassium from compost applications.

The real benefit of organic management at Yanco will be to demonstrate the long-term impact of the intensive organic rotation. Soil health improvement, pest and disease incidence, sustainable crop yield and quality, will continue to be monitored over the coming years to assess these changes.

The primary aim of the Yanco demonstration site has been to show farmers that organic practices can be sustainable and that some practices may offer opportunities for conventional farmers to reduce chemical inputs. This is being achieved, with some Riverina district farmers now practising organic management of corn, soybean and vegetable crops. Alliances between local processors and producers are being forged, enabling producers to investigate opportunities in lucrative organic export markets.

Conclusion

Maintaining soil health organically relies on nurturing the soil's biological and mineral processes. Incorporation of green manures and legumes in the cropping rotation, applications of compost, mineral rock dusts and organic fertilisers, and grazing of livestock combined with appropriate tillage are some of the techniques used by organic farmers to meet this objective.

More research is required under Australian conditions to determine organic soil management strategies for optimum crop performance and to assess the effectiveness of current practice. Essential to this research is gaining a better understanding of the relationships between soil microorganisms, soil and plant health, including mineral uptake, and pest and disease resilience.

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Soil organic carbon and soil structure: implications for agro-ecosystem soil health

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Soil organic matter, the organic fraction of the soil, is a complex mixture of plant and animal products in various stages of decomposition, and soil microbes and substances produced by them. Many Australian soils are inherently low in soil organic carbon (Spain et al 1983). The latter authors estimate that approximately 75% of Australian soils now contain less than 1% of soil organic carbon in their surface horizons. However, many of these soils, including the red-brown earths, solonised brown soils and the grey, brown and red clays, are important for Australian agriculture.

Soil organic carbon influences all three aspects of soil fertility, the physical, chemical and biological (Dalal, Chan 2001). It therefore plays a controlling role in soil quality and, as such, affects the productivity and the sustainability of farming systems. In this paper, the main focus is on the importance of soil organic carbon (SOC) in maintaining good soil structure (soil physical fertility), a pre-requisite for a healthy agro-ecosystem. The complex but important interactions between soil structure and soil biological fertility as affected by soil organic carbon will also be highlighted.

Soil organic carbon and soil structure

Soil structure is defined as the size, shape and arrangement of aggregates and the voids in between, in a soil at a given time. It is the architecture of the soil and can be described both in terms of the pore system as well as the arrangement of primary soil particles into hierarchical structural states (Kay 1990). Soil structure provides the physical spaces or ecological niches for many soil organisms. Moreover, the interactions of the soil structure with soil water content determine a number of important soil physical properties that in turn define the physical environment of the soil ecosystem. These properties include soil water availability and soil water permeability, soil aeration and soil mechanical properties (Smiles 1988).

It is important to realise that soil is the habitat for a range of living organisms that make up a healthy agro-ecosystem (Lee, Foster 1991). The architecture and the physical environment of soil structure determine the types of organisms that can exist in a particular soil (diversity), their abundance and their activities. These are important factors that affect the functioning of the soil as an ecosystem and determine the 'health' of the soil.

For instance, soil structure determines soil moisture levels and the moisture stress that organisms are subjected to at a particular soil water content. For plants, the

limits are field capacity (-10 kPa) and permanent wilting point (-1.5 MPa). This range is commonly known as water holding capacity and it varies according to soil structure or porosity. Soil moisture characteristics also control the mobility of many small soil animals such as nematodes, motile bacteria and aquatic phycocyanetes which are restricted to existing water-filled soil pores. These organisms depend on sequences of water-filled pores of the right size to permit their passage (Papendick, Campbell 1985). The rate of water movement through soil, determined by pore size distribution, controls many important biological activities such as wilting and germination of plants, and hatching of nematode cysts (Smiles 1988).

At the same time, the composition of soil atmosphere is governed by gaseous diffusion processes between the above ground atmosphere and the soil which depend, in turn, on the soil's porosity. As a result, aerobic and anaerobic zones are interspersed throughout the soil and these also affect the prevalence and distribution of organisms in soils.

According to Dexter (1988), a soil that provides an ideal medium for crop production needs well-developed structural form, stability in the face of water and external mechanical stresses, and resilience or the ability to recover its structure after disturbance (Kay 1990). Soil organic carbon affects all three aspects of soil structure - form, stability and resilience (Kay 1997).

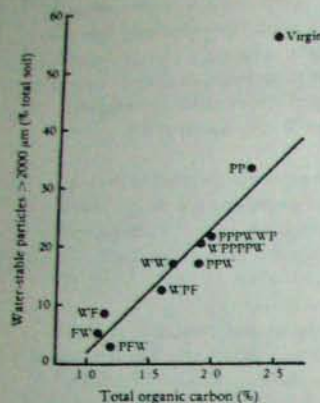
Role of soil organisms

While many soil organisms live in and depend on existing soil pores, larger organisms can make new pores and therefore modify soil structure. Plant roots, earthworms and termites fall into this category. The effectiveness of grass roots in producing soil aggregation by drying and wetting as well as by enmeshing actions are well known. Soil fauna such as earthworms and enchytraeids play an important role in creating soil aggregates (worm casts) and macropores (burrows) and hence modifying the pore size distribution. However, their abundance and activity depend on food supply and are therefore closely related to organic matter inputs and soil organic carbon levels.

Structural stability and soil organic carbon

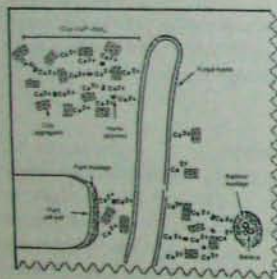
Organic carbon in various forms and in different locations within the soil medium contributes to the stability of soil structure. Results from both Australia (Tisdall, Oades 1980) and overseas (Chaney, Swift 1984) have demonstrated the positive effects of soil organic carbon level on soil structural stability. As shown in Figure 1, soil structural stability increases with increasing organic carbon levels which in turn vary with the frequency of fallowing and pasture in relation to the wheat phase. Fallowing decreases organic carbon levels and therefore has a deleterious effect on structural stability.

Figure 1. The relationship between water-stable soil aggregates and organic carbon under traditional wheat/fallow/pasture rotation (Tisdall, Oades 1980). (W = wheat, F=fallow, P=pasture).



Based on the hierarchical model of soil structure, a soil is made up of structural units of different sizes in the following order: domain (clay aggregates), microaggregates and macroaggregates (Tisdall, Oades 1982). Figure 2 presents a schematic model of macroaggregates (>250 µm).

Figure 2. Schematic presentation of a soil macroaggregate (Munee, Oades 1989).



Different chemical forms of organic carbon are found in different parts of the soil aggregates, acting as binding agents at different levels of soil structure. For example, microorganisms such as fungal hyphae, bacteria and their products exist between microaggregates and act as important binding agents for holding macroaggregates (>250 µm) together. From electron micrograph evidence, it has been proposed that a matrix of particulate organic matter (plant residue), microbial biomass and extracellular materials can attract inorganic particles (clay and silt) and act as centres of water stable macroaggregate formation (Waters, Oades 1991). On the other

hand, humic polymers are found in between clay aggregates (domains) and are important in maintaining stability of macroaggregates. Depending on the quality (chemical nature) and physical location within the soil, the different organic carbon fractions tend to have different lability and turnover time (Table 1). The fraction of soil organic carbon that exists in pores within microaggregates is inaccessible to microbial attack and therefore has a relatively long turnover time and is regarded as being physically protected.

Table 1. Turnover time of soil organic carbon depending on quality and physical location within the soil (Lal 1997).

Type of organic matter	Location	Turnover time	
		Years	Category
microbial biomass	pores, particle/aggregate surface	0.1-0.5	labile
litter	soil surface, pores	1-5	rapid
light fraction	voids, aggregate surface	5-15	moderate
particulate	voids, biopores	5-20	moderate
humus	inter-microaggregate	20-50	slow
humus	adsorbed on intra-microaggregate	50-1000	passive
humus	adsorbed on intra-microaggregate	1000-3000	passive

Soil organic carbon as an indicator of soil health

Conventional tillage

In Australia, significant declines in soil organic carbon have been reported under cropping, particularly when using traditional tillage implements and practices such as stubble burning and fallowing (Dalal, Mayer 1986; Geeves et al 1995). Figure 3 presents the changes in organic carbon in the top layer (0-10 cm) of six Queensland soils after several years of cultivation. It is clear from the data that organic carbon levels tend to decline with time under cropping but at different rates for different soils. Declines tend to follow first order kinetics, occurring rapidly in the first few years then decreasing with time so that the soil organic carbon level approaches a steady value.

Figure 3. Decrease in soil organic carbon in the top 0-0.1 m layer with the period of cultivation (Dalal, Mayer, 1986). 1 Waco, 2 Langlands-Logie, 3 Cecilvale, 4 Billa Billa, 5 Thallon, 6 Riverview.

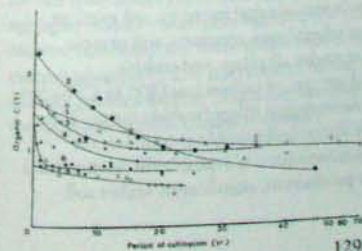
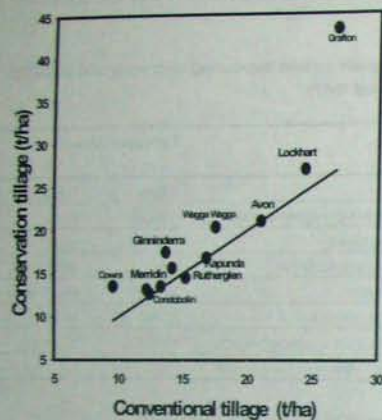


Figure 4. Soil carbon storage (0-10 cm) under conservation tillage compared with conventional tillage at different locations in Australia.



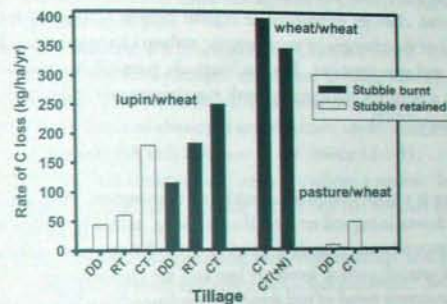
Conservation tillage

A review of soil organic carbon levels stored in the 0-10 cm layer in lighter-textured soils around Australia does not indicate consistently higher levels under conservation tillage when compared with those under conventional tillage (Chan et al 1998). As evident in Figure 4, many of the sites do not deviate markedly from the 1:1 line with the exception of the Grafton site which is located outside the main cereal cropping zone. The ratio of carbon storage between the two systems was found to be positively related to the annual rainfall ($r = 0.76^{**}$). This relationship suggests that in the lower rainfall (<500 mm) areas soil's potential as a carbon sink through the use of conservation tillage to sequester carbon is rather limited under the present management. Most cereal cropping in Australia is carried out under rain-fed conditions in areas with annual rainfall of 250-600 mm.

In fact, under broadacre cropping, there is little evidence to suggest that soil organic carbon under conservation tillage increases with time (Heenan et al 1995). Results of a long-term tillage/stubble management/rotation experiment on red earth at Wagga Wagga show that under continuous wheat-lupin rotations, soil organic carbon declined continuously over 14 years under all tillage and stubble management practices (Figure 5). The highest rate of carbon loss (400 kg C/ha/yr) was found under continuous wheat and conventional tillage/stubble burnt. Near equilibrium level was achieved only under direct drill/stubble retained in the subterranean clover-wheat rotation. Little information is available for horticultural crops. However, under irrigated vegetable production, significantly higher soil

organic carbon levels were detected in the organic production system compared with the conventional systems after three and a half years due to additional input of organic matter in the form of compost (Wells et al 2000).

Figure 5. Rate of soil organic carbon loss under different tillage and rotation treatments in the long term experiment at Wagga Wagga. DD = direct drilled RT = reduced tillage CT = conventional tillage.



Labile soil organic carbon as indicator of soil structure

For many soils, more than half of the soil organic carbon is in very inert forms with long turnover times, such as charcoal (Skjemstad et al 1996). It is therefore logical to expect that changes in the more labile forms of soil organic carbon are more sensitive indicators of soil quality attributes such as soil aggregate stability.

Microbial biomass

The changes in the quantity and quality of soil organic carbon and the effect on soil aggregate stability as a result of growing different crops in rotation with wheat were investigated on a red earth (Oxic Paleustalf) in Wagga Wagga (Chan, Heenan 1999). After two cycles of the wheat and alternative crop rotation, the total organic carbon in the 0-5 cm soil depth was similar (15.1 g/kg), but there were significant differences in water stable aggregation of soil from the different rotations. Wheat/lupin and wheat/barley rotations were the most stable, followed by wheat/canola and then by wheat/field pea.

Rather than total carbon or other extractable fractions, the observed differences in aggregate stability were only significantly related ($P < 0.05$) to microbial biomass carbon. Following the hierarchical model of soil aggregation (Tisdall, Oades 1982), macroaggregates (> 250 μm) created by the different crops were stabilised by microorganisms such as fungal hyphae and their products which made up <2% of the total soil organic carbon content.

Particulate organic carbon

Changes in particulate organic carbon (POC) relative to total organic carbon (TOC) were measured in soils from five agronomic trial sites in New South Wales, Australia (Chan 2001). These sites covered a wide range of different land use and management practices. Particulate organic carbon made up 40-74 % of total organic carbon and tended to be higher under pasture and more conservative management than traditional cropping regimes. It was the dominant form of organic carbon accumulating under more conservative management practices such as direct drilling, retained stubble and organic farming. It was also the form of organic carbon preferentially lost when soils under long-term pasture were brought under cultivation. Across all sites, changes in particulate organic carbon accounted for 81.2 % (range 69-94 %) of the changes in total organic carbon changes caused by differences in land use and management. For the Vertisols, particulate organic carbon was found to be a sensitive indicator of both macroaggregate stability and nitrogen availability (Chan 1997).

Conclusions

Satisfactory soil structure is a prerequisite of a healthy agro-ecosystem. Soil organic carbon is important in determining soil structural conditions, acting both as a food supply for the soil structure-forming organisms, and as a stabilising agent. Under broadacre cropping, soil organic carbon levels are low and are continuously declining, indicating a worrying trend of soil structural decline (degradation) and deteriorating soil health. Little information is available for horticultural crops. Soil organic carbon, particularly labile pools, is a sensitive indicator of soil structure and soil health.

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Using soil tests to make fertiliser recommendations that will keep soils healthy and productive

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To farmers, healthy soil means healthy and productive crops, pastures and trees. While farmers aim to make an income, most also want to hand on their soil in as good, if not better, condition than they received it. This paper is a summary of one agronomist's view of what is practical, factual and important for farmers applying fertiliser, lime and gypsum.

Four principles need to be kept in mind to ensure that fertiliser use is economically sound, practical and sustainable.

- A soil test or, in some cases, a plant tissue test, is the basis of reliable decision-making.
- The soil's physical attributes need to be analysed as well as its chemistry.
- The soil is as deep, or deeper, than the rooting depth of plants.
- The soil chemistry balance should not be changed without good reason.

There are two basic philosophies of soil test interpretation used by soil-testing organisations to arrive at fertiliser recommendations. One philosophy works on the feeding the plant, the other on feeding the soil.

Feeding the plant

To assess what the plant needs, the soil is analysed using standard analytical methods. The results are measured against standards based on long-term field calibration of soil tests that have established base data. These standards indicate whether the nutrient levels in the tested soil are satisfactory and whether the plant is likely to respond to fertilising. This concept includes analysis of nutrients that become toxic to plants if over-supplied.

Some soil testing organisations use analyses that are out of date and not based on rigorous scientific testing. For example, during the 1950s the standards for a healthy soil were based on the principle that healthy crop and pastures grew in healthy, well balanced soils. Soils from paddocks with healthy crops were analysed and standards were drawn up based on these results. The most famous standard derived from this method is that the calcium magnesium ratio must be between 4 and 5 (see below). However, the standard was never scientifically proven and it has since been tested and found wanting.

Feeding the soil

Feeding the soil requires annual applications of nutrients both to replace the nutrients expected to be used by the plant, and to increase the level of nutrients in the soil. Once the soil test shows that nutrient levels are at their optimum, a maintenance application equal to the amount removed by the crop is applied to prevent the crop from lowering soil nutrient reserves.

The conservation of a soil's nutrient-supplying capacity has strong appeal but two problems can arise. First, it discounts the economic aspects so important to the farmer where the soil's delivery capacity of a given nutrient may be adequate for top yields for some years to come. See the discussion on calcium and magnesium below. Second, the estimates for nutrient removal in the crop are usually calculated from average elemental concentrations and estimated or measured yields, and these can vary enormously, for example nitrogen amounts in wheat.

Calcium and magnesium deficiency

Nearly all soils in Australia contain an adequate supply of both magnesium and calcium for the crops and pastures grown in this country. Yield responses in crops and pastures to applied soluble (and thus readily available) calcium or magnesium are very rare (Bruce 1999, Aitken, Scott 1999). Some fruit and vegetable crops are affected by deficiencies of these two nutrients and are no doubt covered in specific recommendations for those crops.

Calcium

Generally, less than 40% calcium of the exchangeable cations less exchangeable aluminium is associated with calcium deficiency. Absolute deficiency of calcium is not common in Australian soils. Acid soils with low cation exchange capacity in high rainfall environments are most likely to show low calcium status. (Bruce 1999).

Where there is a marginal soil calcium deficiency (between 40 and 50% exchangeable calcium or less than 1.0 cmol(+)/kg), and growing conditions are most favourable, a calcium deficiency may occur in those parts of the plant that are furthest from the main flow of water within the plant. Examples are poor seed set in peanuts and subterranean clover, and blossom end rot in tomatoes. More severe calcium deficiency may cause death of growing points, for example November leaf in bananas. Low levels of soil calcium can also adversely affect the nodulation of subterranean clover.

Examples of very severe calcium deficiency (less than 30% exchangeable calcium or less than 0.5 cmol(+)/kg) are most likely in soils with a pH less than 4 that are sandy and low in organic matter, or where there has been excessive use of highly acidifying fertilisers. As these soils have very high levels of soluble aluminium, all but the most acid tolerant plants, such as sugar cane, are killed before the symptoms of calcium deficiency become apparent.

Magnesium

Loss of production in crops and livestock due to a magnesium deficiency in the soil is most unusual in Australia (Aitken, Scott 1999). As with calcium, the best

indicator of availability of magnesium is the exchangeable magnesium expressed as a percentage of the exchangeable cations less exchangeable aluminium.

Less than 2% exchangeable soil magnesium has caused magnesium deficiency in young crops and pastures in southern NSW. However, a more than adequate level of available magnesium in the subsurface layers meant there was no effect on yield as ample magnesium came available to the plant as the roots extended into the subsoil. In NSW, with a few notable exceptions, all soils have ample supply of magnesium in the subsoils (Brendan Scott pers.comm).

At the other end of the scale of exchangeable magnesium, greater than 30% of the cation exchange capacity can be associated with dispersive soils, particularly if the exchangeable sodium is less than 12% (Yin Chan pers.comm).

Grass tetany in cattle is sometimes attributed to low soil magnesium. In fact magnesium is required by cattle in massive amounts, particularly after calving, and cannot be stored in the animal. To vary the magnesium content in a pasture sward by 5 or 6% will not overcome a grass tetany problem arising from insufficient fodder.

Calcium magnesium ratio

There is a theory that for a soil to be healthy it will have a calcium magnesium ratio of about 4 to 5. This ratio does not refer to the cation exchange capacity of the soil. In fact there is no experimental evidence to support this theory, while on the other hand there are several experiments that show that it is not true. Research clearly indicates that the exchangeable cations must be known to compute the basic cation saturation percentage (Haby et al 1993).

Research at Wagga Wagga Agricultural Institute has shown that the calcium magnesium ratio is a poor indicator of magnesium and calcium fertility problems. This research has shown there is no response in the field to increasing the ratio up to 20:1 for number of crops and pastures (Scott, Conyers 1995). In part this is explained by an ample supply of magnesium in the subsoil that balances any deficiency of magnesium or excess of calcium in the topsoil.

Predicting the response to liming

Research in the 1970s and 1980s has clearly shown that knowledge of pH and exchangeable aluminium (Al_{ex}) levels is required to confidently predict a response to lime in crops and pastures. Until this research, exchangeable cations were determined using reagents buffered to either pH 7.0 or 8.4. Liming rates were based on a need for calcium. This is now regarded as outdated technology. For a useful lime recommendation you also need to know whether your crops or pastures are sensitive to soil acidity and the pH below the soil surface layer.

Nitrogen, phosphorus, potassium and sulfur

Traditionally, soil tests have been used to determine how much nitrogen, phosphorus, potassium and sulfur are needed to fertilise plants for optimum crop

and pasture production. However, analysis of the top 10 cm of soil is only one aspect to consider when deciding on fertiliser. For example, the greatest response to phosphorus, sulfur and potassium fertiliser applied to a pasture occurs in the legume component. Where there is no legume there is little point in correcting a deficiency in any of these elements. Similarly, it is essential to know the disease status of a paddock when calculating the rate of nitrogen fertiliser for a wheat crop, because disease will reduce the plants' response to nitrogen.

The top 10 cm of soil is an arbitrary depth agreed to by most Australian organisations involved in correlating soil tests and plant response or conducting soil tests. Without this agreement comparisons between research and soil testing cannot be made.

Phosphorus

Unfortunately, scientists have never been able to agree on which test is the best to predict response to phosphorus. There are two methods commonly used in NSW. These are:

- Bray 1 P: 1 part soil to 7 parts dilute HCl/NH₄F. Shake one minute and filter.
- Colwell P: 1 part soil to 100 parts 0.5 M NaHCO₃ - pH 8.5. Shake 16 hours and filter.

Generally the Bray test is regarded as more reliable in acid soils while the Colwell test is best suited to neutral to alkaline soils. However, there is little to suggest that either test is better than the other. The two tests use differing extractants, shaking times and soil solution ratios to extract phosphorus from a range of sites in the soil and in differing amounts. The Colwell test when compared with Bray over a range of soils may vary tenfold depending on soil properties. This variation is largely due to phosphorus sorption, a simple laboratory test that measures how much phosphorus a soil will remove from solution. The greater the amount removed, the higher the phosphorus sorption and the higher the result by the Colwell test when compared with the Bray test. Unfortunately no commercial soil testing laboratories offer a phosphorus sorption test on a regular basis. In the absence of a measure of phosphorus sorption it is essential to establish knowledge of the local soils, and local experience of the response to phosphorus, before recommending phosphorus fertiliser.

Potassium

Potassium is more mobile in the soil than phosphorus and over time can be leached down the profile. It also can be released into the soil solution from points of storage or from the mineral at a greater rate than phosphorus. Therefore a snapshot of how much potassium is available at any one time as measured with a soil test will not indicate how much may be available in three, six or twelve months time.

There are two tests available at present in NSW. The first is a measure of potassium present in the Colwell phosphorus extract, and the second the exchangeable potassium. There are other tests such as NEAP (non-exchangeable available potassium) that have not been adopted by the soil testing laboratories. Gourley (1999) suggests that it is time that we stopped arguing about the soil test and got on with correcting the obviously potassium deficient soil in Australia.

Nitrogen

The current soil test for crop nitrogen is determined from soil samples up to one metre in depth, as this is the rooting depth of most crops, and nitrogen can easily be leached to that depth. The interpretation of the soil test requires an estimate of how much more nitrogen will be mineralised between the time of the test and when the crop demand stops. An estimate of the proportion of the available nitrogen that will be available to the plants is also required. This is an area of science that is changing rapidly and best source of information is the soil testing laboratories currently offering the test.

Sulfur

Soil analysis has historically been of little value to predict a likely response to added sulfur. Various techniques and extractants have been used, but all have been unsuccessful because they remove only the sulfate portion of the total sulfur, and do not take into account the valuable organic sulfur pool, from which a substantial amount of sulfur is supplied to plants. Since 1992, the KCl-40 sulfur test, a soil test that removes sulfur from sources similar to the growing plant, has been available. This test copies the plant by measuring both readily available inorganic sulfur and the proportion of the organic pool that rapidly mineralises into organic, plant available form (Duncan 1995). Developed at the University of New England, this test has been a significant and valuable breakthrough in assessing soil sulfur levels and predicting plant responses. Like all soil analyses, it requires careful interpretation to be effective. Various local factors need to be taken into account, otherwise it could result in inaccurate fertiliser recommendations.

Trace elements

Trace elements occur in very small amounts. For example, a molybdenum deficiency can be corrected with less than 100g/ha of molybdenum applied as molybdenum trioxide or sodium molybdate every four to five years. This represents 100g mixed into 1600 tonne of soil (the weight of one hectare of soil to 10 cm deep). In addition, analysing a 10g sample drawn from 1600 tonnes to determine the availability of a trace element is not likely to be very reliable. Generally, it is better to use the relationship between soil pH and availability of a trace element to predict a response.

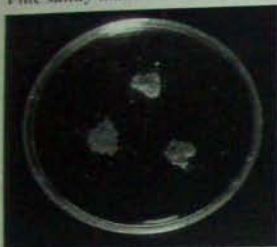
Testing physical characteristics

Structure and texture tests are the most used physical attribute tests. Some aspects of soil structure can be determined by placing a crumb of the soil in a dish of distilled water and leaving it for two hours as shown in Figure 1. If the soil disperses then it is likely that the soil structure can be improved with an application of gypsum of two to 10 tonne per hectare. If the slakes or collapses, the structure is weak due to poor organic matter bonding. The many aspects of improving soil structure with gypsum and lime are discussed in Agfact AC 10 and elsewhere in this workshop.

The other main physical soil test is assessment of texture. Apart from giving a better understanding of the soil, texture can be used in lieu of cation exchange capacity as a guide to lime requirement.

Figure 1. Structural breakdown of aggregates after two hours. The crumbs of fine sandy loam have not dispersed but the one on the left of fine sandy loam has 'slaked'. The crumbs of medium clay have all dispersed, and slaked.

Fine sandy loam



5 minutes



2 hours

Medium clay



5 minutes



2 hours

Conclusion

In my experience, a healthy soil is characterised by a fine texture that maintains good internal drainage. To keep the soil healthy we need to monitor its chemistry and apply fertiliser, lime and gypsum based on vigorous and robust scientific research.

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From mining waste to artificial soil

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Revegetation of industrial sites can require large amounts of topsoil which is often very costly. When Broken Hill Pty Ltd (BHP) steelworks in Wollongong NSW undertook a major revegetation program on its 800 ha site, it created an artificial topsoil from industry by-products to overcome the cost problem. The soilmix comprised coal washery refuse, blast furnace slag and sewage sludge in a 2:1:1 ratio. Coal washery refuse is the by-product of washing coal (shale and clays) and the alkaline (pH 9.4) black waste is pressed into 2-20 mm sized fragments. Blast furnace slag is the by-product of the iron-making process at very high temperatures, has a pH of 9.2 and is granulated to 0.2-2mm size (see Thompson, Makin 1990). The sludge (biosolids) is anaerobically digested after sedimentation, and dewatered at several sewerage treatment plants in the area. This component provides organic nitrogen (5%), phosphorus (1%) and carbon, plus a suite of microorganisms.

The blended BHP soilmix is a black gravelly sand which is relatively homogeneous and initially alkaline. It has a particle distribution of 53% >2mm, 36% sand, 8% silt and 3% clay. It was spread 15cm deep over coal wash mounds in discrete 'gardens' (75-5000 m²) on the steelworks site and vegetated with tubestock native trees, shrubs and groundcover species (Thompson, Makin 1990). A large suite of plant species was initially chosen for tolerance to alkalinity and salt, and species that grew well in the soilmix were subsequently used more frequently. Coarse woodchip mulch was usually spread on top of the soilmix and gardens were watered for a year. After problems with weed growth, a weedmat of tightly woven plastic material was pinned over the soilmix before mulch was laid in most gardens from about 1991.

Characterisation of man-made soil development has mostly involved physical and chemical changes such as mine spoil particle weathering, horizon formation and nitrogen accumulation. The importance of biological activity however is that plant roots, bacteria, earthworms etc may determine the rate of change of the physical and chemical properties (Anderson 1988). Studies focussing on biological activity have shown increased microorganism activity (Cundell 1977, Gildon, Rimmer 1993) and enzyme activity (Stroo, Jencks 1982) with mine soil age. Diversity and abundance of soil invertebrates such as Collembola have also increased over time on rehabilitated sites (Hutson 1980, Greenslade, Majer 1993). Many of the improvements in soil condition over time have been attributed to the accumulation of organic carbon, from either vegetation, including roots, and/or soil organisms. The aims of this research were to determine the changes in the physical, chemical and biological characteristics of the soilmix in terms of its ability to support plant growth and potential long term sustainability. The focus was to quantify the rate

and extent of soil processes occurring in the mix, including particle weathering, nutrient cycling, microbial decomposition and macroinvertebrate colonisation.

Experiments

This research studied the short-term (0-2 yrs) and longer-term (2-10 yrs) soil development in the artificial soilmix. A field trial was established where several soil plots were planted with trees or crop species and important physical, chemical and biological factors were measured intensely over approximately two years. Measurements included particle size distribution, bulk density, soil nitrogen, phosphorus and pH, and plant growth. The longer-term research included a study of a chronosequence of gardens that ranged from six months to eleven years old, and assessment of indicators of soil development and rate of soil formation. Measurements included soil particle size distribution with depth, bulk density, structure, soil carbon, nitrogen, phosphorus, pH, available nutrients, earthworm and slater density, microbial decomposition rates (calico method, Springett 1976) and mulch depth.

Field trial results

In the field trial, tree growth on the soilmix plots was exceptionally good. Average trunk diameter (and height) increased rapidly over the two years monitored: a 14-fold increase in trunk diameter for *Corymbia maculata*, an 8-fold increase for *Acacia* and two-fold increase for *Callistemon*. There were high levels of available nitrogen in the soilmix when the plots were first established. Nitrate-nitrogen content averaged 169 mg/kg and ammonium-nitrogen averaged 50 mg/k. These levels declined rapidly over the first three months (Table 1). Both were less than 15 mg/kg by six months and remained static for the next six months. Total phosphorus initially decreased then built up over time. The pH of the soil mix was initially 7.6 and decreased to slightly below 7 after three years. Bulk density was initially 1.0 g/cm³ and remained the same after three years (Table 1). In the <2mm sized soil portion, there was an increase in the finer fractions after one year, indicating particle weathering.

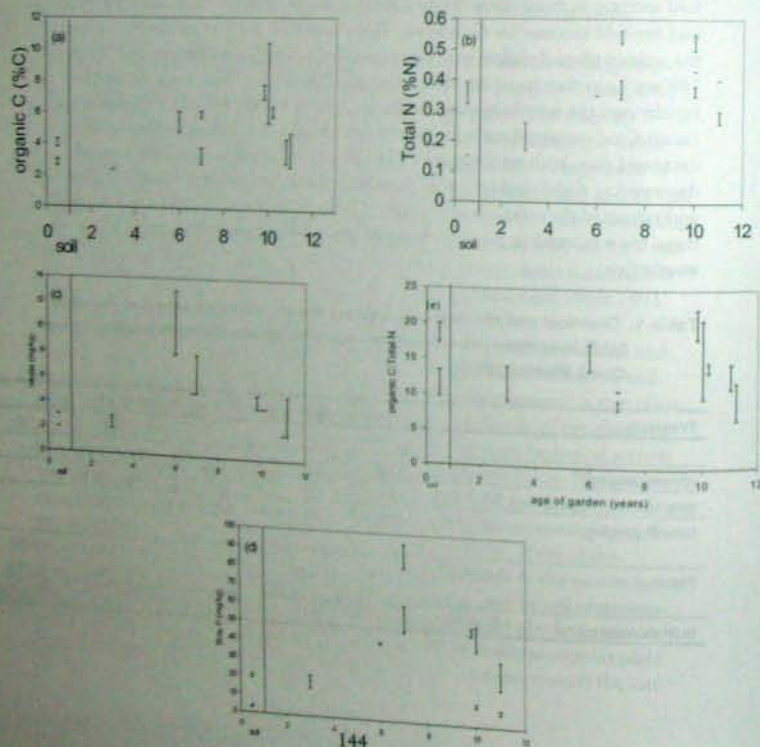
Table 1. Chemical and physical properties of the soilmix in the experimental plots (n=8) over three years (average value with standard error in brackets) from Cox & Whelan (2000).

Property	Time since plot establishment (months)					
	0	3	6	10	12	36
nitrate (mg/kg)	169 (43.8)	43.4 (4.1)	13.4 (3.3)	4.3 (1.0)	13.1 (1.3)	-
ammonium (mg/kg)	50 (13.0)	12.9 (3.5)	14.7 (1.7)	15.3 (2.0)	14.4 (8.1)	-
total P (mg/kg)	740 (115)	267 (67)	389 (61)	851 (177)	2024 (831)	-
PH	7.62(0.02)	-	-	-	7.10 (0.02)	6.85 (0.05)
bulk density g/cm ³	1.0 (0.02)	-	-	-	-	1.0 (0.03)

Chronosequence results

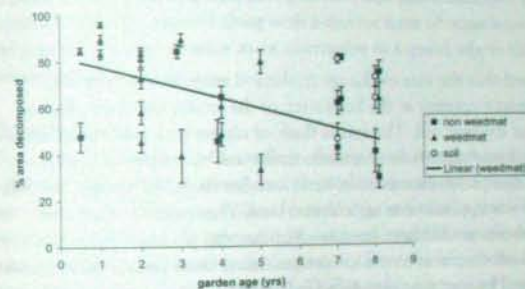
Over the three to 11 years, there was a similar trend for all nutrients measured. Organic carbon, total nitrogen, nitrate nitrogen and phosphate phosphorus were all lowest at the youngest age, higher in the middle years (6-10) and then lower in the oldest gardens (Figure 1). There were no significant relationships between age of garden and each nutrient. The youngest garden (three years) was generally in the nutrient range of the soil gardens, as were the oldest gardens (11 years). Organic carbon reached quite high values, from 2.4% at three years and a highest level of 10.4% at 10 years. Total nitrogen was high overall and averaged 0.2% at three years and 0.44% at 10 years. Average nitrate nitrogen and phosphate phosphorus increased from three to six years, then decreased. The ratio of organic carbon to total nitrogen showed no change over the three to 11 year period and remained in the range of the soil gardens (10-20), due to similar changes in carbon and nitrogen.

Figure 1. Relationship between age of gardens and chemical properties (a-e). Data are range of two (composite) samples. Horizontal lines indicate identical value. From Cox & Whelan (2000)



Decomposition decreased with garden age, with the highest decomposition observed in the one year old gardens (Figure 2). The gardens with weedmat contributed most to this relationship. Gardens with weedmat had a significantly higher decomposition rate than gardens without weedmat. Many holes had appeared in the fabric due to roots and invertebrate penetration, especially at the litter-soil interface. Large purple, brown, orange, white and black colour spots were seen which could be attributed to fungi. Evidence of decomposition was usually seen over the entire calico piece with the 0-3 cm fraction particularly decomposed, but also seen to depths of 20cm. By years 7/8, the % area decomposed in the soilmix was significantly less than the native soil gardens.

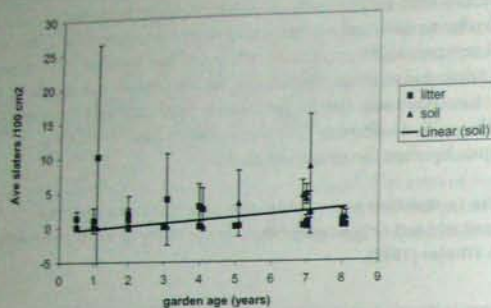
Figure 2. Average area (\pm standard error) of % calico decomposed after three months in soil mix and native soil gardens (six months to eight years old) from Cox & Whelan (1998).



Soil pH decreased significantly with garden age. The youngest soilmix garden had a pH of 8.56 and the oldest a pH of 7.28. Native soil gardens had lower pH levels with a range of 6.32 - 7.33. Slater density increased with garden age, regardless of weedmat (Figure 3). Average slater density ranged from 0-8.3 per 100 cm² for soil and 0-10.1 for litter, with the highest density of 34 slaters recorded. There were more slaters in the litter with increasing litter depth. Very few or no slaters were recorded in the soil from the younger gardens. Most of the slaters were found at the soil-litter interface, commonly buried just below the soil surface when the litter was pulled back.

There was no relationship between earthworm density and garden age, although the average numbers were low and earthworm distribution was quite patchy. Earthworm density was generally highest in the soil for the older gardens and in the litter for the younger gardens. No slaters or earthworms were found in the 'soil only' fraction from gardens with weedmat. These organisms were found, often in abundance, in the litter layer above the weedmat. Other taxa of invertebrates observed in the soilmix and litter included ants, springtails, amphipods, nematodes, mites, spiders and beetle larvae. There were more slaters found in the soilmix than in the native soil.

Figure 3. Average slater density (\pm standard error) in the soil mix gardens from 6 months to 8 years, in soil and litter. From Cox & Whelan (1998).



Discussion

The field trial showed that the rate of change in the soil environment was very rapid. The high nutrient content at the beginning of the experiment contributed and was indicative of sludged soil. The initial flush of nitrate-nitrogen would have resulted from organic nitrogen transformations in the soil via microbial action (Wild 1988). The subsequent decrease over time was also found by Joshua and Salt (1996) when sludge was applied onto agricultural land. This available source of nitrogen and phosphorus would have been used by the trial plants in their expansive growth. Both crop and native species produced considerable biomass over the two years. It is well known that biosolids application increases plant growth (Topper, Sabey 1986, Wong, Ho 1994). This growth also translates to extensive root production, which in turn would contribute to improving the soil structure of this homogeneous material. The transformation of the organic matter by microorganisms into organic acids and the leaching of soluble molecules helped decrease the alkalinity of the soil mix. The actions of the chemical, physical and biological forces interacted to produce quite rapid soil development, and showed that the soil mix had undergone natural soil processes that may eventually lead to self-sustainability.

The chronosequence study gave an opportunity to quantify the soil development over 11 years. The increase in organic carbon and total nitrogen in the soil was a positive indicator of litter and mulch accumulation as the sludge nutrients were used. This showed that the sludge carbon and nitrogen were being utilised by plants and animals, but these nutrients were being incorporated back into the soil system in a continuous cycle. This is the initial establishment of the nutrient cycling process, which is critical in maintaining a self-sustainable ecosystem. Available nitrogen and phosphorus were also at high levels, above that of gardens with native soil. The generally high carbon nitrogen ratio of the gardens indicated the presence of much partially decomposed material (Jenkinson 1988) but was stable over the 11-year period. As the carbon nitrogen ratio is an indication of rate of organic matter

decomposition, it is a useful measure of long-term viability of restoration and rehabilitation.

The importance of biological activity

The very active decomposer microorganisms contributed enormously to the rapid soil development in the soil mix. The organisms were responsible for breaking down organic matter to available nutrients for plants and animals in the artificially created ecosystem. The plentiful nutrients allowed rapid tree, shrub and groundcover growth, which themselves contributed to soil development through root exudates and litterfall back to the soil surface. The larger macroinvertebrates (such as slaters, earthworms and collembola) were responsible for breaking down this litter into very small fractions and incorporating it throughout the soil profile, where the fungi and bacteria then acted upon small particles. Dead and decaying animals provided food for other organisms and plants, and the cycling of nutrients was established. The oldest gardens showed the highest number of slaters, high % organic carbon, stable carbon nitrogen ratio and had established identifiable horizons (data not shown) along with a diverse suite of organisms. The soil mix environment shows promise as an alternative to topsoil, where this precious resource is unavailable.

Conclusions

The role of the plants and animals in the soil is vital and should not be underestimated. The chemical and physical environment is shaped by the activity of microbes, invertebrates and plant roots. As the soil mix contained a suite of microorganisms and also importantly, high amounts of organic nutrients (carbon, nitrogen and phosphorus) at the beginning (from the biosolids), the conditions were suitable for a fertile, active soil. The available form of nitrogen and phosphorus to plants allowed them to grow rapidly, sending roots throughout the soil to stabilise and add to structure. The sludge organic matter, mulch, then litterfall provided a continuous source of organic carbon for the microbes to use as substrate and therefore were present to transform organic material into available forms. The slaters and earthworms shredded and incorporated litter material into the soil where it became available to the microbes. These activities increased soil structure by the formation of soil aggregates and along with natural weathering processes, created distinct horizons as displayed by native soil. The complete hierarchy of soil organisms, from microbes, protozoa, collembola and mites to earthworms is essential for soil functioning, whether the soil is used for restoration, mine site rehabilitation, agriculture or conservation. Incorporation of biological factors with chemical and physical factors is essential in assessing soil function and soil health.

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Organic cereal growing and soil health: a discussion paper

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On broadacre organic farms in the pasture-cropping area of NSW, cereal cropping tends to occur less frequently and grain yields are commonly lower than on conventional farms. For example, on a long-term organic farm at Ardlethan in western NSW, average practice has been two cereal crops following six pasture years, compared with three crops following three pasture years on a neighbouring conventional farm (Derrick 1996). On some organic pasture-crop farms, pasture length may be as long as nine years preceding one or two crop years. On the Ardlethan organic farm, and an organic farm at Yenda in southern NSW, crop yields averaged 52% of neighbouring conventional crop yields (Derrick 1996). In Western Australia, one study (Deria et al 1996) showed crop yields averaged 85% of those on neighbouring conventional farms.

Crop yield reduction and less frequent cropping can contribute substantially to lower gross margins on organic farms compared with conventional farms (Penfold et al 1995). Presumably gross margins on organic farms will be even lower in times of low livestock prices. The constraint of building adequate 'organic' soil fertility through a relatively long pasture phase inevitably reduces organic farmers' flexibility to switch between livestock and cropping enterprises in response to changes in the relative profitability of the enterprises. There is a need to increase average crop yields and cropping frequency on organic broadacre farms.

In our three year project funded by RIRDC we are

- obtaining recent and comprehensive soil nutritional data from organic farms in central and southern NSW
- examining processes by which the quality and productivity of pastures on organic farms can be improved to increase cropping frequency and/or yield.

We hypothesise that improvements to soil nutrient status (particularly phosphorus and sulfur availability and pH) and pasture management are essential.

Experimental program

Soil survey

A survey of organic soils on broad-acre cropping farms has begun in south-western NSW to characterise their nutrient 'health'. The soils (0-10 cm) are being characterised for pH (CaCl₂), total carbon, nitrogen and sulfur (LECO CNS&S analyser), total phosphorus, available phosphorus (Olsen), organic phosphorus, available sulfur, organic sulfur and microbial biomass (substrate induced respiration).

Some initial survey results are given in Table 1. Although there have been few comprehensive studies of soil nutrient trends on Australian organic broadacre farms, the data suggest trends to soil deficiencies in available phosphorus and, not invariably, to deficiency in sulfate. Interestingly, at the Ardlethan organic farm cited above, soil total nitrogen was not dissimilar to that on the neighbouring conventional farm, yet average crop nitrogen concentration was lower on the organic farm (Derrick 1996). Therefore, the reasonable soil nitrogen concentrations on the organic farms as shown in Table 1 may not be as indicative of the nitrogen supply to crops as might be projected for a conventional farming system.

The survey has just been initiated and our conclusions are necessarily tentative. Notwithstanding, Table 1 shows that available phosphorus may be commonly suboptimal and, depending on the organic farm or paddock, soil pH and sulfate also. Compared with conventional farm soils it is not yet apparent that organic soils have higher organic carbon content nor higher organic phosphorus. The ratio of microbial carbon to total carbon (MC / TC) on the one organic farm (Henty, Table 1) assayed so far is perhaps lower (1.9%) than desirable.

Table 1. Soil characteristics. 1P = conventional permanent pasture (Wagga), 1C = conventional pasture -crop rotation (Wagga). Other sites are organic farms.

Soil characteristic	1P	1C	Henty	Illabo	Uranquinty	Ardlethan
1. pH	4.4	4.6	5.1	4.3-5.1	4.3-4.5	5.2-6.1
2. Total carbon (%)	1.9	1.8	2.0	na	na	1.4
3. Total nitrogen (%)	0.22	0.21	0.20	na	na	0.18
4. Available phosphorus (mgP/kg)	10	16	5	8-16	3-6	5-9
5. Organic phosphorus (mgP/kg)	161	164	159	na	na	125
6. Available sulfur (mgS/kg)	na	na	Na	< 3.4	< 3.4	5-17
7. Microbial biomass carbon ug/g	296	169	428	na	na	na
8. Ratio of microbial carbon to total carbon	0.016	0.009	0.019	na	na	na

1. CaCl₂ (1:5,0.01M). 2 & 3. Total C and N (LECO C&N Analyser). 4. Olsen phosphorus.

Suboptimal soil levels of phosphorus, sulfur and pH may indicate insufficient inputs of nutrient and lime or, in the case of available phosphorus, to the use of relatively insoluble rock phosphate. In organic farming systems, high pasture legume productivity is fundamental to supplying nitrogen to succeeding crops, because mineral nitrogen fertiliser cannot be used. We hypothesise that the suboptimal phosphorus, sulfur and pH (for acid sensitive species) on organic farms will inevitably constrain both the rate of soil nitrogen accumulation during the pasture phase and perhaps the ultimate soil nitrogen level. Consequently, the key to increasing crop yield and cropping frequency is to sustain an improvement in the

productivity and abundance of legumes in organic pastures, pivotal to which is to increase soil available phosphorus, and available sulfur where required.

Field experiments

Increasing the soil sulfate supply is readily achievable with gypsum. It is more difficult to increase the availability of phosphorus, and several factors are important: fertiliser composition, soil pH, soil moisture, and the concentration of phosphate and calcium in soil solution. Dissolution of the rock phosphate is facilitated when soil solution phosphate and calcium concentrations are low. This is achieved by removal of phosphate and calcium through plant uptake, preferably. Other ways that these concentrations are reduced is through leaching of the ions or through their fixation to the mineral and organic components of the soil (Bolan et al 1990). Field trials to investigate these factors have been established at two sites that represent scenarios that may occur widely:

- organic soils of low pH (<4.8), low phosphorus and low sulfur
- organic soils of higher pH (> 5.0), low phosphorus, variable sulfate.

At both sites the importance of elevating phosphorus inputs using newer, organic-approved phosphorus fertilisers, and elevating soil sulfate using gypsum, will be tested. In addition, the Illabo site will focus on the effect of modifying pH, either a decrease or increase, on phosphorus cycling. A decrease in pH will be effected using elemental sulfur, and this soil treatment will necessitate establishing an acid tolerant pasture. An increase in pH will be effected with lime, and will be associated with clover pasture. The Ardlethan site will focus on the effect on phosphorus cycling of farming practices that conserve soil moisture and/or increase soil inputs of carbon. The major treatments for each site are summarised below.

Illabo site

pH = 4.5, phosphorus = 7.6 mg/kg, sulfur < 3.5 mg/kg

Treatment A

- acid tolerant pasture (yellow serradella / yellow lupin)
- reactive phosphate rock fines (3% available phosphorus); nil, 500 kg/ha
- Durasulph (6% phosphorus) - granular; nil, 500 kg/ha
- each of the above +, - elemental sulfur 500 kg / ha

Treatment B

- lime responsive pasture (subterranean clover)
- reactive phosphate rock fines (3% available phosphorus); nil, 500 kg/ha
- Durasulph (6% phosphorus) - granular; nil, 500 kg/ha
- each of the above +, - lime; 2000 kg / ha

Treatment C

- wheat undersown with subterranean clover (farm control)
- subset of treatments; +, - gypsum

Ardlethan site

pH = 5.6, phosphorus = 6.5 mg/kg, sulfur = 11 mg/kg (5-17)

Treatment A

F=fallow LGr=legume grazed LCo=legume forage conservation

LGm=legume green manure

F LGr LGr

F LCo LCo

F LGm LGm

F F F

Treatment B

Reactive phosphate rock fines (3% phosphorus) with elemental sulfur 500 / 500 kg/ha, nil (across treatments A & C)

Treatment C

US LGr LGr

(Wheat under-sown with subterranean clover)

The impact of the various treatments on annual pasture composition, productivity and nutrient uptake, soil available nutrients, organic nutrient concentrations, and on wheat production in the fourth year, will be measured.

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Natural growing systems: horticulture and soil health

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This paper considers some threats and opportunities in north coast perennial horticulture in relation to soil health. One context in which these issues could be addressed is holistic natural growing systems approach, in which soil is considered a dynamic, living resource whose condition is vital to the production system.

Soil health is obviously a complex area and consequently systems approaches, rather than compartmentalised, issue-driven approaches, are essential. These systems need to be incorporated in production systems to ensure adoption, hence the need for a natural growing system approach.

Natural growing systems

Natural growing systems place a high priority on issues such as soil health rather than, for example, the narrower view of soil quality. Some of the proposed features of natural growing systems are that they have a strong emphasis on minimising inputs and disruptions, and protecting and replenishing natural capital, especially the soil. They include organic growing systems and more enlightened sections of conventional production systems where best practice systems take account of sustainability issues.

Natural growing systems need to encompass environmentally sound technologies, cleaner safer techniques, and efficient use of raw materials. Some of the strategies that are obvious to a natural growing systems are biomimicry (imitating nature in areas such as biocontrol and nutrient cycling) and repletion of natural capital, while less obvious but essential features are high level product value and resource productivity. The latter strategies underpin the need for economically viable systems that can allow further investment in sustainability, and the need to acknowledge demand for production from a limited resource base. It is necessary to meet national and worldwide demand for food without a massive increase in land recruited for agricultural production.

Soil health issues

Some of the first order issues facing north coast horticulture summarised by Moody (1995) are the need to

- maintain and enhance organic matter levels
- prevent or correct surface and subsoil acidification
- minimise erosion

- maintain fertility by replacing nutrients removed by harvest, leaching, and fixation.

Although Moody was considering krasnozems particularly, this list encapsulates issues facing north coast horticulture generally. We can add to the list the need to minimise the harmful effects of soil contamination by pesticides.

The use of cover crops

Cover crops can help address two major issues for horticulture on the north coast. One is soil protection from erosion, which is critical because of our combination of slopes and high rainfall that make wholesale bare soil unacceptable. There is also the opportunity to alleviate some of the effects of long term monoculture. For example interrow cover crops can provide additional nutrient sources to the crop (eg legumes contribute to soil nitrogen), increase soil organic matter, and improve orchard biodiversity (both above and below ground). However care is needed to avoid species that encourage pests or pathogens of the crop.

An example of the need for cover crops is the macadamia industry. In young plantations reasonable cover can be maintained, but as the density of the canopy increases many species of plants die out due to shading, so shade-tolerant cover crops are needed. The industry's requirement for a flat, dense surface to enable nuts to be harvested from the ground means cover crops must be low growing, dense and amenable to close mowing. Industry-funded research has successfully identified a number of suitable cover crop species, and it now remains to address adoption issues. While the soil erosion aspect of cover crops is evident, the case for adoption could be enhanced if data on more systemic soil health benefits were available.

There are similar opportunities in banana plantations to develop cover crop management techniques as an alternative to bare-earth weed spraying. While some soil protection is afforded by the large amounts of crop residue provided by bananas, further protection by cover crops on slopes would be desirable. Additionally it is tempting to think that cover crops could address some of the soil health effects of long term monoculture (up to 60 years or more).

New technologies to measure soil health through microbial activity assessments will help to realise these potential benefits. However there is no room for simplistically recommending cover crops as they can be over-competitive, leading to yield losses (Johns 1991) which can be as high as 25% in organic crops (O'Donnell pers.comm). Strategies for herbicide use to manage cover crops by strip spraying to limit competition with banana plants, are needed to replace the older approach of removing all plantation floor weeds with routine broad area glyphosate treatments.

Best practice fertiliser technologies

Maintaining soil fertility is essential to ensuring productivity and product quality. Fertiliser practice has important implications for onfarm soil health and off-farm impacts. Growers are making large-scale gains by using better basic data, application methods and management technologies. Management practices like fertilisation and irrigation address the short-term needs of the crop, but the long-term survival of the production system relies on maintenance of soil health, obviously a more

complex matter. Nevertheless, underlying fertiliser programs must be appropriate for more comprehensive soil health strategies to succeed.

Fertiliser application

It is important to treat existing fertiliser recommendations with care. Moody and Aitken (1996) point out that many traditional fertiliser recommendations are based on traditional nitrogen, phosphorus and potassium field trials which are site specific and often ignore other elements such as calcium. The relatively low costs of fertilisers in horticultural systems (about 10% of costs for many tree crops) has also provided growers with little incentive to examine fertiliser use closely.

An alternative approach to fertiliser management is to estimate application rates based on nutrient removal through harvest, fixation and leaching. Estimates using this approach indicate that application rates have been excessive in crops such as capsicum, tomato, coffee, bananas, mangoes and macadamias (Moody, Aitken 1996) and in passionfruit and avocados (Huett, Dirou 2000). Misunderstanding of fertiliser needs led to some spectacular cases of fertiliser build up in bananas (Johns, Vimpany 1997) which have been corrected by adoption of more appropriate application rates combined with fertiliser monitoring and improved application strategies.

Adverse effects of fertiliser application can be minimised easily or avoided. Applying annual fertiliser needs in one or two lump applications is a practice that leads to inefficient uptake and surface runoff. Applying smaller amounts more frequently, at appropriate times in the plant growth cycle, has reduced many adverse effects and inefficiencies as evidenced in banana plantations. Fertigation, the application of fertiliser in irrigation water, represents the ultimate in accurate and timely application of fertilisers to horticultural crops and is increasingly used in best practice systems. Soil moisture monitoring systems such as tensiometers and Enviroscan®, help growers minimise water use, costs and off-farm movement. The adoption of these techniques is increasing, probably driven by economic considerations, but certainly producing desirable environmental protection outcomes at the same time.

Types of fertiliser

An important factor in soil health is the use of appropriate forms of fertiliser. A simple example is provided by Moody (1995) where using ammonium nitrate rather than urea as a nitrogen source reduces the rate of acidification by 75% under the same rates of leaching.

Monitoring fertiliser use

Techniques for monitoring and fine tuning fertiliser applications are relatively well developed. Integration of plant (and or sap) analysis and soil analysis provides essential information. The plant tissue analysis assesses the nutrient status of the trees while soil analysis allows refinement of application rates and checks for side effects such as soil acidification. As an example of a well tuned system for tree crops, avocado nutrition programs often start with a soil and leaf analysis to indicate the required application rates. This can be supplemented by three sap analyses per year

to more closely monitor the achieved nutrient status of the plant (G.Anderson pers.com). The issues raised over soil health indicate more dimensions are needed in soil and tissue analysis, particularly in terms of meaningful indicators of soil organic carbon, organic matter and microbial activity. The response of effective horticultural industries in adopting refined fertiliser programs driven by the best available technology suggests that the main inhibitors to greater attention to soil health are lack of information, reliable indicators and appropriate technologies rather than an indifference to the fundamental issues.

Minimising pesticide usage

Pesticide use exemplifies the need for a holistic approach to soil health. Several pesticides affect the soil, applied directly or indirectly to the soil, intentionally or inadvertently. Nematicides are directly applied pesticides, while herbicides and drift from foliar-applied insecticides and fungicides represent indirect applications. Clearly there are many different pesticides, from a wide range of chemical groups, and there is an important need to examine how each compound degrades in the soil and affects various soil organisms. The dynamics of the effects are also important in developing rational schemes to use these compounds.

For example understanding the dynamics of copper accumulation is important as well as knowing it can pose a threat to soil health in general. Retaining an early season application of copper in the avocado management program is important for the prevention of bacterial blotch, so that removing copper entirely could lead to this minor disease emerging as a major problem. Copper treatment could also have a valuable role in rotating fungicide groups to prevent resistance arising to newer alternative fungicides. In macadamia plantations, the limited use of copper sprays to achieve some residual control of husk spot is likely to greatly reduce the total use of fungicides in this program, and so assist in avoiding selection of resistance. Consequently it is of paramount importance to understand the rates at which copper accumulates and disappears from the system, in order to retain access to minimal but important treatments, if they can be combined with retention of soil health.

Another critical area of pesticide impact is the effect of herbicides. For example, we do not know whether the major effects of a herbicide such as glyphosate stem from toxicity to soil microorganisms or from wholesale depletion of plant material affected by the treatment. If the latter is the case there is presumably room for very limited use of herbicides in confined areas as opposed to broad area spraying, without major ill effects on soil health. Strategies that minimise herbicide usage rather than prohibiting them may ultimately yield better soil health outcomes. Horticultural growers and researchers need to be provided with specific and convincing data to demonstrate adverse effects of pesticides, so that better alternatives can be identified and adopted. Simplistic prohibitions may well be an impediment to better practices. In the absence of specific information on the effects of pesticides on soil health, management procedures that seek to minimise the use of the pesticides in question would appear to be advisable.

An example where the best practice approach has achieved much in this direction is the banana industry. Previous treatments that affected soil health included the application of persistent insecticides to the soil around the base of all plants (after clearing the leaf mulch from the base of the plant) to treat weevil pests, and often routine applications of nematicides to treat parasitic nematodes. Best practice growers have now reduced insecticide usage for weevils by adopting injection of old residual corms which uses 90% less insecticide that is contained within the corm without the need for a bare earth zone around the plant. Better awareness of the management of nematode pests and techniques to monitor their impact has seen many growers move away from routine treatment.

Some major challenges

A major challenge in horticulture is to provide a better understanding of the critical elements of and major threats to soil health, so that limited research resources can be directed to critical areas.

The fastest way to remove inappropriate technologies is to highlight the problem of the inappropriate technologies and provide alternatives.

We need universal indicators of soil health and, more broadly, sustainability, with well-defined threshold levels to back them up. Possibly the biggest issue at present is the lack of suitable indicators. These indicators need to

- be reasonably universal
- satisfy production aims as well as environmental concerns
- account for physical, chemical and biological factors,
- be easy to use under field conditions
- be supported by threshold values for the key indicators.

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Soil extension tools and methodologies

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Ask any land manager how important their soil is and they will invariably reply 'very' or 'without it I wouldn't be here'. Why then is it so difficult to get landholders to participate in soils information days, workshops and field days? Why do people see soils as boring? Soils have a considerable image problem to overcome both outside agriculture and within it. Land managers want to know why things happen and what they can do about it, but this approach has been lacking in soil science, and when information becomes available it is often daunting in its complexity. For far too long we ignored the practical applications of soil classification and testing, and made the language of soil science impenetrable to non-scientists.

NSW Agriculture has worked with landholders over the past decade to develop user-friendly soils information. Soil scientists and soils advisory officers have learned that it is not the soil classification that is important to landholders, but rather what this means for fertility, drainage and management, so have developed information packages accordingly. This process involves two way communication, with landholders and scientists listening to each other. Yet we still have much work to do if we are to encourage the community to become passionate about the soils they stand on.

SOILpak

NSW Agriculture has a series of SOILpak soil management manuals designed to help farmers assess and monitor the health of their soils, and manage the resource within its capabilities. The SOILpaks cover the state's main cropping industries, as these have the most impact on soil health. There are SOILpaks for cotton growers, vegetable growers, southern irrigators, southern dryland farmers, dryland farmers on the red soil of central western NSW, and dryland farmers in the northern wheat belt.

More recently, a SOILpak training package has been developed. The competency-based training course is problem-focused, and currently offers several modules on field work, sodicity, acidity, salinity and hardsetting soils. A two day training workshop covers four modules. The first day includes a general introduction to soils with considerable time in the field at soil pits and work on one of the modules. Farmers learn practical tests/observations they can carry out to assess their soil and the impact of different management techniques. The second day of the workshop is held several days later and includes two more modules appropriate to the group and location. Participants must undertake 'homework' to achieve their accreditation.

Acid sulfate soils: ASS keys to success

The booklet *ASS keys to success* is a direct response to a farmer request for information on how to identify and test for acid sulfate soils. Designed as an on-farm manual, the booklet was written in consultation with farmers from all agricultural industries affected by these soils on the NSW north coast. Throughout its development, continual changes were made in response to comments from farmers and technical experts so that so that the tests described in the booklet are easy to understand and carry out. The booklet takes farmers through the process of assessing an area for ASS risk, with step by step methods for field sampling soil. Topography, water indicators and soil indicators are all used to build up a picture of ASS in the landscape as well as onfarm. The booklet includes case studies and a reference list for further information so that users can take the next step in trialing a management option or looking for more information/resources.

Anecdotal information indicates that the booklet is successful in providing practical information based on the needs of farmers who suspect they have ASS on their property. The publication has proved a useful tool for ASS officers and landcare groups and there has even been interest from local councils and Telstra.

Soil monoliths

Soil monoliths are preserved soil profiles, a convenient and portable method of showing people what is below the soil surface. Depending on the audience, the monoliths provide general information, soil management options, soil classification information, and three dimensional illustrations of common soil degradation problems.

There are currently four sets of monoliths available. The largest and most comprehensive set covers most of the soil types on the north coast. Other sets include soils from the Sydney Basin fringe, and from CB Alexander College, Tocal, both of which have been made to illustrate soil management problems and options, and a set from the central/southern tablelands. Extension agents have found these to be excellent tools to encourage the community's interest in soils and provide useful information. The creator of the monoliths, NSW Agriculture soil scientist Roy Lawrie, showed the value of the monoliths at Tocal where two identical looking surface soils with very different production capability, produced monoliths that revealed deep structural differences.

Soil Sense workshops

Soil Sense workshops have been run on the north coast since 1992. In that time, 21 one day workshops have been held from the Tweed to the Macleay and west to Comboyne as part of the former Farming for the Future program. The workshops aim to help landholders look beneath the soil surface using soil pits. Pits are dug in two contrasting sites to encourage participants to think about the differences and the implications for land management. Participants learn to determine soil texture, assess pH levels and 'read' the information in the walls of the pit. The workshop gives people the information and skills to carry out a few field tests on their own soils and understand what the results mean so they are able to monitor their own

soils. They become more aware of how their actions influence any changes taking place in soil health. As one participant commented: 'It was good to actually feel the soil to use as a comparison to our own soil...I can now carry out similar observations on my own soil with more confidence.' The Soil Sense program is backed up with a series of Soil Sense leaflets, the poster 'How to read your soil' and the ever popular Soil Sense book, now in its second edition.

Integrated approaches

NSW Agriculture's soils program has worked closely with other departmental programs to incorporate soils knowledge into farm management training so that linkages are made between soils and water, irrigation, effluent disposal and vegetation management. A good example of this is the Waterwise on the Farm training course that includes one day looking at soils. Soils sessions are often included in production-based field days for farmers.

The future

The outcome of a decade of soils extension effort is that attitudes to soils are changing. The community is beginning to demand more information on soils and the department is ideally placed to ride this enthusiasm and interest by listening to farmers and the community and provide what they ask for. As one workshop participant commented after a Soil Sense workshop at Grafton, 'there should be more workshops in relation to soils'. The next challenge is letting the community know this information is available and where to get it. It is not enough to produce high quality resources and have qualified staff to present this information. Better marketing and closer linkages with community groups will help new and existing projects reach those who need the information and will guarantee that information is valid, useful and appropriate. Directly involving the community is also a good way to gather information on people's soil information needs while researching particular issues. Encouraging land managers to do their own research on farm will ensure the flow of information is both ways, which can only benefit both the community and NSW Agriculture.

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Appendix NSW Agriculture soils extension resources

Human resources

Soil advisory officers at: Wollongbar Agricultural Institute
NSW Agriculture Deniliquin
ASS information officer at: Wollongbar Agricultural Institute
ASS project officers at: Wollongbar Agricultural Institute
NSW Agriculture Kempsey

Agfacts

Agfacts are single topic publications available from NSW Agriculture bookshop.

- Soil acidity and liming AC.19
- Improving soil structure with gypsum and lime AC.10
- Soil management following drought (see www.agric.nsw.gov.au.)
- Is your rotation mining sulfur? (see www.agric.nsw.gov.au.)

Agnotes

Agnotes are single topic, region-specific publications available from NSW Agriculture offices.

- The role of mulch and organic manures for sustainable horticulture in a subtropical environment 1/038
- Reducing soil degradation and erosion in macadamia orchards 1/039
- The effect of regular heavy applications of lime and dolomite on macadamias 1/040
- Testing soils for pesticide residues 1/044
- Monitoring soil water in orchards with tensiometers 1/068
- Arsenic and DDT residues at cattle tick dip yards 1/085
- Options for the remediation of soil from cattle tick dip sites 1/109.

Acid Soil Action leaflets

Acid Soil Action has a series of information leaflets on acid soils and research updates, available from Mick Duncan, ASA project officer, Armidale.

1. Acid soil action for agriculture in NSW
2. Understanding soil pH
3. Are my soils acid?
4. Planning on liming
5. The causes of soil acidity
6. Pastures and acid soils

Acid sulfate soils

There is a wide range of information available on acid sulfate soils.

- **An illustrated guide to acid sulfate soils**
Available free from NSW Agriculture offices at Wollongbar, Kempsey, Taree and Berry.

- **ASS: An introduction**
An excellent introduction to acid sulfate soils, available free from NSW Agriculture offices at Wollongbar, Kempsey, Taree and Berry.
- **ASS: keys to success**
A practical guide for farmers on recognising and testing for acid sulfate soils, available from Wollongbar Agricultural Institute (\$10.00).
- **Identifying and managing ASS in tea tree plantations**
Available free from Wollongbar Agricultural Institute.

Management guides

- **Lachlan soil management guide**
Available from NSW Agriculture bookshop (\$27.20)
- **North Coast soil management guides**
Six page soil management guides for north coast industries: bananas, cane, grazing (beef and dairy), broadacre cropping, teatree production, vegetables and small crops and orchards, available free from north coast NSW Agriculture offices and Wollongbar Agricultural Institute.
- **Nutrient management guide**
A basic guide to nutrient management and fertiliser use, available from NSW Agriculture offices and Wollongbar Agricultural Institute.
- **Soils and their management**
A home study course for an introduction to soils and their management, available through NSW Agriculture book shop (\$88.00).
- **Soil and fertilisers short course**
A one day course run by C.B Alexander college, Tocal, looking at the assessment of soils and selection of fertilisers (\$126.50).
- **Soil management for NSW orchards and vineyards**
Introduction to practical soil management on farm for orchards and vineyards, available from NSW Agriculture bookshop (\$16.30).
- **Soil Sense for North Coast farmers**
A good introduction to soils in general with region specific landscape information and case studies in dairying, orchards, organics, cropping, beef, cane growing, tea tree growing and banana growing, available from NSW Agriculture bookshop. (\$20)

Salt Action

Several publications have come out under the Salt Action banner, all available from Salt Action officers and Simon Gibbs, NSW Agriculture Deniliquin.

Irrigation salinity facts

- Where do salinity and waterlogging come from?
- Draining and recycling irrigation water
- Scheduling flood irrigations
- Reuse pump systems
- The benefits of trees in irrigation areas
- A well planned approach to tree planting

Irrigation salinity notes

- What is Salt Action?
- Understanding salinity meters
- Monitoring groundwater with testwells
- Managing land by salinity class
- Managing horticulture with testwells
- Water salinity guidelines
- Texturing soils and testing for salinity
- Tensiometers: preparation, installation and maintenance

Salinity: our problem

A general introduction to the problem of soil salinity with indicators to look for and management options for the whole community, available from NSW Agriculture Deniliquin.

SOILpaks

All SOILpaks soil management manuals are available on the NSW Agriculture website www.agric.nsw.gov.au and from NSW Agriculture bookshop.

- SOILpak for dryland farmers on the red soil of central western NSW
- SOILpak for cotton growers
- SOILpak for southern dryland farmers
- SOILpak for southern irrigators
- SOILpak for the northern wheat belt
- SOILpak for vegetable growers

Soil Sense leaflets

Soil Sense leaflets provide information on the most commonly encountered soil management issues, and are available free from Wollongbar Agricultural Institute.

- How to interpret your soil test
- Plant nutrients in the soil
- Fertilisers and the environment
- Cation Exchange capacity
- What is soil pH?
- Why worry about acidity?
- Don't let nitrogen acidify your soil
- Which liming material is best?
- Check your soil structure
- How cultivation affects the soil
- Protect your soil from compaction
- Making clay easier to work
- How earthworms help your soil
- Soil organic matter
- Why is phosphorus important?

Soil handling sheets

These illustrated information sheets demonstrate simple soil testing techniques and are available free from Wollongbar Agricultural Institute.

- See if your soil slakes
- Does your soil disperse?
- Measure your soil acidity
- Feel your soil texture
- See what is in your soil
- Prevent structure damage

Miscellaneous

Assessing the texture of your soil

Two page leaflet to guide you through texturing soil and why it's important, available from the irrigation officer, NSW Agriculture Deniliquin

Fertilisers and your farm

A home study program for a basic understanding of the principles of fertiliser use, available from NSW Agriculture bookshop (\$17.50).

How to read your soil poster

A poster that looks at the soil in profile and incorporates many of the basic field tests for soils such as pH, texture and colour, available free from Wollongbar Agricultural Institute.

Landform and soil requirements for biosolids and effluent reuse

A NSW Agriculture advisory bulletin (no.14) available on the NSW Agriculture website www.agric.nsw.gov.au.

Light soils: using them better

A guide to looking after some of the state's most fragile soils, available from NSW Agriculture bookshop (\$27.20).

Soil monolith collections

Regional collections of soil profiles, available for the north coast, CB Alexander College (Hunter Valley), Sydney Basin and central/southern tablelands.

Water quality: where do nutrients come from?

Fold out leaflet looking at various causes of water pollution including erosion, available from Hunter Water and NSW Agriculture Tocal.

Waterwise course manual

Four-day accredited course organised through NSW Agriculture water management subprogram. For more information contact any NSW Agriculture irrigation officer.

Workshop outcomes

As part of the soil health workshop, participants divided into industry-based groups to consider the main impacts on soil health in the different industries, and look at management options for these impacts

Horticulture group 1

Impacts

- erosion on steep slopes, especially macadamias and bananas
- compaction
- acid soils
- organic carbon levels
- chemical sprays

Strategies to manage impacts

Erosion

- transfer of information to growers
- research ongoing
- cover crops
- matting
- vegetation cover
- engineering solutions
- regulations
- orchard design
- mulching
- harvesting technology

Chemical fertilisers

- soil testing and interpretation
- leaf testing and interpretation
- workshops and education - industry specific or community (involve family)

Horticulture group 2

Impacts

Macadamias

- bare ground
- sweeping and blowing
- herbicide

Bananas

- too steep to be sustainable?
- DLWC legislation

Avocados

- chemicals for pest control

Coffee

- potassium chloride

- chemical fertilisers
- contamination (copper)
- funding for soil improvement
- banana root disease
- off site impacts

- increase awareness of problems associated with chemical fertilisers

Financing soil improvements

- more government funding
- research funding from chemical fertiliser companies
- tax breaks
- education - 'need to pay more for your food'
- pay real costs, include external costs

General

- worms and slaters
- microbes
- bacteria
- cover crops
- mulching
- humus, compost

- overuse of spray herbicide

All crops

- tree size management - shading
- tree numbers - less personal, contractor input and managers
- machinery compaction
- excess soluble fertiliser use, leading to run-off into water
- Copper as biocide is the industry standard

Strategies to manage impacts

- surface water management
- skirting, hedging, pruning
- organic material input
- develop cover crops, with more extension
- develop organic fertilisers - composting husk and poultry manure to reduce pathogen potential

- research and extension
- farm walk with industry bodies
- polyculture vs economics
- dept. badly affected by dry economic policy
- overcome problems in registration of biocontrols and other material

Horticulture group 3

Impacts

- soil erosion
- contamination - current and historical (fungicides, soil fumigants, broad spectrum)
- compaction

- loss of organic matter
- fertiliser - acidity - leaching - rates

Strategies to manage impacts

Priority

- integrate all soil health into complete system - r&d, extension, on site changes/ demo
- guidelines for plantation design

- put farming systems package together

Contamination

- need to better understand site specific problems
- when does it become pollution?

Fertiliser

- need best practice extension/ adoption
- need info on effects of soil biology
- heavily dependent on chemicals, need to balance with natural systems

Recognition

- need political recognition - funding
- need community recognition and support - education
- need departmental recognition
- need integrated approach to R&D, eg steering committee
- need to demonstrate production loss and benefits to growers

Compaction

- r & d on biology and organic carbon effects
- education/ adoption of best practice

Dairy group

Impacts

- soil compaction on wet cultivated soils
- uneven nutrient distribution - livestock/cropping
- off-site impacts - nutrients + sediments
- effluent re-use
- acid soils & acidification

- pasture persistence
- soil structural degradation due to top cultivation
- reduced biological activity - cultivation, compaction
- deregulation - economic
- intensification

- higher nutrient inputs - increased soil fertility
- irrigation - soil structure, soil biota
- increased community awareness, expectations - leading to improvements
- lack of appropriate indicators of soil health

- chemical impacts on soil health
- metal contamination - biota
- drainage or lack of water-logging
- poor community research/extension/industry

Strategies to manage impacts:

Soil structural degradation

- identify appropriate management systems, eg reduced tillage, better drainage
- reduce stocking on wet pastures (rain/irrigation), eg use feed pads and reserves
- increase earthworm populations

- evaluate information needs of farmers / service providers
- evaluate alternative pasture options
- understand soil biota impacts/ interactions

dedicated soil management officer

Communication

- use bench marking/ case studies
- develop appropriate suite of indices - physical, chemical, biological
- increased research/ agency/ farmer communications

Nutrient management

- increased understanding of nutrient cycling fluxes/balances
- increased awareness of fertiliser forms/issues
- increased understanding of soil chemistry/cycling

Cropping group

Impacts

- land managers
- use water where it falls
- carbon management - sustainable farming systems, cultivation, disease/ rotation
- economy
- soil structure

- salinity
- sodicity
- chemicals/ ph
- soil diseases/ rotation
- long term herbicide use
- stubble management

Strategies to manage impacts

- land managers
- appreciation of variability in soil
- farmer education to prioritise issues
- regulation is not an option
- specialist soil advisors
- use water where it falls
- rainfall efficiency
- set efficient targets (kg/mm)
- opportunity cropping
- effective use of irrigation water

- establish perennial pastures
- carbon management
- design sustainable farming systems
- -pesticides
- -diseases
- -rotations - crop, pasture, agroforestry/intercropping, tillage
- -economics

Grazing group

Impacts

- soil erosion
- acidification issues
- lack of legume input
- nutrient depletion (P, N, S, K and trace)
- possible carbon balance issues (burning)

Strategies to manage impacts

nutrient depletion/decline

- more efficient use of fertilisers
- driven by economics
- extensionworkshops eg Acid Soil Action workshop
- research
- extension issues
- nutrient requirements largely known
- more efficient legumes?
- VAM fungi eg genetic modification
- P availability
- causes?

acidification management

- driven by economics
- need community to pay for sustainability
- 'real prices' paid for commodities
- extension

- chemical contamination (eg dip sites)
- weed invasion - loss of productive species, fertility decline
- damage to wetlands/ riparian zone

- long term data needed
- workshops
- more info to urban community
- needs for levies - 'real' prices, includes research funding

- research
- long term data needed
- pricing policies
- look at eg carbon credits

damage to wetlands/riparian zones

- driven by economics
- needs assistance for fencing of wetlands/ riparian zones
- extension
- address cost issues etc
- group activities
- research
- alternatives to fencing

Soil health

There is nothing in the whole of nature which is more important than or deserves as much attention as the soil.

Truly it is the soil which makes the world a friendly environment for mankind. It is the soil which nourishes and provides for the whole of nature; the whole of creation depends upon the soil which is the ultimate foundation of our existence.

FRIEDRICH ALBERT FALLOU 1869



NSW Agriculture

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