SOIL QUALITY IS IN THE HANDS OF THE LAND MANAGER

ADVANCES IN
SOIL QUALITY FOR LAND MANAGEMENT:
SCIENCE PRACTICE AND POLICY

PROCEEDINGS OF AN
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Soil Quality is in the Hands of the Land Manager

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"Soil Quality is in the hands of the land manager"

Advances in Soil Quality for Land Management:
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Introduction

R.J. MacEwan and M.R. Carter

The significance of environmental issues has been increasingly recognised over the last decades. The focus of these issues includes: protection of the dwindling 'natural' ecosystems, assuring air and water quality, and sustaining agricultural resources. This symposium was held in order to clarify the context of 'soil quality' within this more generalised debate. As this is the first time that soil quality has been addressed in Australia, the scope of the symposium was selected to cover a range of topics from technical definition to the need for policy. All of the oral papers were presented at the invitation of the organisers who selected the best available speakers from within Australia and from overseas.

Globally, and regionally, there is an urgency to develop guidelines for protection and monitoring of the quality of soil and land resources. The completion of this task is confounded by the apparent complexity and diversity of soil ecosystems in combination with a wide range of land uses imposed on those systems. Ultimately, the protection of soil quality will only be ensured by appropriate actions at the level of the farmer and land manager, hence, the theme was adopted for the symposium that - *Soil Quality is in the hands of the land manager.*

However, if the capacity to positively control soil quality is to be truly in the hands of the land manager, there are questions that need to be answered at many levels, and by different players. Land managers need good technical support in the form of interpreted research results that can be applied to improving their management systems. Research needs the support of government and industry in the form of funding, but is also in need of strategic support with policies in place that give priority to the types of research that will answer the most urgent questions. Policy makers need good advice from technical specialists so that sound policy is developed in the framework of the known and the knowable, and not just in response to a political whim or panic.

Altogether, a partnership is needed between three, often discrete, groups; the land managers, the policy makers, and the scientists or researchers. Such a partnership needs facilitation, so an enormous effort is needed to develop suitable extension programs in which extension personnel are well versed in the science, industry practice, and government policies affecting soil quality, and who are able to increase the capacity of managers to change and monitor their systems appropriately. The task of developing extension programs depends largely on understanding the foundation of science, current management practice, and policy.

Accordingly, the symposium was established with the following aims:

- Provide an international forum for debate on the science of soil/land quality.
- Improve understanding of functions, processes, attributes, and indicators of soil/land quality.
- Examine the practical application of the soil quality concept in land management and land use policy making, especially in areas expressed by the following questions:
    - How can soil quality concepts based on ecological 'function' be used by the land manager to better manage land, especially in agro-ecosystems?
    - What soil properties can serve as practical measures or attributes of soil chemical, physical, and biological quality?
    - Are there differences in the assessment of functions in agro-ecosystems, compared to natural ecosystems?
    - Can functions be managed or manipulated by land managers to better manage land and obtain sustainable land management?
- Update land quality indicators.

The papers contained in this document comprise edited, extended abstracts of the 23 invited oral papers. In addition, short abstracts of poster papers that were brought to the symposium have been included, but not edited.

Summary and Conclusions

M.R. Carter and R.J. MacEwan

The Symposium, 'Advances in Soil Quality for Land Management: Science, Practice and Policy', brought together a wide cross-section of scientists, land managers, and those involved with the agricultural industry. The ordered structure or sequence of the Symposium from 'Science of Soil Quality' to 'Industry Practice and Grower Perspectives', and concluding with 'Programs for Soil and Land Quality' reflected the natural progression, or scaling up, from soil to land quality. The latter includes 'soil' as a component, along with vegetation and water.

The impetus to define and assess soil quality is in many ways derived from outside the scientific community, being related to the concern of society with the overall quality or health of the environment. Thus, the onus is placed on the soil scientist or land manager to characterise and define soil quality. However, this can pose a major difficulty in that while water and air quality can be readily defined in regard to human and animal consumption, a similar scenario does not apply to soil. Soil, as a living system, is a fundamental resource with various functions and only indirectly influences human or animal health.

Some general impressions and conclusions from the Symposium are given below.

1. Soil quality is not a new topic, but one undergoing development in response to the idea that soils are part of land or terrestrial ecosystems. Thus, soil quality brings together old and new ideas about soil and land.

2. Ecosystem concepts such as function, processes, attributes, and indicators, proved to be a useful framework to describe soil quality. However, a precise definition of soil quality proved to be elusive. This is probably related to the innate difficulty in defining soil itself, and the multi-faceted nature (i.e. scientific, personal, social) of environmental concerns.

3. Overall, it was recognised that although soil quality describes an objective state or condition of the soil, it also is subject or evaluated partly on the basis of personal and social determinations. The framework (i.e. function, process, attributes, indicators) of soil quality has utility when it is directed or focused towards the manipulation, engineering, and/or management of the soil resource. Thus, soil quality is a technology, an applied science, directed towards problem solving (e.g. better soil management) and involves social and economic aspects. In this context, soil quality is seen as a key to sustainable land management.

4. The basic idea of 'fitness for use' in regard to agricultural and/or industrial use of soil, which is reflected in early and ongoing attempts at classification of 'soil suitability' or 'land capability', was seen as a basic premise of soil quality. If a soil is not suitable for a specific use then it is not appropriate to attempt to assign or describe quality for that specific use or function. In many cases, however, it is not possible to make a perfect match between the soil and its intended use. Under these circumstances, quality must be built into the system using best management scenarios.

5. There are a large range of attributes, such as chemical, physical, and biological properties, that can be used to describe soil quality. Generally, soil quality attributes need to be characterised for specific soil and situations, or soil uses. However, there are some attributes or groups of attributes (i.e. common data sets) that have a wide utility and can serve a wide range of purposes. Thus, in many situations a 'minimum data set', composed of a limited number of key attributes, can be readily assembled. Except for some singular situations (e.g. disturbed hydrology), where a dominate soil response can be characterised by a single attribute, a set of attributes or indicators are usually required to evaluate soil quality.

6. It was recognised that there is a need for adequate methodology to easily and efficiently characterise soil quality attributes, and a need to better understand how attributes are measured and characterised. The need for standardisation, in regard to both methodology and 'critical limits', was identified as a major impediment to the evaluation of soil quality. Soil quality standards are required to ensure that soil sampling, description, and analysis procedures can set the limits for a quality soil and detect adverse changes in soil quality.

7. Soil science and principles of land management are poorly understood both in the agricultural and wider society. Thus, there is a need to educate all aspects of society about soil and transfer knowledge of the same, especially to the land manager. For soil quality concerns, there is a special need for close interaction among

scientists, technologists, and land managers, especially as the perceived function or purpose ascribed to soil often varies within a community.

8. Industry and grower presentations and perspectives emphasised the importance of characterising soil quality as part of their common concern with sustainable land management. The need to identify and select key indicators of soil quality for specific soil situations, climates and cropping systems was considered to be of prime importance. Also, the close involvement of the research community with these endeavours was emphasised, especially in the area of indicator scale and variability, and the relation of indicators to animal and human health. The drivers behind these concerns were economics/profit, need for better management skills, need for greater understanding of soil processes, and the need for long-term sustainability of agricultural systems.

9. Assessment of soil and land management programs underlined the importance of soil and land quality indicators. In this context a need was identified to provide soil quality guidelines to local government bodies, to incorporate more soil indicators in the 'Top Crop' program, and to implement soil quality programs on the basis of specific industry needs. In regard to the latter, some agricultural industries (e.g. cotton) already provide useful approaches or models.

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Soil quality: a key to sustainable land management?

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Definitions and assumptions

English has two common words for *terra firma* - “land” and “soil”. Land has the wider implications, referring to terrain, in which soil, vegetation and water are components. Soil is restricted to the upper part of the earth surface in which plants grow. As, in this Symposium, we are focussing on soil rather than land, it is these conventional physical, chemical and biological parameters of soil that are the focus of our attention. What we are concerned with, however, is the *quality* of that soil, but quality is a value term, and must be defined in relation to each specific context. While the term has become synonymous with the “health” of the soil, we need to ask healthy for what or whom?

The soil conditions required for native fauna and flora may be very different from those required for exotic, domesticated species grown by people for their agricultural needs. In a recent paper, Pieri *et al* (1995), have defined “land quality” as the condition of land relative to the requirements of land use for agricultural production, forestry, conservation and environmental management, or all managed lands. Wildernesses, deserts, and unmanaged common lands are explicitly excluded from this definition. A comprehensive definition of land use attempts to include all terrestrial ecosystems (Sombroek and Sims, 1995).

Nevertheless, Pieri *et al*., (1995), embrace a very much wider set of land uses than is often implied in standard soil science literature, where the focus on “healthy” soils is largely on soils used for annual crop production. In such cases, the underlying assumption is that the criteria that define a healthy agricultural soil are the same for all soils and land uses, and that thresholds and optimal conditions for universal soil attributes are those required to maximise productivity of temperate and subhumid agricultural crops. The contributors to the Soil Science Society of America’s “definitive” publication on soil quality for a sustainable environment (Doran *et al*, 1994) do not tell us what the optimal soil properties are for cultivating tea, rice or olives, for example. Tea grows quite happily at pH 4.0, rice is comfortable with oxygen levels that would cause anoxia to other grain crops, olive trees are not troubled by levels of free calcium carbonate that cause iron choloris in citrus. The minimum data set proposed by Larsen and Pierce (1991) should perhaps be defined as the minimum data set to use for temperate agriculture in affluent societies.

Sustainability depends on the objective

For Australia, trapped after two hundred years in the realisation that most of our Eurocentric agricultural production systems are now considered unsustainable (SCA, 1991), there is an additional concern, and that is to be able to identify what attributes and processes are required for returning parts of the environment to native species. We have a real paucity of information on how to cultivate or manage non-domesticated, or demi-improved native species such as eucalypts, acacias and native perennial grasses. Native grasses are now being actively encouraged back into high rainfall temperate pastures of the Tablelands, through the efforts of research granting agencies, State agricultural agencies and an extension exercise called “Prograze” that assists producers to identify and manage their pasture composition and status. Can soil scientists assist the meat industry with indicators of soil quality for optimising the growth and persistence of mixtures of native and introduced species, such as cocksfoot, phalaris and *Danthonia*, for example? Over the past fifteen years many concerns have been expressed about pasture decline in southern Australia, with surveys, enquires and many research studies confirming that productivity, composition and water-use are all declining across some thirty million hectares (Wheeler *et al*, 1987; Reuter, 1989; Fisher, 1996). Of all the factors raised by these enquires, only one soil attribute is regularly reported, and that is acidity. The other major factors of importance that are repeatedly mentioned are grazing management and stocking rate, weeds, and plant diseases and pests. In this agro-ecosystem is some complex set of soil quality attributes the key to sustainable land management, or is it as simple as soil pH? Correcting pH improves soil structure, enhances nitrogen fixation by rhizobia, increases microbial biomass, reduces metal mobility and gives plant biomass responses of two to threefold in medium to high rainfall environments (Robson, 1989). Do we really need to look further, and particularly should we be measuring a suite of primary attributes that includes particle size and plant available water at a cost per sample that may be greater than the price of a hectare of land?

Are there good and bad attributes?

We must also be careful that we do not assume positive and negative values beyond the context of the system in question. While the control of erosion from bare surfaces of arable cropland is an undisputed requirement for agricultural sustainability, it may not be valid to assume that no erosion is the most sustainable circumstance in all environments. It is becoming accepted, for example, that flood plain erosion and deposition are natural processes required to maintain healthy riverine environments, and the post-war surge in control and regulation of major rivers for irrigation and hydroelectricity is now seen to have a number of adverse effects on flood plain ecosystem health. In such cases, a conflict appears to be developing between the demands of settled rural communities, particularly where irrigation and damming of rivers is involved, and environmental sustainability of the ecosystem (Murray Darling Basin Commission, 1995).

Sustainable land use is spatially heterogeneous and dynamic

Identifying the critical soil parameters for sustainable land use, therefore, requires a decision-tree approach, whereby we progress from the traditional FAO land capability approach to the question of land suitability, and ask, what is the most suitable use for this land, given its inherent attributes? This is the approach being used by land resource planners in a number of countries, often with considerable reliance on predictive simulation modelling (Acton and Gregorich, 1995). Again, the context is agricultural in most cases in which the fundamental principle for evaluating sustainability of agriculture depends on an assessment of the soil quality, as these are affected by land use practices. In reality, agricultural lands are interspersed with non-agricultural lands, whether these are only remnants of native vegetation, forests, urban settlements, transport routes or wildernesses.

Hamblin and Foyel (1996) have recently described a simple decision-tree approach for the identification of managed lands where there is concern over the sustainability of current land use, using a ‘triage” system of diagnosis and treatment (Figure 1).

Step 1. Classification (Eco-region)

Primary attributes
- terrain
- soil type
- vegetation type

Step 2. Current land condition (Indicators)

Ranking Process
- economic return (rents)
- land value

Step 3. Triage or Risk Assessment (assessing issues and selecting appropriate action)
- prioritise the risk on biophysical grounds
- identify the category of land use
- select the appropriate treatment (change, improve, leave alone)
- monitor progress using indicators (intensity will depend on risk level)

Step 4. Match current land use condition to risk analysis
- develop policy to change or maintain current land use (economic, legal, infrastructural, social)

Figure 1. A triage system for identifying unsustainable land use

The real biophysical risks (Figure 1, Step 3) are not those target values of attributes that are refined to optimise agricultural production, but the minimum threshold values of attributes necessary to support life. While some life forms are capable of surviving exceptional conditions (bacteria living in hot springs, algae living in salt lakes), most terrestrial life forms are severely affected when the soil environment contains large concentrations of heavy metals, anthropogenic organo-chlorine compounds, and radioactivity. Table 1 distinguishes these serious threats from the sub-optimal conditions that can restrict the achievement of maximising biological production, which is the concern of agronomists for agriculture.

Table 1. Biological Hierarchy of Sustainability

(Source: Standing Committee on Agriculture and Natural Resources, 1993).

Biological Status	Agricultural Equivalence	Example
Growth	Optimal for climatic potential	no nutrient deficiencies
Reproductive ability	Suboptimal (<50% WUE)	minor nutrient imbalances
Survival limits	At critical thresholds for the species	toxicity or deficiency
Death	Acute toxicities	radioactivity, heavy metals, PCB derivatives

Off-site impacts and market failure

The spatial inter-relationships between agricultural land use and other uses has sprung into greater focus in Australia as the consequence of increased recognition of the adverse effects resulting from large-scale land clearance on dryland salinity, acidification and water quality, and the continuing problems from wind and water erosion in southern Australia. Off-site impacts from agriculture constitute a significant economic effect for the whole economy, and are conservatively estimated to be affecting 80% of our drinking water purification costs, for example (Bursill per comm). These off-site effects constitute market failure that currently result from the dissociation of land condition from land value. This is currently an issue of intense interest to major financial institutions, agencies such as the Murray Darling Basin Commission and rural research corporations (Land and Water Resources Research and Development Corporation, 1995).

These concerns for greater consistency between biophysical condition and valuation systems are also reflected in the progress towards greening the System of National Accounts (SNA). Substantial work has been carried out over the past decade, by the UN Statistical Office, the World Bank, The World Resources Institute and the Worldwide fund for Nature (WWF), on developing alternative valuation systems for natural resources for inclusion into the SNA. These are described in recent publications by Lutz (1994), Serageldin and Steer (1994) and others. Although they are still unsatisfactory, they represent a change in thinking among economists that is very welcome, and a return in a sense to the Hicksian economic model that recognises a sustainable income as being one that does not erode capital. In these developments soil and land resources are poorly described, and the activities that are considered to degrade soil resources are trivialised to being described by “soil erosion” or tonnes of soil lost. Indicators of natural resource status are likewise sparse or absent for soil and land resources (UNEP, OECD systems), as reported by Hamblin (1995). Soil scientists assist by providing repeatable and relevant indicators of soil condition that are associated with biological and economic condition, as these change over time.

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Concepts Of Soil Quality

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Background

Interest in assigning quality to soil has been an ongoing concern of scientists and land managers for many years. Early concerns were mainly expressed in the need to rate soils for their suitability for crop growth and other uses. Draft requirements for tillage and the cost of inputs (e.g. drainage) to change a soil condition were also factors that determined the quality of a soil. These concerns were further developed by the initiation of classifications for both land capability and the regional suitability of soils for various uses. These endeavours usually utilised soil properties, landscape factors, and climate in assessing the quality of a soil for a specific use.

Modern concerns with soil quality evolve around the various functions that soils perform in ecosystems (see Table 1). Soil is recognised to be a critical component of the earth's biosphere. Thus, soil quality becomes inseparable from the idea of system 'sustainability', and is considered a key to sustainable land management and a key indicator in environmental science. The emphasis here for soil quality is a shift away from 'suitability for use' to whether the soil functions are operating at some optimum capacity or level within an ecosystem. Placing a value upon soil in regard to a specific function, purpose or use leads to the concept of *soil quality*. However, in contrast to water and air where the function can be directly related to human and animal consumption, the function placed upon soil is often diverse and usually not directly linked or involved with human health.

Soil quality can only be assessed by measuring properties and, therefore, involves both an observer and an interpreter. The range of observers, from individuals to interest groups to society as a whole, and the concomitant range in their value systems, ensures diverse views on soil function and, consequently, measures of soil quality. Linked with this is a recognition of the intrinsic value of soil due to it irreplacability and uniqueness, and the idea of a relationship between people and soil (Warkentin, 1995).

Defining Soil Quality

Early concepts of soil quality dealt mainly with various soil properties that contribute to soil productivity, with little consideration of a definition for soil quality itself. However, mere analysis of soil properties alone, no matter how comprehensive or sophisticated, cannot provide a measure of soil quality unless the properties evaluated are calibrated or related against the designated role or function of the soil. Thus, implicit in any definition of soil quality is an understanding of the stated function of the soil, or what the soil does. A simple definition of soil quality could be 'fitness for use'. However, definitions of soil quality have been subject to an ongoing development. Anderson and Gregorich (1984) proposed that soil quality be defined as *"the sustained capability of a soil to accept, store and recycle water, nutrients and energy"*. However, agriculture is now viewed as part of a much broader ecological system, which interacts with, and affects other various parts of the system. This development is expressed in the expanded concept of soil quality evident in the work of Larson and Pierce (1994). They define soil quality *"as the capacity of a soil to function within its ecosystem boundaries and interact positively with the environment external to that ecosystem"*. This definition also recognises that soil serves other functions both within and beyond agricultural ecosystems. A more detailed definition has been developed by the Soil Science Society of America (1995) as follows: *"Soil quality is the capacity of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation"*. This definition is similar to that of Doran *et al.,* (1996) where soil quality is the *"capacity of a soil to function, within ecosystem and land use boundaries, to sustain biological productivity, maintain environmental quality, and promote plant, animal and human health"*.

Inherent Versus Dynamic Soil Quality

The above definitions imply that soil quality has two parts: an intrinsic soil part which covers a soil's inherent capacity for crop growth, and a *dynamic* part influenced by the soil user or manager. The distinction between inherent and dynamic soil quality can also be characterised by the genetic (or static) pedological processes versus the kinetic (or dynamic) processes in soil as proposed by Richter (1987).

Attributes of inherent soil quality, such as mineralogy and particle size distribution, are mainly viewed as almost static and usually show little change over time. Assessment of inherent soil quality can be achieved by utilising national land resource inventories. Such databases, the fruit of much long-term data collection, can be analysed in a computerised geographic information system (GIS) to develop broad regional assessments of inherent soil quality. Many present databases cover climatic information (e.g. growing degree days), soil texture and depth. Land resource inventories also often include data on soil porosity, nutrient retention, and both physical and chemical rooting conditions (e.g. physical and chemical barriers to root growth).

Generally, dynamic soil quality changes in response to soil use and management (Larson and Pierce, 1994). Attributes of dynamic soil quality are subject to change over relatively short time periods. For example, total organic matter may change over a period of years to decades, while pH and labile organic matter fractions may change over a period of months to years. In comparison, microbial biomass and populations, soil respiration, nutrient mineralisation rates, and macroporosity can change over a period of hours to days. Thus, maintenance and/or improvement of dynamic soil quality deals primarily with those attributes or indicators which are most subject to change, loss and depletion, and strongly influenced by agronomic practices.

Soil Quality And Scale

Soil quality can be assessed at the pedon, landscape, ecosystem, and global scale. However, there is an increasing difficulty in both measuring and managing soil quality as scale increases. In the past there has been some confusion in separating the definition of soil versus land quality . It is now recognised that soils are part of a larger environmental system, and that *land* is a term that better reflects the natural integration among soil, water, climate, landscape, and vegetation characteristics (Hamblin, 1995). Land quality, then, is a broader concept than soil quality as it describes the state of the combined or integrated entity of soil, water and vegetation. The distinction between soil and land quality can also be illustrated by the relatively recent pedological focus on soil as a spatial three-dimensional entity (Lavkulich, 1995). In this comparison, pedology has developed from 'site' analysis to two-dimensional 'soil profile' analysis, to three-dimensional 'pedon' analysis, with more recent emphasis on three-dimensional 'polypedon' or landscape units. These developments are reflected in the cartographic concept of a 'catena'. Spatial aspects are also being emphasised by the interest in geographical information systems and spatial statistics.

Evaluating Soil Quality

A useful framework to evaluate soil quality is based on the following sequence: functions, processes, attributes or properties, attribute indicators, and methodology (see Table 2.). Soil quality is evaluated on the basis of the function in question. Functions deal with 'what the soil does', or ‘what the soil is asked to do’. Each function can be characterised by specific soil processes that support the function which is being imposed upon the soil. Soil quality attributes can be defined as measurable soil properties that influence the capacity of the soil to perform a specific function. Generally, attributes describe a critical soil property involved with the process. In many cases the specific property may be difficult to measure directly, so an indicator (an associative property; i.e. surrogate or proxy) or pedotransfer function (a related property; Bouma, 1989) can be used to serve as an indirect, practical measure of the attribute. Indicators can represent a single attribute or may also represent a set of attributes. It is generally acknowledged that indicators should be easily measured, have some sensitivity to variations in soil management (but not overly sensitive), and have a relatively low sampling error. Indicators that have a relatively long record of sampling or are found in historical records are of particular use. The choice of indicator would be based on the provision of available methodology, including ease of duplication, and facility for accuracy and speed.

Various studies have attempted to identify sets of attributes or properties which can characterise a soil process or processes in regard to a specific soil function (Doran and Parkin, 1994; Gregorich *et al.,* 1994; Larson and Pierce, 1994). A major goal in soil quality studies is to ascertain, where possible, links between properties (or indicators /proxies /surrogates) and a specific function of the soil (e.g. crop productivity). Once a property is identified for a specific soil type or situation, information is needed in regard to *soil quality* standards for a given set of conditions. This involves information on the critical level and range of the attribute (property) that is associated with optimum crop production. Development of soil quality standards can be a difficult process, especially defining the limits or critical range (Pierce and Larson, 1993).

Identifying key soil attributes that are sensitive to soil functions allows the establishment of *minimum data sets* (MDS) (Larson and Pierce, 1994). Such data sets are composed of a minimum number of soil properties that will provide a practical assessment of one or several soil processes of importance for a specific soil function. Ideally, the property should be easily measured, and the measurements be reproducible and subject to some degree of standardisation. In cases where the property of interest may be difficult or expensive to measure, an indicator or pedotransfer function may provide an alternative estimate.

Assessing Change In Soil Quality

Dynamic soil quality for crop production is concerned with changes in soil quality attributes or properties due to land use and management. One of the goals of sustainable agricultural systems is to maintain soil quality. Thus evaluation of soil quality, in addition to characterising functions, identifying attributes, and developing MDS also requires strategies to evaluate soil quality change. Larson and Pierce (1994) discuss both the *comparative assessment* and *dynamic assessment* approach to evaluate soil quality change. The former is commonly used and involves a single comparison of one system against another. However, this approach may provide little information on trends in soil quality over time. In contrast, dynamic assessment compares or evaluates soil quality attributes over time. Larson and Pierce (1994) identify both computer models (which use attributes as variables) and statistical (i.e. temporal pattern of attribute mean and standard deviation) control as a means to assess soil quality change over time. Other approaches are use of archived soil and plant samples from long term experiments, and geostatistical methods. In regard to change in soil quality, standards are needed to assess if the recorded changes are within natural variation or optimum range of the soil attribute in question, or if the changes are related to management practices that may require changes if quality is deteriorating. Since within a minimum data set individual attributes or indicators may show opposite or various changes (e.g., organic matter increasing, but porosity decreasing), the interpretation of such changes and the required management response underlines the importance of ‘experience’ and ‘skill’ in the soil manager.

Soil Quality For Improved Soil Management

The goal of the land manager is to sustain and improve the quality of the soil resource base. Thus, soil quality is in the hands of the land manager (Pierce and Larson, 1993). Monitoring soil quality does not in itself change the soil condition, but serves only to indicate if changes in management are required. Therefore, sustainable land management practices must be designed to ensure that the processes that regulate soil quality are operating in a positive manner, and that soil quality is under control. Pierce and Larson (1993) emphasise that sustainable land management should include the following assessment: evaluate land suitability for specific use, identify key soil quality attributes for the specific system and derive a minimum data set, establish soil quality standard limits, identify management inputs that strongly influence soil quality attributes (e.g., residue levels influence soil organic matter), employ soil quality control techniques to monitor the system, modify management as needed to maintain soil quality control.

Summary

Soil quality involves placing a value upon soil in relation to a specific function or purpose. Functions can vary in relation to both use of soil and scale. Although assessment of soil quality can range from the field to the global scale, it is easier to characterise at the pedon or polypedon scale. Once a function has been established then soil processes and attributes that describe the function, and indicators that are related to the attribute(s) along with respective methodologies, can be identified and characterised. The latter allows the development of soil quality standards and control techniques, and subsequently the design of sustainable land management systems. Overall, soil quality provides a useful framework to both monitor and improve land management.

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Table 1. Examples of functions ascribed to soil that are used to assess quality

SSSA (1995)
- Sustaining biological activity, diversity, and productivity
- Regulating and partitioning water and solute flow
- Filtering, buffering, degrading, immobilising, and detoxifying organic and inorganic materials
- Storing and cycling nutrients and other elements within the earth's biosphere

Larson and Pierce (1994)
- Medium for plant growth and productivity
- Partitioning and regulating of water flow in the environment
- An environmental buffer

Blum and Santelises (1994)
- Biomass production
- Soil as a reactor (filters, buffers, transforms matter)
- Soil as a biological habitat and genetic reserve

Warkentin (1995)
- Recycling of organic materials to release nutrients and energy
- Partitioning of rainfall at soil surface
- Maintaining stabile structure to resist water and wind erosion
- Buffering against rapid changes in temperature and moisture, and chemical elements
- Maintaining habitat diversity by providing a range of pore sizes
- Storage and gradual release of nutrients and water
- Partitioning of energy at the soil surface

Table 2. Example of a framework (given in part) for evaluating soil quality (i.e. as a medium for plant growth) using the sequence of process, attribute, indicator, and methodology.

Process	Attribute or property	Indicator for attribute	Possible method for attribute
Capacity to accept, hold and release water	Infiltration	Infiltration rate, sorptivity	Tension permeameter
	Water holding capacity	Desorption curves	Tension table, pressure plate
	Permeability	Hydraulic conductivity	Guelph permeameter
Capacity to accept, hold and release energy	Organic matter	Organic carbon	Dry combustion
	Labile organic matter	Microbial biomass	Chloroform fumigation
		Carbohydrates	Acid hydrolysis
		Macroorganic matter	Dispersion/sieving
	Particle size	Clay	Hydrometer/pipette

The pedological context for assessment of soil quality

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Introduction

Pedology, as the discipline concerned with understanding the variety of soils and their distribution, is the science that should be most directly concerned with questions of soil quality. The identification of soil differences (soil attributes) sets the stage for determination of soil quality (interpretation of soil attributes functionally). Understanding the relationship between these differences and soil functions provides the basis for guidance to managers to use soil resources appropriately. The work carried out by pedologists in the field involves the assessment of a wealth of soil morphological features that can be readily interpreted in relation to soil processes and therefore to soil quality. This paper therefore has two principal objectives:

- to review some well established concepts in pedology that have relevance to soil quality, and
- to give some examples of the use of some pedological indicators of soil quality.

Pedology

Pedology has two broad purposes: to describe and classify, and to interpret soil differences with respect to their management requirements. An appropriate recent definition of pedology can be found in Wilding (1994) as "*that component of earth science that quantifies the factors and processes of soil formation including the quality, extent, distribution, spatial variability and interpretation of soils from microscopic to megascopic scales"*. This definition introduces the word ‘quality’ in a general way, and a search through pedological literature does not clarify the term and how it is intended to be applied. It is fair to presume though, that soil quality, for the pedologist, includes the descriptive aspects of the science and the interpretive aspects of those attributes. For example, the field description of soil attributes such as presence and degree of development of gleyed Bg, or eluviated E or A2 horizons can be used to determine soil quality in relation to drainage class. Thus, description and its interpretation can then be explained in relation to constraints the soil would present to choice of land use. In addressing the questions ‘What is the soil like?’ and ‘How suitable is the soil for a particular purpose?’ we are obviously involved in issues of soil quality. Such categorisation of soils can be considered as recognition of the more enduring aspects of soil quality appropriate to decisions about land capability and soil suitability (e.g. Dent & Young, 1981).

Soil classification

Soil classification systems (e.g. Soil Survey Staff, 1988) are important tools within the context of soil quality. They are our attempts to bring conceptual order into the complex world of soils and to allow knowledge gained in one location to be used in another, given that we are transferring that knowledge to similar soil conditions with the same management. The great variety of soils and climates makes classification a large task even if soils were considered to be unchanging entities. To appreciate the real scale of the task we have to recognise that soils are changing, their evolutionary history is only partially understood, their future is dimly perceived, and they are used for a range of purposes all with unique requirements in relation to soil function and land use. The demands on soil classification are therefore so diverse that they cannot be satisfied by a single system at any point in time or for any part of the world. Changes in classification have been and will continue to be made but their value depends on how easily class groups can be interpreted in relation to soil functions and processes. A sound basis for interpreting soils and their response to management resides in improved understanding of soil processes and the interpretation of these from soil morphology in soil landscapes.

Soil formation and soil quality

Soil formation or pedogenesis has always been a focus for pedologists. The origins of soil attributes, distinctive horizons, and profiles must be understood in order to develop conceptual models for soil evolution over long time periods. Such models have intuitive, predictive power in soil mapping, but can also provide the basis for modelling shorter term pedological changes such as those induced by management.

Factors of soil formation were proposed in the 1860’s in the USA by E.W. Hilgard (Jenny, 1961a) and in the 1880’s in Russia by V.V. Dokuchaev (Krupenikov, 1993) and have been developed in a semi-quantitative fashion by Jenny (1941, 1961b, 1980) as the now well accepted: *Soil = f{Climate, organisms, relief, parent material, time...}*equation. Processes of soil formation were initially defined after the effect, i.e. they were named after the soils. Initial efforts at soil classification described soils as: podzols, laterites, solonetzs, etc, and processes such as: podzolization, laterization, solonization were proposed to explain the genesis of these soil differences. This led to ambiguities in soil classification. Soils with a degree of similar morphology but different genesis were misleadingly named and grouped together, e.g. podzolics and podzols (Wilde, 1953).

Simonson (1959) proposed a more general framework for soil genesis based on four groups of processes: additions, transfers, transformations and removals. A dynamic approach to pedogenesis, building on the perspectives offered by Jenny and Simonson, can be used to provide a framework for the assessment of soil quality at different spatial and temporal scales. An analogy appropriate to our conceptual framework for pedogenesis has been used in ecology by Hutchinson (1965) as the ecological theatre and the evolutionary play. We can envisage the soil forming factors as setting the stage or conditions for soil formation: the ecological theatre. The play that is enacted within the theatre is the suite of processes interacting over time and modifying the original solum. When we open a soil pit we peek briefly into a moment taken from the play and view the imprint of all that has occurred up to that moment. Human intervention in the play is both as actor and co-director, re-defining the plot and changing the scope of the theatre.

Figure 1 illustrates the connection between soil forming factors and processes and the resulting three dimensional soil body, known as the pedon (Soil Survey Staff, 1988). In natural conditions the pace of pedogenesis is such that it is barely perceptible within human generation spans. In managed conditions the pace, and direction, of pedogenesis can be altered through engineered effects on the soil forming factors and processes. Microclimate is modified by irrigation, fallows and mulches. Organisms are reselected and controlled for agriculture and forestry Relief is altered by land forming as levelling or contour bank construction Parent material is augmented with fertilizers and mulches but deprived by crop and residue removal. These modified factors in turn influence the rates of the soil forming processes. Fertilizers, tillage (erosion), crop removal and irrigation (leaching fraction) alter the balance of additions and removals, while irrigation affects transfers within the system, e.g. by mobilisation of free $CaCO_3$ in the upper part of the pedon and precipitation deeper in the B horizon. Transformations such as humification/mineralisation, mineral weathering and clay degradation are all modified by the increased oxidation due to tillage, and hydrolysis due to changed moisture regimes. These human induced changes in pedogenesis have been referred to as metapedogenesis (Yaalon and Yaron, 1966). In assessing sustainability of land use practices the metapedogenic influences need to be distinguished from ‘natural rates’ of change in pedogenesis. The former may be beneficial, aggrading soil quality (e.g. drainage), or harmful, resulting in soil degradation and lowering of soil quality. The sustainability pathway applies pedotechnology (Fanning and Fanning, 1989) to avoid ‘pedonemesis’.

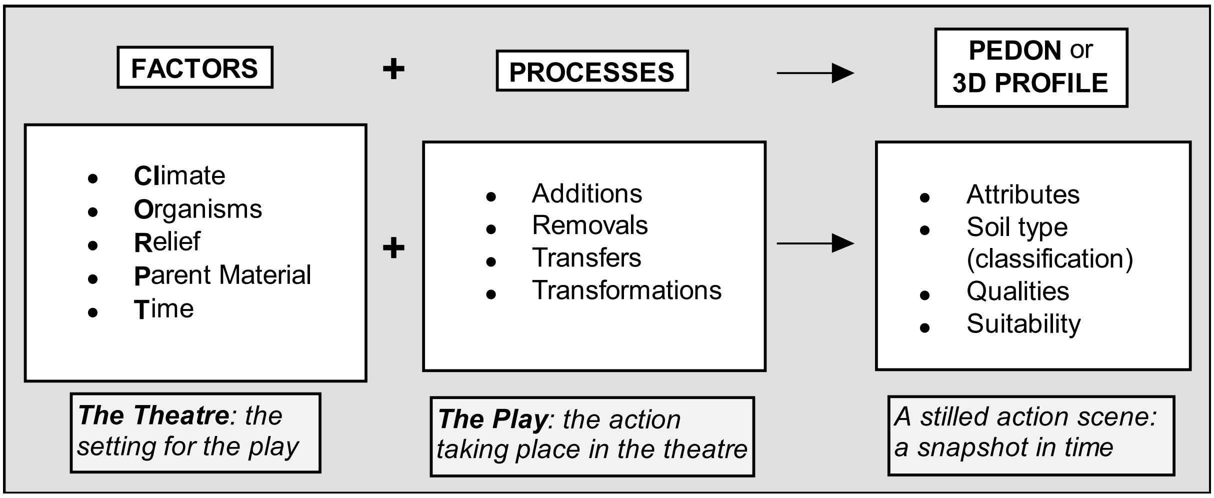

Figure 1. Pedogenesis as the relationship between soil forming factors and soil forming processes. The analogy of the ecological theatre and the evolutionary play: the land manager appears as actor and co-director in metapedogenesis affecting both factors and processes through interventions in soil and crop management.

Soil age and soil quality

We usually assume that the soil, characterised by its profile, is a relatively permanent feature; we do not see what it has been, nor what it is about to become. But pedogenesis is dynamic: soil attributes and soil quality naturally change with time. We must also recognise the general entropic direction of all physical processes increasing disorder, and dissipating energy. Soils are formed from parent rock by weathering processes which increase entropy in ordered mineral material and result in less well ordered clays, oxides and soil fabric (Yaalon, 1960). Soil can not return to the state of unweathered parent material without renewal of the land surface through erosion or tectonics. However, because the soil is an open system exchanging both energy and matter with its surrounding environment, some increase in order, hence decrease in entropy, does occur (Smeck *et al.*, 1983). Inputs of energy enable incorporation of other material elements uncommon in the regolith, particularly carbon by photosynthesis and nitrogen by bacterial fixation, but order is only temporarily created in the structures of the biological entities. Thermal solar energy (driving evapotranspiration) and gravity (driving water movement, leaching and soil washing) provide energy inputs that accelerate the increase in soil entropy by removal of material but decrease entropy by sorting soil materials into horizons.

We can therefore envisage the soil passing from youth to old age. In the early stages of soil formation, weathering processes have an overall positive effect on soil qualities affecting plant growth; releasing nutrients into solution from crystalline forms, forming clays, developing porosity and structure, accumulating organic matter and increasing the capacity to exchange cations and anions. Order in the soil system is increased as organic matter accumulates and horizonation develops. In the later stages, the same driving forces have an overall negative effect on soil quality. Increasing clay contents of subsoils have adverse effects on water and air movement, leaching increases acidity, or accumulation of soluble salts or insoluble salts and oxides reduces the quality of soil for nutrient supply and rooting environment. The rates at which these thermodynamic trends proceed depend on the soil forming factors, particularly the parent material and climate (temperature and moisture). A chronosequence of soils studied by Thompson (1992) in Australia illustrates these relationships.

Even given a uniform parent material and constant climate it has been pointed out that different processes peak at different stages in the development and ageing of soil (Fig. 9.19, p242 *in* Jenny, 1980). We need to appreciate where we are on the temporal scale for the soil under consideration, adopting a geological time frame, in order to put sustainability into perspective.

Spatial scale, pedogenic processes and soil quality

Dijkerman (1974) suggested an organisational hierarchy, based on size, of seven subsystems for soil studies and discussed the relationship of empirical scientific methodology to these different levels. Other writers have adopted a similar approach (Hoosbeek & Bryant, 1992; Sposito and Reginato, 1992). The pedon (Soil Survey Staff, 1988) is accepted as the basic three dimensional unit of soil encompassing the variations in horizon and profile features that would fully characterise the soil type under investigation. The pedon exists in the larger subsystem hierarchy of polypedon, toposequence, and catchment or region, and contains smaller sub-systems of horizons, peds, mineral organic complexes and minerals. Investigation of soil at the pedon scale should always include details at the horizon scale and context at the catena or catchment scale (soil-landscape): it is naturally observed as a sample representing the larger polypedon, paddock or management unit and is not seen as an isolated entity.

Description and quantification of attributes of sub-systems, including their spatial variability, is advanced at all scales. Interpretation of features within sub-systems in relation to their significance to management and production systems is also possible. Soil quality assessment can therefore be related at all scales of pedological interest. However, the temporal variability of soils is less well understood or documented. Assessment of soil qualities that may change in management time scales requires clarification of rates of change of pedological attributes in response to pedogenic processes (Table 1 and Table 2).

Hoosbeek and Bryant (1992) reviewed progress towards the quantitative modelling of soil processes. They characterised models with respect to their relative degree of computation (qualitative to quantitative), complexity (functional to mechanistic) and level of organisation (microscopic to megascopic). They concluded that while qualitative models have aided in soil survey and understanding soils in landscapes, there is a need to devise quantitative models to predict how soils will change in future. This is particularly important if soil quality and land quality indicators are to be used to judge sustainability, and not merely suitability, of current management practices.

Pedological indicators, pedogenic processes and soil quality

Reliable indicators should be clearly defined, consistent, specific, sensitive to change and easily measured (Casley and Kumar, 1987). Pedological attributes useable as indicators of soil quality are mostly relevant to assessment of soil suitability for a particular use, but are also used to infer soil processes and could therefore be appropriate to soil quality assessment and monitoring. Processes may be controllable or uncontrollable. Those that are controllable may be reversible or irreversible. Indicators of processes may be observable in one direction only, (e.g. gleyed colours are an excellent indicator of developing waterlogged conditions but soils that have been drained may still display gleyed features, see James and Fenton, 1993). Relationships between scale of investigation, pedogenic processes, sensitivity to change (years), and the indicators of these processes, are suggested in Table 1.

Table 1. Soil modifying and soil forming processes: their relationship to spatial and temporal scale, and suggested indicators for their recognition.

Scale	Processes	†	‡	Sensitivity (years)	Indicators
Global and Continental *Extremely small scale* <1:5000000	Plate tectonics	U	I	10^3 - 10^6	Vulcanism, continental changes
	Soil formation	U	I	10^2 - 10^4	Degree of soil development
	Erosion	U	I	10^2 - 10^6	Valley form, river development
	Salinisation	U	R	10^2 - 10^4	Halophytes
	Urbanisation	C	I	10 - 10^2	Loss of agricultural land
Regional, catchment or catena *Small scale* <1:100000	Soil formation	U	I	10^2 - 10^4	Soil types
	Erosion	C	I	10^{-1}-10^3	Gullies, tunnels etc
	Salinisation	C	R	10 - 10^3	Area of discharge/salt affected land
	Acidification	U	I	10 - 10^3	Restricted crop & pasture species
	Waterlogging	U	R	Seasonal	Area with slow surface drainage
Paddock or polypedon *Large scale* >1:25000	Erosion, deposition	C	I	10^{-2} - 1	Surface features
	Salinisation	C	R	10 - 10^2	Discharge features
	Acidification	C	R	10 - 10^3	pH
	Waterlogging	C	R	Seasonal	Ponding, pugging, sealing
Pedon (3D Profile) *Human scale* *1:1*	Erosion, deposition	C	R	10^{-2} - 1	pedestals, rills, layering
	Profile development	C	R	10 - 10^4	Depth, horizons
	Salinisation	C	R	10 - 10^2	Vegetation response
	Acidification	C	R	10^2 - 10^4	pH
	Waterlogging	C	R	Seasonal	surface features (pugging, seals), colour
	Sodification	C	R	10 - 10^4	soil dispersion in rain water
	Root penetration and water use	C	R	1 - 10^2	depth and pattern of roots vs textures
Horizon (Pedon in detail)	Erosion, deposition	C	R	10^{-3} - 10^2	Surface features
	O.M. accumulation/depletion	C	R	1 - 10^2	L,F,H.Consistency (hard setting), OC
	Thickening, thinning	C	R	10 - 10^2	Native site comparison
	Leaching, acidification	C	R	10 - 10^2	pH
	Clay translocation	C	I	10 - 10^2	Coatings, turbidity of run off
	Soluble salt accumulation	C	R	10 - 10^2	EC, visible crystals
	Carbonate, gypsum accumulation	U	I	10 - 10^3	Nodules etc
	Gleying	C	I	1 - 10^2	Colour, mottling
	Iron enrichment	U	I	10^2 - 10^4	iron pans, buckshot, pore linings, Bs
	Compaction	C	R	Seasonal	Ped shape, pores, bulk density, roots
	Loosening	C	R	Seasonal	Ease of tillage, cloddiness
	Root penetration, water use	C	R	Seasonal	Roots vs. pores vs texture
	Animal activity, burrowing etc	C	R	Seasonal	Number/area(vol)
Ped	Aggregation	C	R	1 - 10^2	Water stability
	Cementation	U	I	10 - 10^3	Consistency, grain coatings
	Slaking§	C§	R§	10^{-4} - 10^{-2}	Crusts, seals
	Dispersion§	C§	I§	10^{-4} - 10^{-3}	Cutans, turbidity
	Compaction	C	R	seasonal	Pores, ped/clod density
Mineral	Hydration, hydrolysis, solution	U	I	10^{-4} - 10^4	%unweathered minerals
	Salts (formation/ transformation)	U	I	10^{-3} - 10^2	EC, visible crystals (halite)
	Clay formation	U	I	millennia	%clay and 2:1 vs 1:1 layer silicates
	Clay degradation	C/U	I	10^2 - 10^4	low pH, water logging, bleached colour
	Fe/Mn oxide formation	U	I	10^{-3} - 10^4	Colours: red/ yellow (formation)
	Fe/Mn oxide transformation	C/U	R	10^{-3} - 10^4	bleached/ grey colour (transformation).

Where: † Controllable=C; Uncontrollable=U; ‡ Irreversible=I; Reversible=R

§ Slaking is a reversible soil process because aggregation of slaked soil components can be encouraged with organic matter additions. Dispersion, although it can be prevented by flocculating agents, cannot be reversed due to the total disintegration of peds, destruction of soil fabric, and loss of clay. Both slaking and dispersion are controllable processes.

Relationship between indicator and scale: regional and higher

At small scales of investigation (1:250,000 and smaller) soil data become generalised and sustainability indicators are more relevant to land quality than soil quality as mapping units at scales smaller than 1:50,000 cannot represent a single kind of soil (Dent & Young, 1981). Data collected at larger scales may be used to map areas affected by particular quality defects, such as waterlogging, salinity, or acidification. These are the effects of landscape position, land use and rainfall rather than soil type and so allow interpolation and extrapolation to broad areas from specific instances. Reporting of sustainability indicators at these scales is used for political and economic purposes, providing information for broad considerations in land protection strategies such as decisions about allocation of funds for research or for on ground works. The reliability of such assessments depends on the density and quality of data collected at larger scales. These data may be opinions expressed by experienced field agronomists or conservation staff, questionnaire results from land holder surveys, extrapolation of detailed field research to larger areas, or mapped attributes collected by extensive field survey. The theme of this symposium that "soil quality is in the hands of the land manager" is also scale dependent. At regional scales the land manager is the funding agency or policy making body (e.g. government department, catchment management board) - soil quality is in the hands of these groups because of the priorities given, or not given, to soil management.

Pedological indicators at the paddock/polypedon/pedon scale

Ultimately, the land manager as primary producer is the person most in contact with the soil and land in its varied states, and is most affected by the response of the soil to management practices. While soil is certainly in the hands of these land managers, soil quality will only be in their hands if they have the tools and training to recognise, and respond to, adverse soil changes. Consequently, the path to soil quality assessment must include increasing the interpretive abilities of the land manager. This is most appropriate at the paddock/management unit scale (polypedon) and must entail the interaction of pedologists, agronomists and land managers. The application of indicators of soil quality at the paddock/management unit scale requires the following: (i) an appreciation of inherent soil quality, (ii) the choice of indicators appropriate to soil type and landscape position, and (iii) an understanding of the natural range of values for the selected indicator/s.

Table 2. Classification of soil morphological variables according to type of data collected and sensitivity of the variables to change during the lifetime of the land manager.

†	Type of data	Parameter	Sensitivity during lifetime of manager
20	Ordinal	Abundance of coarse macropores (>2mm)	Changeable, tillage, compaction, animals
19	Ordinal	Abundance of fine macropores (<2mm)	Changeable, tillage, compaction, animals
26	Nominal & ordinal	Condition of dry surface soil	Changeable (crusts, hard setting, erosion)
3	Ratio	Depth of horizon	Changeable in A horizons
42	Ordinal	Horizon boundary (distinctness)	Changeable at A/B and Ap/A2
43	Nominal	Horizon boundary (shape)	Changeable at A/B and Ap/A2
2	Nominal	Horizon suffix	Changeable, A1 to Ap, A2 to A2g
6	Ordinal	Mottle abundance	Changeable, waterlogging/gleying
10	Ordinal	Mottle boundaries	Changeable, waterlogging/gleying
9	Nominal	Mottle colour	Changeable, waterlogging/gleying
8	Ordinal	Mottle contrast	Changeable, waterlogging/gleying
7	Ordinal	Mottle size	Changeable, waterlogging/gleying
5	Interval	Munsell Colour (Value/chroma)	Changeable, loss of OM, gleying
4	Nominal	Colour (Hue)	Relatively fixed (less sensitive than V/C)
30	Ordinal	Pans (continuity)	Changeable
31	Nominal	Pans (structure)	Changeable
29	Nominal	Pans (type)	Changeable
39	Interval	pH	Changeable
41	Ordinal	Root abundance	Changeable Species dependent
40	Ordinal	Root size	Changeable Species dependent
13	Ordinal	Size of peds	Changeable, tillage
44	Ordinal (or ratio)	Soil permeability	Changeable in A horizon
23	Ordinal	Stickiness	Increases with loss of OM
14	Nominal	Type of peds	Changeable, compaction
12	Nominal	Pedality	Only slightly changeable
21	Ordinal	Soil water status	Always changing
38	Ordinal	Carbonate effervescence	Relatively fixed but may decrease with leaching of irrigated soil high in CaCO3
22	Ordinal	Consistence (air dry strength)	Relatively fixed, changeable (hard setting)
32	Ordinal	Pedogenic segregations (abundance)	Relatively fixed but may accumulate, e.g. irrigation of soil high in soluble $CaCO_3$
34	Nominal	Pedogenic segregations (form)	As for 32
37	Nominal	Pedogenic segregations (magnetism)	Relatively fixed, but increases with fire
33	Nominal	Pedogenic segregations (nature)	As for 32
35	Ordinal	Pedogenic segregations (size)	As for 32
36	Ordinal	Pedogenic segregations (strength)	As for 32
45	Ordinal	Soil drainage	Relatively fixed
27	Ordinal	Water repellence	Relatively fixed but changeable
17	Ordinal	Cutans (abundance)	Long term, fixed
18	Ordinal	Cutans (distinctness)	Long term, fixed
16	Nominal	Cutans (type)	Long term, fixed
15	Nominal	Fabric	Long term, fixed
11	Ordinal (Ratio)	Field texture	Long term, fixed
1	Nominal	Master horizon	Long term, fixed
28	Ordinal	Pans (cementation)	Long term, fixed
25	Ordinal	Plasticity (degree)	Long term, fixed
24	Ordinal	Plasticity (type)	Long term, fixed

† Represents order of appearance in McDonald *et al* (1990)

Attributes commonly recorded in soil description at the pedon scale (McDonald *et al*, 1990) are shown in Table 2. These have been grouped to approximate their sensitivity to change during the lifetime of a land manager. Those identified as 'long term, fixed' attributes are also changeable, but changes are unlikely within generation spans of land managers. The type of data collected have been identified as (i) nominal, where data are simply named and put into non quantitative classes, e.g. horizon designations, (ii) ordinal, where data can be ranked as more or less in semi-quantitative classes, e.g. air dry consistency, (iii) interval, where data can be quantified in terms of equal intervals on a scale having no zero, or only a relative zero, e.g. Munsell colour, or (iii) ratio, where data can be quantified in relation to a true zero, e.g. horizon thickness. Most pedological attributes are recorded in a qualitative (nominal), or semi quantitative (ordinal), way. Such data are easily obtainable but are useful as indicators only when gross differences exist between the condition of a parameter prior to, and following a period of management. Inherent high variability of these properties, even within a relatively pure soil mapping unit (Wilding and Drees, 1983), means that there is unlikely to be any improvement in assessment of soil quality by finding more precise quantitative methods for most field observed pedological attributes.

Most favoured indicators

Indicators that can be readily applied by land holders must fit the criteria of Casley and Kumar (1987) and be easily interpretable. Table 3 sets out suggestions for the most appropriate pedological indicators of soil quality that could be adopted by the trained land manager at the management unit level, i.e. paddock. All of the suggested indicators also have appropriate responses at the management level that can be made in order to modify soil quality but there is no place in this paper to detail these. Similar indicators have been used in a soil diagnostic key for waterlogging and salinity in a South Australian catchment (Fitzpatrick *et al.*, 1994).

Table 3. Indicators, observations and their significance: the most useable indicators of soil quality at the pedon and polypedon, or management unit scales.

Indicators	Observations	Processes or functions affected
Surface Features	Thin surface crusts, surface seals, smears with cracks	Soil structure decline (topsoil)
	Stoniness, Pedestals, Rills.	Soil loss (incipient topsoil losses)
	Fence line deposition, material washed onto roads.	Soil and nutrient loss
	Prolonged ponding of water after rain or irrigation	Soil structure decline (topsoil or subsoil)
	Pugging damage, vehicle wheel sinkage.	Waterlogging, soil structure decline
	Bare soil (no plant cover or litter)	Organic matter decline in topsoil. Runoff.
	Bare wet soil, death of preferred plant species, oily films in surface water discharge, salt efflorescence when dry	Mobilisation and accumulation of salt, development of dryland salinity.
Roots and Pores	Number and depth of roots	How well the soil space is being used.
	Root occupation of visible pores (biopores and fissures)	Water use, nutrient cycling, recharge.
	Frequency of visible pores (by horizons)	Drainage and aeration.
Horizon Boundary	Connectivity of pores between horizons, pans.	Root growth, drainage, aeration (whole pedon)
Soil Consistence	Air dry strength of soil - allocation to ordinal class in the range rigid to loose. (A surrogate for texture but also affected by other factors, e.g. organic matter, sodicity)	Root growth, water movement, tilth development
Aggregate Stability	Aggregate behaviour (each horizon) in pure water: swelling, slaking, dispersion (Emerson test).	Soil structure decline: development of seals and crusts. Infiltration, aeration, drainage. Shoot emergence.
EC, pH	1:5 soil:water suspension (pH also in $CaCl_2$)	Salinisation, acidification
Colour	High value/ Low Chroma (Munsell), mottling, rusty linings in root channels.	Waterlogging, drainage and aeration Iron mobilisation, accumulation and removal
Bulk Density	Direct measurement, core method or volume replacement. Calculate relative compaction, total pore space, air filled porosity at field capacity.	Soil aeration and drainage, root penetration

Conclusion

A suite of indicators appropriate at the pedon and polypedon scale has been proposed. The interpretation of these indicators is not equally applicable to all soils and should also be made in the context of the soil landscape (catena and catchment scale) processes. Sensitivity of indicators requires evaluation across a range of soils and production systems. Ideally, soil quality monitoring should be carried out by the landholder. Soil scientists and land management groups must work closely to test the above indicators, and to develop appropriate programs for soil quality monitoring.

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Biological aspects of soil quality: functioning of soil in the transformation and storage of energy

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Introduction

All human agriculture involves some input of energy that can influence soil quality. Examples range from low energy methods involving tillage and harvesting of land by humans and domestic animals; through to high energy systems using tractors and agrichemicals. For any agricultural system to be sustainable requires that soil quality be maintained with a balance between total energy input and output.

Modern agricultural systems are "open" systems, they are not self-contained entities but exchange energy with their surroundings (Addiscott, 1995). We export most produce off the farm, and rely on many off-farm inputs for production and to maintain soil quality. The operation may be cash profitable, but in energy terms may be out of balance. For example, electricity produced in Britain in the 1970s, required an energy input of 3.63 GJ for every 1 GJ of electricity generated (Tatchell, 1976). The generating operation was cash profitable because the input energy (mainly coal, oil and gas) only incurred costs of extraction and distribution. However, in terms of *energy* balances, the stored sunlight in fossil fuel was greatly undervalued.

Ecological energetics and thermodynamics.

Ecologists have for many years used energy flows and contents as a unifying way to compare diverse ecosystems (e.g. Phillipson, 1966; Weigert, 1976). For biological systems the energy inputs, contents and flows can conveniently be expressed in terms of "radiant energy" or in "heat equivalents". These units of energy are inter-related so heat equivalents, radiant energy, and units of work can all be expressed in common units. The basic SI unit is the Joule (J), equivalent to 4.217 calories. A closely related unit is the Watt (W), the amount of energy expended when 1 J is sustained for one second ($W = J\ s^{-1}$).

Diverse ecosystems can be compared using thermodynamics. The energy equivalent of a topsoil can be compared with a tree; a lake ecosystem with a forest, a cow, or a gallon of petrol. The unifying concept is that energy can neither be created nor destroyed, but only changed in form. Thus the energy in sunlight can be converted to fixed energy in grass, and the energy in grass to a cow, and so on. The energy forms, losses and conversions at each stage can be measured.

Entropy and energy storage in soils

Entropy is a measure of the order existing in the universe. It formalises the common observation that, given time, disorder increases and everything will fall apart. Systems that exchange energy with their surroundings ("open" systems), tend towards maximum entropy (disorder). The fact that order *does* exist on our planet reflects the temporary order resulting from energy inputs. These inputs, sometimes over many thousands of years, have formed the minerals, organic and inorganic chemicals, and living organisms that establish the intrinsic quality of a soil (Addiscott, 1995). To maintain or alter this intrinsic level of quality requires a continued input of energy. For our own solar system all energy is ultimately derived from the sun and geothermal sources. Our sun contains energy for another 5000 million years (Hawking, 1988), and in the present context, can be considered infinite.

Energy inputs to soil

The biological condition and quality of our present day soils reflects the major energy inputs over the last few thousands of years. For this paper I shall consider only a few examples of recent biological inputs to soil and to how they relate to soil quality. There are many other non-biological aspects of energy storage in soil such as heat and water storage. This heat and water storage is of great importance in regulating soil temperatures and biological activity. Other more complex energy attributes such as the physical aggregation or strength of soil (North, 1976) also greatly influence soil quality. Biological organisation such as in the genetical diversity of soil organisms is also a relevant component of soil quality, but is beyond the scope of this paper.

Soil as a biological energy store

A useful concept is to consider soil as a battery that has been slowly charged up to a maximum capacity. Soil under any climax ecosystem represents a considerable energy store. A typical soil profile contains stratified soil horizons of differing textures, organic and chemical characteristics, along with a complex of weathered minerals, accumulated organic materials and living organisms. These characteristics represent *order*. They are the end result of energy inputs by wind or water transport, biological evolution, chemical and biological weathering and mineralisation and biological fixation of carbon dioxide and nitrogen gas. On a local scale, these processes *decrease* global entropy because they *increase* order in organising "random" molecules into more complex organic molecules (Addiscott, 1995).

Soil organic matter is the basic resource for microbial activity in soil. Biological activity is also necessary to *create* organic matter. Energy must be accumulated in the form of plant and animal matter and be incorporated into soil by decomposition processes (Allison, 1973; Carter and Gregorich, 1996). If we deplete this accumulated (historical) organic matter stock and decrease soil quality, then we must rely on current biological processes for restoration. To pursue the "soil battery" analogy, if we discharge the battery, we either have to import energy from an additional source, or wait for the battery to recharge by natural processes. In the context of our own planet, the energy has to come from somewhere - either stored sunlight (oil, coal, hydro) or contemporary sunlight (heat, wind, solar).

Discharging the battery

The utilisation of soils for agriculture can cause a rapid decline in quality and organic matter content. The "global experience" is that initial clearance of climax vegetation for agriculture results in a decline in soil organic matter (Ayanaba *et al.*, 1976; Voroney *et al.*, 1981; Lal, 1986; Ellert and Gregorich, 1995; Gregorich and Janzen, 1996). This is because soil disturbance causes increased mineralisation and the organic C returned to the soil from the cultivated crop is frequently less than under climax vegetation. Retention and enhancement of soil organic matter has been identified as a major objective to maintain soil quality in virtually all countries of the world (Allison, 1973; Mulongoy and Merckx, 1993; Doran, 1996: Gregorich *et al.*, 1994).

Replacing soil organic matter

It has proved very difficult to restore organic matter once it has been lost. In New Zealand some soils in Central Otago have declined in quality due to poor stock control and rabbit infestations. Soil organic C has dropped from 3% to 2% over 10-25 years. This drop reflects a loss of about 30 Mg of organic C per ha in the top 23 cm of soil. The C input required to restore the soils was examined by Parshotam and Hewitt (1995), using the Rothamsted organic matter model. This model has been successful in simulating longer-term organic matter dynamics in both temperate and tropical ecosystems, and to predict changes in organic matter contents under differing management (Jenkinson and Rayner, 1977; Addiscott, 1995) . The results, validated against long-term field trials, show that organic matter contents take many decades to stabilise (Jenkinson and Rayner, 1977; Jenkinson *et al.*, 1987; Whitmore, 1993). To replace that organic C lost in the Otago study requires an input of at least 1.8 Mg C/ha/year for nearly 50 years (Parshotam and Hewitt, 1995). This long-term input represents a huge recharging of the soil battery, equivalent to nearly 90 Mg of plant C with an energy content of around 3.4 TJ. This amount of energy is equivalent to some 100,000 litres of petrol, enough to drive car around the world about seventeen times. For tropical soils, with a higher rate of turnover, Whitmore (1993) estimated that annual organic inputs of at least 2.5 Mg C/ha were required just to maintain soil organic matter contents in Nigeria. The very large amounts of plant input are required because as a "rule of thumb" only about 10% of the input is incorporated into soil organic matter, the remainder is mineralised within 1-2 years (Jenkinson and Rayner, 1977; Whitmore, 1993). The mineralised proportion is essential for the supply of nutrients to plants, but the stable humus fraction forms the basis of the longer-term nutrient and physical reserves of the soil. The amount becoming stabilised in soil will depend on how quickly the 10% or so becoming incorporated into soil is subsequently decomposed. Rates of decomposition depend upon the organic matter composition, soil type, and the temperature and moisture regime. However, in the longer time scale, the plant materials themselves have little influence, with the energy content of different plants being remarkably uniform (Table 1). This means that recharging the soil store of organic matter depends mostly on the productivity, rather than the composition, of the plant species. Productivity is generally dependent on climate and soil types, in terms of utilising the total energy available for photosynthesis plants all have low efficiency, typically 1-5% (Table 2).

Table 1. Energy contents of dominant vegetation communities

Vegetation	kJ g^{-1} dry matter
Mangrove	15.7
Tropical rainforest	16.3
Spartina marsh	17.0

Herb oldfield	17.5
Pinus sylvestris	20.0

Adapted from Golley (1976)

Table 2. Photosynthetic efficiency (production as a percentage of net radiation) of various plant communities

Plant	Location	Days in leaf	Efficiency (%)
Scots pine	Britain	360	2.2 - 2.6
Sugar cane	Java	360	1.9
Beech	Denmark	164	2.5
Rice	Japan	150	2.2

Soil as a nutrient store

In natural ecosystems plant requirements for nutrients such as N, S, P and trace elements are met wholly or in part by mineralisation of organic matter (Allison, 1973). The nutrients accumulated in soil organic matter represent a massive nutrient reserve. A soil with 1% organic C in the top 0-10 cm will contain about 1200 kg of organic N per ha. This N has been accumulated almost entirely by biological nitrogen fixation and incorporated into the soil organic reserve by subsequent decomposition by soil microorganisms. Biological processes also mineralise the organic reserves to plant-available inorganic forms. Over one year, some 1-5% of the organic N will typically mineralise, so a soil with 1200 kg N will provide around 50 kg inorganic N/ha. In a wheat-legume rotation in Australia about one third to one half of the annual nitrogen requirement of a cereal crop is met from organic matter reserves (Angus, 1992) To maintain production where yields are N limited, any depletion of the N reserve will need to be substituted by fertiliser.

Is it more efficient to rely on nitrogen fixation by legumes utilising "free" sunlight, or to supply nitrogen to crops by applying nitrogen fertilisers? The energy requirements to "fix" atmospheric N by legumes has been estimated to be around 190-270 MJ/kgN (Pate, 1983), whereas that needed to make urea fertiliser is around 78 MJ/kgN (Tatchell, 1976). An immediate reaction is to conclude that fertiliser N is more efficient than legume N. However, no energy costs of distribution are included, which can very often exceed the cost of manufacturing the fertiliser. Legume N is already *in situ* and needs no further distribution, but also incurs additional costs in production (e.g. initial sowing, weed control).. It is difficult to assess the relative benefits from the two sources. The widescale adoption of wheat-legume rotations in Australia indicates that farmers consider the legume to be preferable to fertiliser. In an examination of the economic benefits of legumes in Western Australian wheat-legume rotations, Panell and Falconer (1988) concluded that legumes were superior to fertiliser, but that the greatest benefit from legumes was derived from disease break rather than N nutrition.

Monitoring for soil quality

Monitoring for soil quality should include some measures of the stored energy in soil - particularly the organic matter resources and the microbial processes that accumulate and release these resources. Several authors have shown the more biologically active soil organic matter components such as light fraction organic matter, particulate organic matter, and the soil microbial biomass to be more sensitive to land use changes than total organic matter measurements (Powlson *et al*., 1987; Sparling, 1992; Ellert and Gregorich, 1995). For broad ranging surveys of soil quality, the simple and most cost effective methods are those more likely to be adopted. Some examples of basic indices currently being trialed in New Zealand are given in Table 3. The individual measures are simple, interpretation is more problematic. Land managers are searching for a "single number" to give them an indication of soil quality and sustainability. Currently, we cannot provide this advice. For example, no absolute organic matter content can be specified to represent "good" or "bad" quality; all soils differ and quality concepts change with differing land use. Organic matter levels looked upon with alarm in New Zealand would be welcomed in many parts of Australia. Quality standards need to be specified for particular soil types and regional characteristics. The rates of change of quality parameters (Larson and Pierce, 1994), rather than absolute values, are likely to be of greater use in monitoring soils. The expression of results on a volumetric, rather than a weight basis is also essential for valid comparisons. Table 4 shows how opposite trends in organic matter and mineralisable N status could be concluded by expressing the data on a weight, rather than volumetric basis.

Table 3. Chemical and biological indices currently being trialed in New Zealand to monitor soil quality

Measure	Information
Total organic C	Organic matter status
Microbial biomass C	Readily mineralised organic C

Soil respiration	Overall soil microbial activity
Total soil N	Soil N reserves
Potentially mineralisable N	Estimate of plant available N
Soil pH	Soil acidity or alkalinity

Results are combined with soil physical data: bulk density, non-saturated hydraulic conductivity, moisture release characteristics, particle size analyses, and expressed on a volumetric basis.

Table 4. Trends in organic C content and mineralisable N under native Kahikatea forest and adjacent ryegrass-clover pasture when expressed on a weight or volumetric basis.

Land use	Expressed by weight		Expressed by volume		Bulk density (g/cm^3)
	C content (mg/g)	Min-N (µg/g)	C content (mg/g)	Min-N (µg/g)	
Forest	266	310	86.5	101	0.33
Grazed forest	284	292	125	129	0.44
Pasture	205	236	145	167	0.71

From Sparling (unpublished data).

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Soil Quality: Chemical Aspects

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Introduction

Soil quality can be defined as "the capacity of a soil to sustain biological production, maintain environmental quality, and promote plant and animal health" (Cameron, 1995).Implicit in this definition are the factors of productivity, sustainability, and minimal impact on the "downstream" environment. It is convenient to categorise soil quality into chemical, physical and biological components. However, this reductionist approach is for convenience only, as soil quality requires an holistic approach, and it is not possible to consider one component of quality in isolation. With this in mind, we will concentrate on the chemical aspects of soil quality in this paper.

Functions In The Assessment Of Soil Chemical Quality

The soil chemical component of quality relates to how the soil fulfils the following functions: (a) storage and gradual release of nutrients, (b) buffering of habitat against rapid changes of potentially toxic materials, and (c) recycling of organic materials in soils to release nutrients for further synthesis into new organic materials (Warkentin, 1995).Note that each of these functions deals with nutrient or toxic element supply to the soil solution, which is the ultimate source of these elements to the plant root.

Nutrient supply can be encapsulated in the Quantity-Intensity concept (Schofield, 1955).This concept recognises three supply attributes: quantity, intensity and buffer capacity. Quantity is the potential amount of nutrient available for uptake during the growth period of the plant. Intensity is the activity (or, in the simpler sense, concentration) of the nutrient in the soil solution at a particular time. Buffer capacity is the change in quantity brought about by a unit change in intensity. Function (a) above is fulfilled by maintaining an optimum intensity of the nutrient in the soil solution, whereas function (b) requires a low intensity of the toxic element in the soil solution. Both these functions are best served by a soil with a high buffer capacity. Function (c) depends on a high content of mineralisable organic matter and an effective microbial population to ensure a continuous supply of nutrient to the soil solution for incorporation into microbial or plant cells.

The minimum data set required for assessment of soil chemical quality therefore requires measurements of the attributes of quantity, intensity, and buffer capacity (although if two of these are measured, the other can be inferred) as they apply to nutrients and toxic substances. Table, summarises the relative magnitudes of these attributes if the soil is to fulfil the functions of chemical quality adequately.

Table 1. Relative magnitudes of nutrient supply attributes necessary to fulfil soil quality functions.

Function	*Attribute*	*Magnitude*
(a)Nutrient release	Quantity	High
	Intensity	Optimum
	Buffer Capacity	High
(b)Buffering of toxic substances	Quantity	Low
	Intensity	Low
	Buffer Capacity	High
(c)Nutrient recycling	Quantity	High
	Intensity	High
	Buffer Capacity	High

Minimum Data Set For Assessment Of Soil Chemical Quality

Nutrient supply

Although the availability of all the essential nutrients can be described in terms of quantity, intensity and buffer capacity, different processes govern these attributes for different nutrients. These processes can be mainly microbially-driven [as for nitrogen (N)], or thermodynamically-driven [as for phosphorus (P) and the cationic macronutrients].Whereas intensity can be interpreted as the activity of nitrate plus ammonium in the soil solution for N, and the activity of orthophosphate in the soil solution for P, the interpretation of quantity and buffer capacity of these nutrients is not as unequivocal. Quantity of N is the potential amount of organic N which can be mineralised during the growing season. Quantity of P is the amount of P adsorbed on surfaces which is capable of desorbing into the soil solution in response to a lowering of the activity of orthophosphate in the soil solution due to plant uptake. Apart from an adequate quantity of organic N being present for potential mineralisation, other conditions must be satisfied for a soil to supply sufficient N during the crop cycle. Loss processes of volatilisation and denitrification must be minimal, the organic matter must have a low C/N ratio to prevent immobilisation, and must be of a chemical composition which is amenable to microbial decomposition. These last two factors can be thought of as the buffer capacity term for N. To supply sufficient P, the soil requires a large pool of surface-adsorbed P which is readily released into the soil solution. To supply sufficient cationic macronutrients, the activity ratio of each cation (i.e. activity of the cation/ sum of the activities of all cations in the soil solution) must be optimal, and there must be a sufficient quantity of the cation on the exchange complex (or in soluble soil minerals) to supply the quantity of nutrient required.

It is apparent from the above that to assess the ability of a soil to adequately supply each nutrient, different soil chemical analyses will be required; there is no universal soil test capable of assessing the ability of the soil to “store and gradually release nutrients.” The sufficiency, or otherwise, of each nutrient will need to be assessed individually, an impractical proposition for defining chemical quality. However, if the assumption is made that any nutrient deficiencies can be corrected by application of the appropriate rate of fertiliser, the scenario for defining this aspect of soil chemical quality becomes more simple. In effect, fertiliser application takes care of the quantity factor, and it is the buffer capacity factor that then decides the relative quality of the soil. But buffer capacity can have contradictory effects on soil quality. If there is sufficient quantity of the nutrient already present in the soil, then the ideal is a soil of high buffer capacity, i.e. the soil can maintain the activity of the nutrient in the soil solution despite continued plant uptake. However, if there is insufficient quantity of potentially available nutrient in the soil, then a soil with a high buffer capacity will require an inordinate amount of applied fertiliser if the optimum activity of the nutrient is to be attained. This is particularly relevant to P deficient soils of high buffer capacity such as Oxisols. The dilemma then becomes one of defining the optimum buffer capacity.

Defining quality with respect to nutrient release, therefore, cannot be achieved in a simple manner, and it is suggested that the best approximation is to assess soil quality based on indicators, which in a generalised sense, are related to nutrient buffer capacity. This approach is underpinned by the assumption that fertiliser of some kind will probably need to be applied even to soils which are assessed as fulfilling the nutrient release criterion of soil quality. The indicators which are most critical for nutrient buffer capacity are organic matter content (important for N, and to a lesser extent, P), clay content (important for P and cationic macronutrients), and pH. The latter indicator has ramifications for N in terms of the activity of the microbial population which mineralises the organic matter, for P in terms of the clay mineralogy which determines buffer capacity, and for the cationic macronutrients in terms of their likely saturation of the exchange complex, and consequently, their activity ratios in the soil solution.

Buffering of Toxic Substances

Excessively acidic, saline, sodic, mineralised and anthropogenically contaminated (generally with heavy metals or pesticides) soils are likely to have toxic effects on plant growth. The diagnosis of the first three limitations to plant growth is conveniently achieved by the use of the indicators of pH and electrical conductivity (EC), both of which are intensity measurements. Soil solution pH measures the activity of the hydrogen ion (and, by inference in mineral soils, aluminium activity), and diagnoses excessively acidic soils. Electrical conductivity is a measure of cumulative ion activity, and combined with pH, diagnoses saline and alkaline sodic soils. Remediation of acidic, saline, or sodic conditions is assisted by the soil having a low buffer capacity. Thus, a low pH buffer capacity means that only small additions of lime will be required to ameliorate aluminium or manganese toxicity in an excessively acidic soil. Buffer capacity with respect to pH is determined by organic matter content, clay content, and change in ECEC with change in pH (Aitken *et al.*, 1990).Likewise, a soil with a low cation buffer capacity (as reflected by a low ECEC) will require less gypsum for the correction of sodicity than one of high ECEC, because the extent of the cation exchange surfaces in the soil governs the size of the reservoir of exchangeable sodium.

Unless soil is from a recognised contaminated or mineralised site, it is unlikely to have a pre-existing heavy metal (cadmium, zinc, arsenic, chromium) toxicity problem, although there may be concern about the levels of Cd in soils with a long history of P fertiliser application (eg. horticultural soils).Soils in urban and peri-urban locations are increasingly being considered for use as recipients of heavy metal wastes, and where the soil is expected to fulfil this function, a high buffer capacity for the particular heavy metal/s is required. This enables large amounts of contaminants to be added to the soil without causing unacceptable increases in the concentration (i.e. the intensity) of the contaminant in the soil solution. As in the case of the other toxic conditions, the buffer capacity of the soil for the toxic element is the key factor in determining the quality of the soil. Buffer capacity with respect to heavy metals depends on the particular element, but soil pH, organic matter content, ECEC, and clay content can be considered to be the major factors (Alloway, 1990).

Pesticides are not natural components of soil systems so their dynamics in the soil chemical environment may be more complicated than those of nutrients or heavy metals. However, if their chemical properties are known, their behaviours in the soil can be inferred. There are some constraints on the direct measurement of these substances because of high analytical detection limits in soils, so the primary indicators of quality for pesticide effects may not be chemical (eg. restricted germination and rooting depth, or changes in soil microflora).

Nutrient Recycling

Nutrient recycling is the mineralisation of organic compounds from the soil organic matter or freshly added vegetative biomass (eg. leaf litter and decomposing roots).Apart from requiring a sufficient quantity of mineralisable organic compounds to meet the plant's needs, other preconditions must also be met. The organic material must have a low C/nutrient ratio, otherwise the mineralised nutrient will be incorporated into new microbial biomass. The chemical composition of the organic material is also important, as it has been shown that material high in polyphenolic compounds has a low breakdown rate (Palm and Sanchez, 1991).As it is impractical, from the viewpoint of soil quality assessment, to analyse the soil organic matter and likely organic input materials, we suggest that the most appropriate index for the function of nutrient cycling is organic C. This, at least, allows the potential for nutrient recycling to be assessed, bearing in mind the other factors which might contribute to low mineralisation rates.

Inferences From The Minimum Data Set

Several indicators suggested for a minimum data set are common to two or more of the functions of soil chemical quality (Table 2), and it is possible to use surrogate measurements to estimate both clay content and ECEC. Texture can be used as a field technique to infer clay content of soils except those that behave sub-plastically or thixotropically. Clay content and organic C can be combined to estimate ECEC, although the coefficients of these terms in the predictive equation will vary depending on clay mineralogy and the surface charge characteristics of the soil organic matter. Kaolinitic clays have a lower clay activity ratio (ECEC/clay content) than smectitic clays, and so a knowledge of the soil's mineralogy is required if ECEC is to be inferred from these two parameters.

Table 2. Minimum data set for the assessment of functions of soil chemical quality.

Function	*Minimum data set*

(a) Nutrient supply	pH, organic C, clay content, ECEC
(b) Buffering of toxic elements	pH, EC, organic C, clay content, ECEC
(c) Nutrient recycling	pH, organic C

Given values for the minimum data set measurements, several inferences can be drawn with respect to the ability of a soil to fulfil the functions of soil chemical quality. These inferences are indicated in Table 3.

Table 3. Inferences for soil quality assessment which can be drawn from the minimum data set.

Indicator	*Use for soil quality or process assessment*
a)pH	• acidity, alkalinity, alkaline sodicity status • cation status (plant nutrition) • pH dependent availability of nutrients (Fe, Mn, Zn, Co, B, Mo), toxic elements, and ionic pesticide/herbicide residues • anionic residues with a high pK_a accumulate in soil layers with high pH • influences mineralisation rate
b)ECEC	• a function of clay content and type, and organic matter • a measure of negative charge at existing soil pH • can indicate acidity or sodicity (exchangeable Al or Na, respectively) • exchangeable cation composition (type and amount) • buffering capacity for positively charged ions • usefulness improved by knowing soil pH
c)Organic C	• main source of variable charge properties (and therefore adsorption) in near-surface soils • source of complexing ligands • source of dissolved organic carbon • can infer total N from C/N ratios • relationships with soil structural condition and biological properties
d)Clay content	• can infer adsorption properties if mineralogy or ECEC and pH are known • can be used to predict soil colloid behaviour such as soil structural response to sodium • related to water holding capacity
e)EC	• use mainly relates to salinity, depending also on soil texture (clay content) and flocculation state of soil colloids • relates also to quality of irrigation water.

The Time Element In Soil Quality Assessment

At any point in time, the quality of a soil can be defined and compared with that of other soil types. In contrast to this static comparison, soil quality can also be monitored over time to determine whether a particular land management system (be it effluent disposal, crop rotation etc.) is causing the quality of the soil to degrade. Soil quality in this latter context requires discrimination of the temporal trends in different quality indicators from trends which are a consequence of the land management. To achieve this discrimination requires the application of statistical quality control which is best captured in control charts similar to those used for analytical methodology (Larson and Pierce, 1994).A minimum data set is defined, and control charts are constructed for each indicator of the set.

Separation of short term temporal changes from long term trends in the control charts allows assessment of a particular land management system; the long term trend of an indicator (either upwards or downwards) identifies whether that indicator in the minimum data set is aggrading or degrading. Since quality is composed of several indicators, some of which may be aggrading, while others are degrading, the overall assessment of the effects of the land management system on soil quality requires an integration of these trends. Pierce *et al*., (1983) calculated a normalised sufficiency for several indicators in the minimum data set, and then determined a productivity index (PI) based on the product of the sufficiencies of the individual indicators of soil quality. By comparing the PI's of several alternative land uses, it is possible to identify the systems which are improving, or degrading, soil quality.

The Profile Element In Soil Quality Assessment

Whereas consideration of changes in some minimum data set indicators can be restricted to the surface layer (0-10 cm, or depth of tillage), changes in other indicators must be considered on a whole of profile basis. For example, surface application of liming materials might ameliorate acidity in the zone of incorporation, leading to an improvement in the soil pH indicator. However, further down the profile, the management system may be causing accelerated acidification. Taken over the entire profile, soil pH is actually declining (i.e. this indicator is degrading).Similar considerations apply to the indicator of electrical conductivity because of the consequences of subsurface salinity on root growth and function. Furthermore, because pedogenesis leads to horizonation, it is possible that the variation in soil properties down the profile may offer a continuum which satisfies all soil quality functions, but at different depths. Thus, Barry *et al*., (1995) found that the buffer capacities for P and heavy metals of the horizons in an Alfisol varied widely, and whereas the highest P buffer capacity occurred in the B2 horizon (120-150 cm), the highest Cd buffer capacity occurred in the A11 and A12 horizons (0-25 cm).

Implications of Changes in Functions to Soil Quality

From the preceding discussion, it is evident that nutrient balance and buffer capacity are both fundamental to the maintenance of soil quality, and we have suggested a minimum data set of key indicators to quantify both these attributes. To verify the efficacy of these key indicators, it is instructive to consider the generalised factors which affect soil chemical quality, ensuring that each factor can be described by one or more of the key indicators (Table 4 in association with Table 3).

Of the factors considered in Table 4, redox status is not described by any of the suggested key indicators. Consideration needs to be given to the inclusion of redox potential (Eh) in the minimum data set. However, the inherent variability in this property, and the occurrence of microsites of low Eh in a soil which is oxic in an overall sense, mitigate against the usefulness of measuring Eh on the bulk soil.

Erosion is the other factor which requires additional measurements for its assessment. These measurements could range from visual ratings of land condition to chemical analysis of sediments, and expression of this nutrient loss as a proportion of the nutrient reserves of the soil *in situ.*

Table 4. Factors with direct effects on soil chemical quality.

Quality decrease		*Quality increase*	
Chemical Imbalance	Decreased Buffering	Chemical Balance	Increased Buffering
• acidification	• organic C loss	• maintain nutrient balance	• increase organic C
• nutrient	• erosion		• prevent erosion

imbalance • salinisation • sodification • toxic substance accumulation • reducing conditions	• pH changes • mineral weathering	• avoid toxic substances accumulation • manage redox status	• modify pH

Conclusion

From a consideration of the functions of soil chemical quality, it is evident that the attributes of buffer capacity and nutrient balance and supply are the main determinants which must be assessed. It therefore becomes necessary to derive a minimum data set which can be easily determined, and which reflects these attributes. We suggest the following indicators: soil pH, EC, clay content (or texture), organic C and ECEC. Much more development work is required if this minimum data set of indicators is to be applied to assess soil quality. In particular, the derivation of "sufficiency indices" for each indicator must take profile distribution and crop root distribution into account. However, the identification of the key indicators is the first step in this process, and we have demonstrated the ability of these key indicators to describe most of the generalised factors which affect soil chemical quality.

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Standardisation for soil quality attributes

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Introduction

In recent years there has been increasing concern about the quality of the soil and the soil's ability to perform a wide variety of functions. In the last two years within the United Kingdom this concern has been highlighted by the Royal Commission of Environmental Pollution, a body independent of government, who have been addressing the nature of soil, its use and abuse, and the information which we have and need about the soil if we are to use the soil sustainably. The report published in February 1996 (Royal Commission on Environmental Pollution, 1996) provides a benchmark in the focusing of concerns about the soil and its sustainable use. The Royal Commission's report addresses a wide range of soil uses and problems with particular emphasis on the sustainable use of soils, the identification of contaminated soils and their remediation, but perhaps most importantly for Soil Science and Soil Scientists it emphasises the important role of the soil in the context of many of our wide ranging land use and indeed broad environmental activities. The Report stresses that we must be aware of the way in which we use the soil but also of the often very wide range of uses which we expect the soil to satisfy. This has been broadly referred to as 'multifunctionality', and is I believe, a topic which must be considered in much greater detail because it would appear that this topic is often used with very little consideration of what true multifunctionality in a soil entails. It is a term which might be the ultimate, but rarely achievable goal, in soil use. Consideration of the extent to which we embrace the concept of multifunctionality in our evaluations of soil quality is an essential part of the process of deciding what properties should be identified and measured in order to make these evaluations. It is my belief, that when making evaluations of soil quality we must consider whether we are evaluating with respect to some multifunctional criteria or with respect to some much more specific criterion of use. In essence evaluations of soil quality must have as their first question:- 'Soil Quality for What?'

Throughout much of the twentieth Century there has been very little concern about Soil Quality. In part, this has been because we have had a resource which whilst not infinite has not, until recently been considered scarce. In addition, in contrast to the other key components of the environmental system, air and water, there are few immediate public perceptions that the quality of the soil is declining. With respect to air there has been public outcry when, as a result of pollution through the combustion of fossil fuels, the air quality is such that the population have suffered respiratory problems, and similarly with water, when the water has proved to be unfit for human consumption or the aquatic life has been killed, there has been publicly expressed concern. This 'visual' evidence for changes in air and water quality has lead to widescale public concern, and in many countries this has lead to 'health related' standards for air and water, on the basis of 'fit to breath' and 'fit to drink' criteria. With the soil there has been few such 'visual' indicators, perhaps the most widely observed by the general public is that of soil erosion, and in some cases this has possibly lead to an over emphasis on indicators of soil quality linked to erosion. A further problem with the soil is that these changes often take place gradually and it may be difficult to observe differences except over timescales of tens of years. For example, one soil quality indicator might be some measure of soil fertility, but how do we measure this and how do we separate the outcome of soil fertility in terms of crop yield from the normal variability which occurs from year to year because of climatic variability, the occurrence of pests and diseases, etc.? The current concern with soil quality has arisen from two broad sources, the concern with land that has been contaminated by what might be broadly described as our industrial and agricultural activities, the concern to view our land use activities in the long term, and in particular to assess whether these activities are sustainable (leaving aside the question of how sustainability is defined!). As illustrative material in this paper I shall use attempts to deal with methods for the evaluation of soil quality with particular emphasis on contaminated and potentially contaminated land.

Contaminated land and soil quality indicators

Addressing the problem of contaminated land has provided much of the focus for recent developments in the standardisation of methods of soil analysis for the assessment of Soil Quality and the setting of soil quality reference or indicator values. The setting of these standards has raised many problems, both for the soil scientists and for the legislators, in part these problems have arisen because the soil is such a diverse material consisting of varying proportions of mineral material, organic material, water and air (Shepherd *et al.*, 1992). The interactions between these materials are complex and the nature of these interactions must be considered in the development of reference values. It is important to be aware that constituents of the soil, either natural or added, will be 'held' to varying degrees depending upon these interrelationships, and as is illustrated below the value for a particular soil property may vary by a considerable degree depending upon the manner in which the soil is sampled, pre-treated and analysed. It is perhaps surprising that when indicator values are set and evaluations made against these values are used by the non-soil scientist, they may be unaware of the need to specify these important steps in the process from the soil in the field to a figure or set of figures on the sheet of paper! It is often the case that even where indicator or reference values are given for particular soil quality levels these are difficult to use because of the poor or incomplete definition of the methods to be used in the analysis of the soil. For example within the United Kingdom the Interdepartmental Committee on Redevelopment of Contaminated Land (ICRCL) of the Department of the Environment produced a set of 'Trigger Concentrations' in 1983 and revised in 1987 (ICRCL, 1987) which attempted to set 'action values' for potentially contaminated land. Table 1 presents a subset of these values for selected metals.

Table 1. UK Interdepartmental Committee on the Redevelopment of Contaminated Land - Selected Trigger Values (ICRCL, 1987)

Hazard to health	**Planned Use**	**Trigger Concentration (mg/kg air dried soil)**
Cadmium	Domestic gardens	3
	Playing fields, open spaces	15
Lead	Domestic gardens	500
	Playing fields, open spaces	1000
Chromium (total)	Domestic gardens	600
	Playing fields, open spaces	2000
Zinc	Any uses where plants are to be grown	130

Whilst this was an important step forward and set an important precedent in that it varied the 'trigger values' depending upon use, it raises many questions because no definition was given as to whether these values were 'totals' or 'available' nor as to the method which is to be used in their analysis. The general assumption has been that the values were for 'totals', but as many of you will know, and I shall raise below, the 'total' content of a particular metal in a soil is dependent upon the method of analysis amongst other things. It is possible to choose your analysis for a particular sample and present results for 'total content' which might cover a wide range of values.

The Netherlands produced a similar set of guidelines in 1983 (Moen, *et al.*, 1986; Moen, 1988) which provide a development on the concept of 'trigger concentrations'. These guidelines or 'Indicative Values for Soil Clean Up' are perhaps more widely known as A, B, C values and are based on the following:-

A = Reference Values
B = Indicative Value for further investigation
C = Indicative Value for clean up

Table 2. Netherlands Reference Values (1983) for selected metals (Moen *et al.*, 1986)

Metal	**A**	**B**	**C**
		(mg/kg) dry weight	
Chromium	100	250	800
Zinc	200	500	3000
Lead	50	150	600
Cadmium	1	5	20

Background values

The Dutch Indicative values raise a very important feature of any soil quality assessment, particularly when dealing with contaminated or potentially contaminated soil. What is the natural or background level? In searching through the literature it becomes apparent that there is very little information on the natural levels of many of the 'contaminants' under consideration. Whilst in the Netherlands with the relatively limited range of soils and soil parent materials it may be possible to specify with reasonable confidence the background levels, in may other countries or regions the variability in levels that occur naturally may be considerable, but often not available. The lack of such information makes an assessment of the degree or extent of contamination very difficult to evaluate. A recent study in Germany (Dinkelberg and Bachmann, 1995) has attempted to provide a summary of background levels of 'total values' for selected metals in relation to broad parent material types. This summary was based on a countrywide survey. Table 3 provides a selection of the values identified for four metals.

Table 3. Background values of selected inorganic pollutants in German soils (total concentrations mg/kg) (Dinkelberg and Bachmann, 1995)

Parent material	Cd	Cu	Pb	Zn
Sands	<0.3	13	40	51
Loess	<0.3	25	51	89
Glacial Till	<0.3	14	32	76
Clays	1.1	27	61	121
Basalt	0.8	71	49	168

These results show considerable variability across the five broad 'parent material' types, but it is interesting to note that only with respect to lead for soils on clay parent materials are the 'A' values of the Dutch Indicative Values exceeded.

The importance of specifying the method of analysis used and the need to specify appropriate methods

The two sets of 'indicator or trigger values' referred to above, and the background values have all referred to 'total values' for the particular metals under consideration. There is, however, a potentially serious problem when dealing with total values if the method of analysis is not specified. Table 4 presents the results of three analyses for 'total' levels of Lead, Zinc and Chromium in a single soil using three analytical methods. The different methods produce different 'total values' for each of the metals considered, and whilst Method B produces the highest value for all three metals considered the difference between the results from Method B and the other two analytical methods is relatively small for Lead and Zinc, but substantial for Chromium. Analysis of the total levels of Chromium vary by greater than 30 fold between the three methods.

Table 4. Comparison of three 'total' digestion methods for contaminated soil (Duncan *et al.*, 1995)

	Nitric-perchloric Method A (mg/kg)	**Nitric-perchloric Method B (mg/kg)**	**Nitric-hydrochloric (mg/kg)**
Lead	355	369	301
Zinc	402	406	382
Chromium	1700	6170	172

Nitric-perchloric acids Method A (0.25g soil, 8ml acid, 180°C for 1 h)
Nitric-perchloric acids Method B (0.25g soil, 8ml acid, 180°C for 3 h)
Nitric-hydrochloric acids (0.25g soil, 6ml acid, 120°C for 2 h)

Whilst these data illustrate the importance of clearly specifying the method of analysis when presenting results, it is perhaps more important to consider analysis in terms of the purpose to which the data are to be put. For example we might consider the following:-

Total dissolution e.g. geochemical prospecting

Pseudo-total dissolution (*aqua regia)* e.g. pollution studies

Selective extraction e.g. to determine mobility

Alternatively the selection of the method of analysis might be related to the pathways under consideration, for example we might consider:-

Nature of the Pathways

Relative importance of Pathways

These pathways are exceptionally diverse, but might include:-

Human Consumption a. *Direct ingestion of soil*

b. *Direct ingestion of plants grown in soil*

Damage to Buildings

Influence on crop growth

The appropriate analysis to provide information relevant for each of these pathways (and sub-pathways) is likely to be very different, this might lead us to consider the methods of analysis in relation to the processes and pathways under consideration. Important in this sequence is chemical speciation where we must address the **process** of identifying and quantifying the different species, forms or phases present in the soil, and the **description** of the amounts of these species, forms and phases. These species, forms and phases can be variously defined, for example; **functionally**, such as plant available species; **operationally,** such as *aqua regia* extractable species; or as specific chemical compound/oxidation states. Whenever we undertake analysis for soil quality assessment we must ask ourselves the question '**Do we know what to measure?**'

Soil quality for what?

As mentioned above there is much concern about the need to consider the function of the soil when assessing soil quality. In this context with Europe there is a suggestion that we should consider the use and quality of soils with respect to **multifunctionality** (Vetgers *et al*., 1988). In essence there appears to be a belief that the best quality soil is one which is capable of supporting a wide range of functions and that soil quality assessment should address this multifunctionality. If we are to endeavour to assess soils in this manner do we know what analytical procedures to use in this assessment. It is my belief that whilst multifunctionality has a strong appeal relatively little thought has been given to the complexity of its meaning, and almost no attention to how we might analyse the soil to assess its multifunctionality. Until these concepts are more fully elaborated it is impossible to identify the soil quality indicators which may be used to measure multifunctionality, and similarly it is impossible to develop standardised methods of analysis. Standardised methods of analysis must be related to the purpose to which the information is to be put.

Soil variability

A question which must be addressed in any assessment and measurement of soil quality is, 'what are the sources and magnitudes of variability?'. It is imperative that all users of soil quality information are aware that variability in the final tabulated results of the analysis of a soil may be contributed from a variety of sources. In broad terms this variability might be analytical or spatial:-

Analytical Variability - Sampling
- Method
- Laboratory

Spatial Variability - Natural
- Man Induced

The first of these may be addressed either through clear specification of protocols for sampling and laboratory methods, or the accreditation of laboratories and between laboratory quality control schemes (Griepink, 1993). Spatial variability is more difficult to deal with, but it is essential that users of soil information are aware that soils are inherently variable in their natural context and that frequently the activities of man will impose further patterns of variability on these natural patterns.

Recently, to address the quality of the laboratory and their methods of analysis, standard soil reference materials have been made available in Europe through the Bureau of Reference. Regrettably the materials available are limited in number, but three are now available:-

BCR 141 Calcareous Loam,
BCR 142 Sandy Loam
BCR 143 Sewage sludge amended soil

For each of these soils the *aqua regia* extractable Cd, Cr, Cu, Mn, Ni, Pb and Zn have been determined and certified (Vercouteri *et al*., 1995). The availability of these and a wider range of reference materials is an essential component in the development of standardised approaches to soil quality determinations.

Soil quality analysis and environment

An important question which must be addressed, when we are concerned with the potential environmental impact of particular soil components, is how we relate the results of our analytical procedures to the environmental context in which we find the soil (Bavinck *et al.*, 1988). We must consider whether we analyse the soil material under standard conditions (for example of pH and temperature) or under ambient conditions. The normal procedure in Soil Science is to choose standard conditions, but in taking this decision we must consider how the results are to be interpreted in the context of the ambient conditions.

Soil quality indicators

Due to the availability of information the focus of this paper has been with respect to the chemical analysis of soils, and indeed to date much of the analysis of soil quality has focused upon the presentation and interpretation of the results of soil chemical analysis. Soil chemical attributes are just one part of the soil system and there is a need to pay more attention to soil physical and biological conditions. In particular soil biological conditions may provide a more dynamic indicator of soil conditions, but we must ensure that we develop methods to analyse the biological conditions which are appropriate and further that we are able to interpret this information.

The stages in the evaluation of soil quality

The evaluation of Soil Quality is a complex and expensive process. Whilst analytical procedures are an important component of this process they only constitute one step. Although most attention has been paid to the analytical procedures it is essential that equal attention is given to the other steps in the process (Table 5), because failure to satisfactorily undertake anyone of these steps may invalidate the whole evaluation process.

Table 5. The Evaluation of Soil Quality from Field to Final Report

Step	Action
1	Site description and identification
2	Sampling protocol
3	Sample storage
4	Sample pre-treatment
5	Analysis
6	Interpretation
7	Presentation of results

International standardisation of soil quality

In the context of the increasing concern about the quality of the soil and the absence of reliable and comparable methods of analysing this quality, in 1985 the International Standardisation Organisation established a Technical Committee (ISO TC 190) to consider the development of standard analytical techniques (Hortensius and Nortcliff, 1991; Hortensius, 1993). This Technical Committee has a sub-committee structure (Table 6), which stresses the need to consider the full range of soil attributes in the assessment of soil quality including physical and biological properties, but also emphasises the need to consider the analysis of soil quality in a broader context than the laboratory analysis.

The technical committee have already produced a large number of standards, particularly in Sub-committees 3 and 4.

Table 6. ISO TC 190 Soil Quality - Sub-committee structure

SC1 Description and codification
SC2 Sampling
SC3 Chemical methods
SC4 Biological methods
SC5 Physical methods
SC6 Radiological methods (disbanded)
SC7 Soil and Land Evaluation (from 1995)

Conclusions

The evaluation of soil quality is an important activity which, I anticipate, will become of greater importance as we become more aware of the sensitivity of the soil to damage and the need to consider the sustainable use of soils (see for example the Royal Commission for Environmental Pollution, 1996). An important element of an evaluation of Soil Quality is the need for standard methods of analysis for the attributes. In the selection and use of these standard methods of analysis it is essential, however, that the methods of analysis are appropriate for the purpose to which they are being put. Furthermore, analyses and the results from these analyses must not be undertaken in the laboratory in isolation, they must be considered in the context of the environment in which the soil is found.

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Roots, soil, water, solutes, and sustainability

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Soil, for the purposes of this meeting, is what plants grow in. One of its most important attributes is that it buffers variations in water supply. The better it can absorb water when it rains and hold that water against drainage while remaining sufficiently well-aerated to support the normal metabolism of roots and the soil biota, the better is it able to support plant growth - especially in an environment marked by a very variable rainfall. The role of soil as a hydraulic buffer is much affected by the activity of roots in modifying the soil and influencing the flows of water through it. In accordance with the title of the symposium, I discuss the quality of soil in relation to water - and not only in relation to water, but also to the solutes whose distribution and carriage in moving water so strongly affect the quality of the land through their effects on the availability of water, dryland salinity, and acidification.

The term "quality" transcends science. It depends on the purpose to which we wish to put the land, and is therefore much more a social or an engineering notion than a scientific one. It depends on the time scale of our interest; the short term notion of profitability, in the agricultural context that pervades this meeting, gives way to the long term one of sustainability if we look several decades ahead. In nature, soil quality has little meaning: it is pointless to compare the 100 μm of soil that satisfies a lichen with the metres of soil that are needed to support the giant trees of the Australian wet sclerophyll forests. But studying the properties of natural ecosystems, before their conversion to agriculture, does helps clarify how we can go about preserving and improving the quality of agricultural land.

Salts and water in natural soils

There are clear effects of its texture, its wettability, and the depth of its horizons, on a soil's ability to accept and hold water, while maintaining the soil well-aerated. What is not so clear is the role of vegetation, both above ground and below, in modifying the soil's capacity to buffer the water supply, especially in a saline environment. In the semi-arid landscapes that characterise much of Australia, salts, predominantly sodium chloride, have accumulated to potentially toxic concentrations. These salts are toxic usually because of the osmotic effect that they exert, which can sharply reduce the availability of the soil water to plants. In natural ecosystems, interactions between roots and soil stabilise the location of these salts, so that they tend to be sequestered deep in the subsoil, which roots typically traverse through biopores or other continuous macropores such as fissures. During infiltration and redistribution of water after rain, the fresh water tends to flow in these pores that the roots occupy thereby creating niches that are much more favourable for root activity than is the bulk soil. Furthermore, many types of trees and shrubs channel rain down their stems to the top of the root system from where it flows into deeply penetrating macropores.

Australian subsoils are typically inhospitable to roots, not only because salinity is common but also because of widespread sodicity and high bulk densities which hinder the growth of roots and reduce the ability of the soil to store water. Niches that favour root activity in these subsoils are therefore especially important. Two well-documented examples of such niches at work come from Western Australia, one in the jarrah forests, and one in the mallee.

Johnston *et al*., (1983) explored the hydrology under jarrah forests on lateritic soil profiles. They showed that large pores containing coarse material penetrated the fine-textured pallid zone, that these pores were occupied (and presumably formed) by roots, and that they penetrated as far as a deep aquifer. In winter, perched water tables develop on top of the poorly permeable subsoil, and water flows from these through the large vertical channels into the deep aquifer. In summer the roots are able to maintain a water supply to the trees by extracting water from the deep aquifer.

Nulsen *et al*., (1986) showed the remarkable influence of mallee roots on the flow of water. About a third of the rainfall intercepted by the foliage was channelled to the base of the stem where it was guided by roots occupying continuous large macropores deep into the soil profile. They used dye to trace the movement of the water, which appeared deep in the profile associated with roots channels. They revisited the site of these observations a few years after it was cleared of the native vegetation and sown to improved pasture. Preferential flow in macropores had disappeared; dye applied to the surface remained in the topsoil after rain.

Agricultural land

In Australian agricultural systems, especially those in the semiarid "wheat-sheep" zone and the adjacent "high-rainfall" zone, the landscape has been much disturbed by the clearing of perennial vegetation and its replacement with annual crops and pastures. Some of the pasture include perennial species, but these are not as deep-rooted as the original vegetation and furthermore they tend to be dormant in summer. The hydrologic consequences of these changes have been profound. Water that enters the soil during substantially long periods when rainfall exceeds evaporation is prone to drain beyond the reach of the shallow-rooted crops and pastures. In so doing it carries with it salts that together with the water may accumulate in lower parts of the landscape where they manifest themselves as secondary salinity.

This drainage water typically contains nitrates that have also escaped the root system; the agricultural lands are much richer in nitrogen than the undisturbed ones that they replaced, because of nitrogen fertilisers and because of much-enhanced nitrogen fixation. These nitrates carry with them nutrient cations such as potassium and calcium, which tend to be replaced on the cation exchange complexes of the soil by acidic cations such as aluminium. Acidification of the soil thus accompanies the loss of the nutrient cations. This process occurs in cropped land mainly in the autumn, when mineralisation and nitrification occur faster than roots can sequester the nitrate. But in grazed pastures, acidification may occur throughout the year: under the abundant urine patches generated by the high stocking rates made possible with improved pastures, acidification occurs whenever nitrification in the patches is followed by leaching (Black, 1993). Black has calculated that at moderate to high stocking rates most of the soil surface will have received at least one dose of urine after about ten years of grazing.

The very variable nature of Australian rainfall means that undesirable drainage events are episodic. In most years wetting fronts may not penetrate beyond the reach of the roots of annual crops or pastures. In those years, the buffering properties of the soil in relation to water may be of little concern. The plants get all the water that is available, apart from losses by direct evaporation from the soil surface. It is during a run of wet years that substantial amounts of water escape the roots, leading to local recharge. Thus it is appropriate to look for episodic solutions to these hydrologic problems.

Sustainability: solutions and indicators

In coping with the twin maladies of secondary salinity and acidification that arise from disturbed hydrology, it is evident that we have to reestablish, at appropriate scales of time and space, the hydrologic pattern that preceded clearing. The return of deep-rooted perennials to the agricultural landscape is essential. But, given the episodic nature of the problem, it does not necessarily follow that these perennials must be trees. Trees are likely to be effective only when they occupy a large proportion of currently, albeit unsustainably, productive land, and they therefore threaten the short to medium term economic sustainability of the farming systems used on that land. Where the tree roots do not colonise the whole of the deep subsoil, water may still escape in large enough amount to destabilise the salts. The lateral flow of water to the deep roots of perennials will rarely exceed a metre - that is, the essentially vertical streamlines of the draining water will not deviate far in response to lateral gradients in soil water suction induced by the roots. The interception of the draining water by tree roots will, therefore, barely exceed the vertically projected area of their root systems. Nevertheless, trees may be a suitable option where the water table has come close to the surface. Then the lateral influence of the tree roots would be very much greater than in the vadose zone, for water could flow rapidly within the saturated zone towards the trees' roots. Even then, a large area of land would still have to be put under the trees, because of their inability to lift their transpiration rates to very high levels, exceeding say, 10 mm per day over the projected areas of their canopies. A further complication for this possible solution is that if the groundwater is brackish, the root zone of the trees will eventually become highly saline as the trees remove the water, but not the solutes, thereby leading to the trees' demise.

A better solution than trees, at least in principle, and especially for the vadose zone, is to make use of very deep rooted perennial plants such as lucerne that can operate intermittently, but nonetheless effectively, in stabilising the hydrology. Such perennials could, through tactical use, catch all of the water and nutrients that escaped the roots of a succession of annual crop plants and which may have accumulated in, say, the second and third meters of the soil profile. Once they had dried out the deep profile, a phase of cropping would again be in order, and perhaps even essential, for the perennials would have exhausted their deep water supply.

Such a system of alternating annual and deeply rooted perennial vegetation will work at its best when the collection of continuous macropores that roots occupy in the subsoil is in good shape. The more effective the roots of the annuals in collecting water and nutrients from the subsoil, the better their performance is likely to be, both economically and hydrologically, and the less frequent the necessity to implement the perennial phase. We know very little about the properties of these pores that roots preferentially occupy. We do know that tap rooted perennials, such as lucerne and skeleton and other weeds, can create them. We do know that cultivation disrupts them, making it hard for roots to locate them, and we do know that when roots find them they are able to penetrate much more deeply into the subsoil. But we know almost nothing about their physics, chemistry, and microbiology, which collectively determines their worth as niches in an otherwise adverse environment. How we manage this system of macropores will critically determine the long term health of the land.

The essential and primary indicator of sustainability in the context of these interactions between water, solutes, soil, and plants, is that the local recharge in agricultural lands must be held, at a time scale of about a decade, close to what it was before the native vegetation was cleared. We have, as yet, no reliable means of assessing this indicator. The best surrogate for it may well be the soil water suction at a depth of 2m. At suctions greater than about 3 atmospheres the hydraulic conductivity of soil is so low that drainage rates are acceptably low. Once the suction exceeded about 1 atmosphere it would be a sign that a deep-rooted perennial is called for.

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Structural aspects of soil quality

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Introduction

Context

Soil structure has a major influence on the ability of soil to support root development, to receive, store and transmit water, to cycle carbon and nutrients, and to resist soil erosion and the dispersal of chemicals. Land use practices which are sustainable must maintain the structure of soil, over the long term, in a state that is optimal for a range of processes related to crop production and environmental quality. This paper focuses on the quality of soil structure in the context of crop production.

Definitions

The term tilth is often used to describe the quality of soil structure and is a popular term that predates modern agriculture. The term soil tilth embodies an integration of many characteristics of soil structure and reflects the practical experience of generations of people who have worked the soil and their impression of the conditions that lead to greatest productivity and ease of management. This discussion will not refer to tilth directly, but will focus on measurable characteristics of soil structure that reflect elements of tilth.

Three different aspects of soil structure will be considered: form, stability and resiliency. The term structural form will be used to describe the heterogeneous arrangement, or architecture, of solid and void spaces that exist in soil at any given time. Structural stability will describe the ability of soil to retain its arrangement of solid and void space when exposed to different stresses whereas structural resiliency will describe the ability of soil to recover it's structural form through natural processes when the stresses are reduced or removed. Terms such as self-mulching and tilth mellowing have been used to describe specific aspects of resiliency.

Factors influencing soil structure

The dominant factors influencing the structural characteristics of soils are texture, clay mineralogy, composition of exchangeable ions and organic carbon content. Other factors influencing soil structure include management (e.g. tillage, traffic, cropping and irrigation practices), weather (e.g. the frequency and intensity of rainfall events, the rate and extent of soil drying, freezing/thawing events), and biological processes (e.g. root growth, burrowing by earthworms, microbiological activity). Few, if any, of the these factors function in isolation from other factors. For instance, the alteration of a soil structural characteristic by a wetting event depends on preceding drying conditions and the rate of wetting. The magnitude of the alteration depends partly on texture and mineralogy. The impact of the wetting event is further influenced by the extent to which management practices have altered the suite of exchangeable ions, the composition of the pore fluid and the organic carbon content of the soil. Consequently, the structure of a soil that is characterized at a given point in space and time represents an integration of all of these factors and may not represent the structure that will be found on the same soil at a different location or at a different time. This should be a major consideration when we consider the development of indicators of the quality of soil structure.

Defining the quality of soil structure for plant growth

Processes controlling growth

A definition of the quality of soil structure for plant growth should relate to processes that are controlled by soil structure and which are important to the growing plant. The most significant processes are the provision of water and oxygen and the development of an adequate root system. Characteristics of soil structural form, particularly pore characteristics, have the greatest impact on these processes.

The extent to which soil structural *form* influences water and oxygen supply and the mechanical impedance offered to root development strongly depends upon soil water content and evaporative demand. Under rainfed conditions, this means that the impact of a given structure on plant growth varies with climate. Quality of soil structure for plant growth should, therefore, be defined in relation to soil water and climatic conditions.

Structural characteristics and their relation to plant growth

Morphological characteristics of soil structural form and the variation in these characteristics with depth can be observed in a soil pit and described qualitatively; an experienced pedologist can even predict some quantitative characteristics from such visual analyses (as illustrated by McDonald and Julian, 1966; McKeague et al.,1982; Wang et al., 1985). The influence of soil structure on the distribution of roots or the infiltration of precipitation can also be observed and described qualitatively. Although site assessment is a vital element in characterizing soil structure, such assessments should be complemented by quantitative measurements. A number of measurements of structural form have been used including: total porosity (or bulk density), relative bulk density, macroporosity, pore size distribution, pore continuity, aggregate size distribution and soil strength. The least (or non) limiting water range (LLWR) has also been proposed.

- **Total porosity, bulk density and relative bulk density**

Total porosity is seldom measured directly but is normally calculated from bulk density after the particle density is measured (or more commonly assigned an assumed value). Bulk density is strongly influenced by texture and organic carbon content and, for a given soil, reflects the impact of stresses such as traffic or tillage. Interpreting the influence of differences in bulk densities on plant growth in different soils has proven, however, to be difficult (e.g. Stone *et al*., 1985). This difficulty is due, in part, to the importance of pore size distribution in processes influencing plant growth and the fact that management practices and different textures and organic carbon contents can result in different pore size distributions - as well as total porosity (or bulk density). The relative bulk density (the observed bulk density divided by the bulk density measured under a standard compaction treatment) is an attempt to normalize bulk density for texture and organic carbon content and has been related to the relative yields of crops under the temperate humid conditions of Scandinavia (Hakansson, 1990) and eastern Canada (Carter, 1990a). Relative yields varied parabolically with relative bulk density and were found to reach a maximum at relative bulk densities between 0.77 and 0.84.

- **Macroporosity and pore continuity**

Macroporosity and pore continuity are also strongly influenced by texture and organic carbon content. The macroporosities of all soils, but especially medium textured soils, are very sensitive to management. Macropores are, in general, the least stable of all pore size classes, and collapse when they experience various stresses. Macroporosity influences different mechanical characteristics (e.g. Carter, 1990b), and the impact of macroporosity on these characteristics is most significant when the pores are drained. Exploration of soil by roots can also be influenced by the extent and dimensions of the macropore space (Jakobsen and Dexter, 1988). The greatest impact of a loss of macroporosity or a decrease in pore continuity is on the movement of water and solutes (Ahuja *et al*., 1993; Blackwell *et al*., 1990; White,1985), but this impact is largely restricted to water potentials close to zero where these pores are water-filled. Changes in relative bulk density primarily reflect changes in macroporosity and therefore the impact of macroporosity on plant growth may be best described by the changes in relative yield with relative bulk density.

- **Aggregate size distribution**

Aggregate size has been related to the germination and early growth of seedlings since the distribution of aggregate sizes influences the pore characteristics of the seedbed, seed-soil contact and the supply of water to the developing seedling. Aggregate size distribution also influences seedling growth when water is not limiting, presumably as a consequence of limitations related to soil strength (Donald *et al*., 1987). Attempts have been made to define optimum aggregate size distributions for different crops under different climatic conditions (see review by Braunack and Dexter, 1989). Measurements of aggregate size distributions are most relevant to the germination and early growth of plants on soils that are tilled, structurally stable, and are not compacted by traffic. The measurements have less relevance to later growth, or to early growth on untilled soils or tilled soils that that are unstable or compacted by traffic.

- **Potentially available water**

A characteristic of pores that can be related to water content is the volume fraction of pores defining the potentially available water content (Veihmeyer and Hendrickson, 1927). The concept of this characteristic has generated controversy for many years (see commentary by Hillel, 1980, p 216-222). It is now understood that water is not equally available to plants across the range of potentials from field capacity to permanent wilting point and that the variation in the rate of extraction of soil water with water potential is influenced by the evaporative demand. Notwithstanding the limitations associated with the concept of available water, it is useful as an indicator of the “potential storage capacity” of different soils for water that can be utilized by plants. The degree to which this potential capacity is ever fully realized depends on rainfall and infiltration characteristics (see Gardner *et al*., 1984, for an illustration of the failure of swelling soils to ever wet up to field capacity at depth). Implicit in the use of the concept of available water is the assumption that if the range in water content between field capacity and the permanent wilting point is large, the water content falls outside of this range less frequently, and therefore the plant experiences severe stress less often. Potentially available water has been used for irrigation scheduling and is used in many crop growth and hydrologic models. In the latter application, however, arbitrary adjustments are often made to account for changes in the rate of water extraction by plants with potential when the potential falls between field capacity and the permanent wilting point (e.g. Timlin *et al*., 1986; Feddes *et al*., 1988; Huwe and van der Ploeg, 1991). Available water is strongly influenced by texture and organic carbon content (Ratliff et. al., 1983; da Silva and Kay, 1996a) but is not strongly influenced by increases in bulk density that can arise from traffic or other stresses (da Silva and Kay, 1996a). Increases in bulk density can, however, result in limitations to plant growth due to poor aeration or high soil strength in some soils even when the water content is between field capacity and the permanent wilting point. This represents the greatest shortcoming to the concept of available water.

- **Least limiting water range(LLWR)**

A characteristic of structural *form* that is directly related to water and oxygen supply, soil strength and can incorporate a water content dimension, is the least (or non-) limiting water range (Letey, 1985). The LLWR is defined by water contents at which aeration, water potential and mechanical impedance reach values that are critical or limiting to plant growth. The upper limit of this range is defined by the water content at field capacity or the water content at which aeration becomes limiting - whichever is smaller. The lower limit is defined by the water content at the permanent wilting point or the water content at which soil resistance to penetration becomes limiting - whichever is higher. The LLWR integrates many of the characteristics of pores into a single parameter and does so in a way that is directly related to plant growth. Preliminary studies under humid temperate conditions in Canada (da Silva and Kay, 1996b) have shown that the growth of corn plants decreases linearly with increasing frequency that the soil water content falls outside of the LLWR. The frequency with which the water content falls outside of the LLWR would be expected to increase as the LLWR gets smaller in soils that drain freely and experience similar climatic conditions. Studies in Australia (Emerson *et al* ., 1994), using the same limiting values for aeration (10% air-filled porosity) and resistance to penetration (2 MPa) as used by da Silva and Kay, showed that small values of the LLWR coincided with a paucity of roots of peach trees in orchard soils. The value in using the LLWR rather than potentially available water is illustrated in a survey of eight Canadian soils (Topp *et al*., 1994). Over 90 % of the horizons tested in this study developed a penetrometer resistance greater than 2 MPa at water potentials greater than -1.5 MPa and nearly 50% of the horizons had aeration limitations at field capacity. Preliminary studies (McKenzie *et al*., 1988) on a self-mulching vertisol under cotton production in New South Wales suggested, however, that standard techniques to measure aeration and strength on soils with vertical macropores may lead to anomalous interpretations of the LLWR. On the basis of these studies, the LLWR merits further evaluation as a measure of the quality of soils for crop production.

An additional level of sophistication beyond just measuring the LLWR would be to characterize the temporal variation in the water content profile in relation to the LLWR so that the frequency with which the water content falls outside of the LLWR can be calculated. These data would represent a particularly important complement to measurements of the LLWR at a given depth when the water content is largely controlled by water flow characteristics at other depths (e.g. Gardner *et al*., 1984). This information would also be important in comparing soils under much different climates.

Implicit in attempts to correlate plant response with any pore characteristics that have been measured at a single point in time is the assumption that soil structure has remained constant over the time period of concern. This assumption warrants more careful assessment than it has received to date.

Defining structural quality when structure is temporally variable

Measurements related to pores, aggregates or the LLWR must be made at different times if the structure is temporally variable. Under these circumstances, it would seem appropriate to ask two questions: (a) what are the maximum and the minimum values of a structural characteristic that are possible on a given soil under existing climatic conditions? and, (b) do the data exhibit a long term trend? If there is a trend a further question is relevant: what is the rate of change of this characteristic?

Under given climatic conditions, the rate of change in the structural *form* of a soil under specific management must be related to the *stability* and *resiliency* of that soil. There are very few studies, however, that establish a clear link between these structural characteristics. The large volume of literature on, for instance, aggregate stability is in stark contrast to the almost total absence of literature relating aggregate stability to rates of change of bulk density, potentially available water, or LLWR. Establishing relations between rates of change or half lives of structural *form* and both *stability* and *resiliency* would enable researchers to predict rates of change in properties of soil structure that relate directly to plant growth from other properties that can be more readily measured.

Potential indicators of the quality of soil structure for plant growth

Public demand for research information often outruns the ability of the research community to provide information - information that scientists are confident is both reliable and relevant. The need for indicators related to the structural quality of soils may be such an example. The best of the *existing* parameters that could be used to characterize structural quality for crop production would appear to be relative bulk density and potentially available water. The challenge facing researchers is to develop alternative parameters that do not incorporate the limitations associated with existing parameters. In the opinion of these authors, the best alternative is the LLWR.

Before the LLWR is widely used, however, additional assessments of the limiting values for both aeration and resistance to penetration in relation to plant response are required. In addition, it is necessary be able to predict the LLWR from more readily available soil characteristics. The latter requirement may be met through greater use of pedotransfer functions. Preliminary studies on a limited number of nonswelling soils under two different tillage treatments have shown that the LLWR of these soils could be calculated if the clay and organic carbon contents of the soils are known and the bulk densities are measured (da Silva and Kay, 1996a). The mineralogy, suite of exchangeable cations and composition of the pore fluid were similar in all soils. The pedotransfer functions described the variation with water content of water potential (the water release curve) and of soil resistance (the soil resistance curve). The subsequent calculation of the LLWR was based on these curves. The influence of management (i.e. tillage) on the LLWR could be accounted for entirely by its influence on organic carbon content and bulk density. Any influences of weather and biological factors were assumed to be embodied in the existing variables. This approach merits further examination on a broader range of soil and climatic conditions and relevant management practices.

Particular attention must be directed to situations in which the LLWR varies over time. Included among such situations when the time scale encompasses a single growing season are the collapse of seedbeds of unstable soils, the behavior of swelling soils and the response of soils that range in characteristics from self-mulching to hard-setting. At time scales of years, the impact of changing organic carbon content needs to be considered in more detail.

Future challenges

Answers to the following questions would allow us to respond with greater confidence to the demand for indicators of the structural quality of soil:

- how do plants respond to spatial and temporal variability in soil structure and is this response reflected in final yield?
- what are the limiting values for aeration and soil resistance to penetration for different crops and are these limiting values independent of other soil characteristics?
- what is the relation between LLWR and crop yield under a given set of climatic conditions for soils that are structurally stable and nonswelling?
- can the concept of LLWR be applied to swelling soils and if so, what soil characteristics are necessary to describe the soil-water release curve and the soil resistance to penetration-water content curve?
- how does the LLWR change with wetting/drying, freezing/thawing events and the activity of soil fauna and how do *stability* and *resiliency* characteristics relate to these changes?

Finding answers to these questions should be given high priority in future research.

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An Ecological View Of Soil Quality

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An ecological view sets the concept of soil quality within the framework of the broader environment. It recognises that soils are necessary to the proper functioning of an ecosystem, contributing to the system's ability to withstand the adverse effects of such disturbances as drought, pests, pollution, and human exploitation, including agriculture. An ecosystem was first defined as "the whole system, including not only the organism complex, but also the whole complex of physical factors, forming what we call the environment" (Tansley, 1935). It has also been described as a topographic unit, a volume of land and air plus organic contents extended areally over a particular part of the earth's surface for a certain time (Rowe, 1961). This latter definition is particularly appropriate for agroecosystems, because it indicates that ecosystems change over time and are dynamic.

Soils are components of terrestrial ecosystems, which also include atmosphere, water, vegetation, and animals. As components of ecosystems, soils function to regulate biotic processes (e.g., supplying plants with mineral nutrients and water) and to regulate the flux of elements (e.g., turnover and storage of C, N, P and S). An ecological view of soils considers their function to affect other components of the ecosystem (i.e., aquatic, atmospheric and biological), as well as adjacent ecosystems. Thus soil alters the chemical composition of precipitation and redistributes water through the environment; contributes to the gas, water and heat balance of the atmosphere and serves as a reservoir for biodiversity and genetic material.

Differences Between Natural And Agricultural Ecosystems

Agroecosystems, which are the major form of domesticated ecosystems, differ from natural ecosystems in several basic ways (Odum, 1984). Natural ecosystems are controlled through internal feedback loops, and information exchange among several system components governs the system's response to inputs (Ellert *et al*., 1996). Control of agroecosystems is external and goal-oriented, with humans imposing external goals or inputs in an attempt to regulate the systems.

Agroecosystems rely on processed fuels (i.e., sunlight stored in fossil forms) rather than natural energy (i.e., contemporary sunlight). They greatly reduce biological diversity in order to maximise yield, and depend on artificial rather that natural selection to select and control dominant plants and animals.

Nutrient cycles differ between natural and agricultural systems. In natural ecosystems, nutrients move from soil to primary producers, and then to consumers and decomposers (Crossley *et al*., 1984). This system conserves nutrients, retaining them from the soil and atmosphere. The internal cycling of nutrients is greater than the amounts coming in from the atmosphere or leaving through leaching. In agroecosystems harvest and, to a lesser extent, leaching losses are the major nutrient outputs, and fertiliser is the major nutrient input. Ellert and Gregorich (1996) reported that soil phosphorus levels were 24% higher in agricultural soils compared to adjacent forest sites and attributed the increases to fertilisation. Human management alters the flow of nutrients through agricultural systems. Insecticides control the transfer of nutrients from primary producers to consumers. Harvesting and cultivation regulate the quantity and timing of nutrients that reach decomposers (e.g., plant residues are returned to the soil in a large pulse to the decomposers at the end of the growing season). Cultivation also incorporates crop residues into the soil, increasing the rate of decomposition of the residues (Crossley *et al*., 1984).

Integrative Levels Of Organisation

Rowe (1961) described a level-of-integration scheme for studying ecosystems. This scheme perceives systems at various levels of organisation, with the higher levels containing or integrating the lower levels and thus relating structurally to them. Anderson (1983) suggested using this approach to study soils.

The fundamental unit of soils-oriented ecosystem studies is usually the soil horizon. Researchers usually begin by measuring properties of horizons (e.g., thickness, organic matter content, pH), using the results to characterise the pedon. The pedon, in turn, is part of a group of similar soils in a catena or field. Similar soils are part of a more generalised soil landscape or soil type. These soil types comprise soil zones, which in turn make up larger ecozones. Levels of soil organization below the horizon, such as aggregates and organo-mineral colloids, are the object of research into the internal processes, or physiology, of soil. Understanding these processes is fundamental to understanding the higher scale of soil organisation. Interactions among the chemical, physical and biological components of soil determine the soil's quality and its ability to perform its role in the ecosystem. For example, we cannot scale up to regional levels of greenhouse gas emissions without a detailed understanding of processes such as decomposition and denitrification that occur at a microsite level.

The value of the integrative approach to the study of soil quality is that it examines the object of study in its natural context within the ecosystem. It still permits detailed research on specific soil properties and processes, but requires that results be interpreted in relation to the whole.

Recent work in Canada has emphasised the need to conduct research at the ecozone level in order to assess the regional or global impacts of agriculture on the environment. In Canada 15 ecozones have been delineated based on the interaction of climate, human activity, vegetation, soils, geology and physiographic criteria (Ecological Stratification Working Group, 1995). The agricultural lands in Canada lie mainly within two of the 15 ecozones, the Prairies in western Canada and the Mixed Wood Plains in eastern Canada.

Rowe (1961) also suggested that ecosystems can be classified according to similarities in form, structure and composition, viewed from various perspectives. Similarly, the effect of soil quality on ecosystems can be interpreted from a number of different views of soil. A morphological view focuses on classifying the anatomical components of the system. A physiological view of soil quality characterises internal functions in and between the anatomical parts. An ecological view is directed toward the relationship of soil to the larger enveloping geographic system with which it continuously exchanges materials and energy.

Ecosystem Response

Ecosystem response is aptly illustrated by changes in soil organic matter. The level of organic matter or carbon in soil changes whenever the rate of input (i.e., net primary production) is different from the rate of output (i.e., decomposition). Organic matter accumulated in uncultivated soils over many years and this process of accumulation is summarised by Odum's (1969) concept of succession. In the early stages of ecosystem development, the rate of primary production exceeds the rate of respiration. As long as the primary production exceeds respiration, organic matter will accumulate in the ecosystem. In a mature ecosystem the rate of respiration approaches the rate of primary production, and, as a result, the rate of accumulation of organic matter approaches zero.

When an ecosystem is converted to agriculture, respiration and production rates diverge, disrupting the steady state characteristic of the undisturbed natural system (Janzen *et al*., 1996). Stored C is lost from soil under cultivation, because respiration increases. This loss continues until the rate of respiration equals that of primary production and a new steady state is reached. In Canada most arable land was first cultivated during the last century. Recent studies suggest that 25% of the C was lost upon converting land to agriculture. For example, Gregorich *et al.,* (1995) measured C losses from 15 to 30% in arable soils compared with adjacent forest sites.

Land management practices also affect the respiration/production balance, and thus the steady state (Janzen *et al*., 1996). Adding fertiliser, using tillage practices that alter the soil moisture/temperature status, or changing the crop rotation essentially re-starts ecological succession. Soil organic matter levels will increase under a management practice if C inputs exceed respiration but will decrease if decomposition exceeds C input. New management practices have less potential to increase organic matter levels in soils previously managed using C-retaining practices than in those that have undergone substantial C losses.

Characterising Ecosystem Response

The response of ecosystems to perturbation or disturbance interests ecologists and has direct application to the area of soil quality. Agriculture disturbs the natural equilibrium of the ecosystem. Resistance to degradative stresses and resilience in the face of these stresses are important measures of the soil's function within an ecosystem.
Resistance is the ability of a system to maintain structure when disturbed. Resilience refers to the ability of the system to recover and return to dynamic equilibrium after disturbance. The degree, manner and rate of recovery of a soil to near-original state are also important properties of resilience (Westman, 1978). Elasticity is the time required to restore the system to a stable state after being subjected to a disturbance. Amplitude is the zone within which the system is able to return to a stable state. Measurement of the amplitude involves determining the threshold beyond which the system can no longer be repaired.

Soil exhibits resistance in response to agricultural stress imposed on it through various management practices. In some agroecosystems, soil degradation may occur under management practices that diminish soil quality and productivity. This degradation may be curtailed or stopped with the adoption of improved management. With improved management and/or increased input costs, the soil may be restored to its original state of productivity. If degradation continues, a threshold may be reached at which the physical, chemical and biological properties of the soil are irreversibly altered; at this point the original productivity cannot be restored regardless of management or inputs to the system.

Numerous studies have demonstrated the rate and extent of soil degradation. Studies describing the rate of soil aggradation, however, are comparatively few. Campbell *et al.,* (1995) measured the response of soil organic matter to reduced tillage in a soil that had been previously cropped to tilled fallow-wheat for about 80 years. Reduced tillage, combined with continuous cropping and application of fertiliser, increased the amount of organic C in the 0-15 cm layer by 5 Mg ha^{-1}. Most of the increase occurred within the first few years following adoption of improved practices, and C content appeared to have reached a plateau within about 6 years. In eastern Canada, Angers (1992) observed that organic matter levels accumulated and reached a new plateau within 5 years of seeding a perennial forage. These results suggest that most of the increases in soil organic matter in response to the adoption of improved practices occur within a few years and may plateau within a decade.

In assessing the quality of a particular soil it may be important to assess both the degradation and aggradation phases in order to make recommendations for sustainable tillage or cropping practices. Some evidence suggests that the rate of aggradation in soil structure is different from that of degradation. Perfect *et al.,*(1990) determined that the average half-life for structural improvement of soil under forages was 4.5 years, whereas the average half-life for structural decay under corn with conventional tillage was 0.2 years (Topp *et al*., 1995). These data suggest that including forages in corn rotations under conventional tillage may do little to improve soil structure.

Within a given management and climatic area, the amount and rate of gain in organic matter may be affected by soil properties such as texture. Campbell *et al.,* (1996) reported that soil C gains resulting from no-tillage after 11 years were directly related to clay content. In three soils with clay contents ranging from 100 to 420 g clay kg^{-1}, soil C under no-tillage increased from 0 to 3.9 Mg C ha^{-1}. These results suggest that the quantity of mineral colloids determines the soil's ability to further decompose crop residues and thereby influence the extent and rate of recovery. The type of clay mineral also plays a critical role in the stabilisation and storage of C in soil.

Conclusion

An ecological view of soil quality extends far beyond the fence row and even past the ecosystem. This perspective is by nature integrational and thus requires an interdisciplinary approach by soil and other agricultural specialists. Such an approach to soil quality is needed to answer the larger question of agricultural sustainability. Good soil quality is the foundation of agricultural sustainability, but it is not a stand-alone concept. Current economic and political pressures encourage the compilation of a list of soil-sustainability indicators. Following a pressure-state-response model of environmental conditions, soil quality is linked to both human activity and socio-economic and environmental effects. Soil quality, or the state of the soil, responds to the management practices imposed on the soil. In turn it has socio-economic effects related to productivity and environmental effects beyond the agroecosystem itself, such as greenhouse gas balances and off-farm water quality.

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Soil Health And Global Sustainability

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Background

Increasing human populations, decreasing resources, social instability, and environmental degradation threaten the natural processes that sustain the global ecosphere and life on earth (Costanza *et al*., 1992; Postel, 1994). Global climate change, depletion of the protective ozone layer, serious declines in species biodiversity, and degradation and loss of productive agricultural land are among the most pressing concerns associated with our technological search for a higher standard of living for an ever growing human population. Past management of agriculture and other ecosystems to meet the needs of increasing populations has taxed the resiliency of soil and natural processes to maintain global balances of energy and matter (Bhagat, 1990; Sagan, 1992). The quality of many soils in North America and elsewhere has declined significantly since grasslands and forests were converted to arable agriculture and cultivation was initiated. Mechanical cultivation and the production of continuous row crops has resulted in physical soil loss and displacement through erosion, large decreases in soil organic matter content, and a concomitant release of organic C as carbon dioxide to the atmosphere (Houghton *et al*., 1983). Within the last decade, inventories of soil productive capacity indicate severe degradation on well over 10% of the earth's arable land as a result of soil erosion, atmospheric pollution, extensive soil cultivation, over-grazing, land clearing, salinization, and desertification (Oldeman, 1994). The quality of surface and sub-surface water has been jeopardised in many parts of the world by intensive land management practices and the consequent imbalance of C, N, and water cycling in soil. At present, agriculture is considered the most widespread contributor to non-point source water pollution in the USA (CAST, 1992a; National Research Council, 1989). The major water contaminant in North America and Europe is nitrate-N; the principal sources of which are conversion of native to arable land use, animal manures, and fertilisers. Soil management practices such as tillage, cropping patterns, and pesticide and fertiliser use are known to influence water quality. However, these management practices can also influence atmospheric quality through changes in the soil's capacity to produce or consume important atmospheric gases such as carbon dioxide, nitrous oxide, and methane (CAST, 1992b; Rolston *et al*., 1993). The present threat of global climate change and ozone depletion, through elevated levels of atmospheric gases and altered hydrological cycles, necessitates a better understanding of the influence of land management on soil processes.

Present-day agriculture evolved as we sought to control nature to meet the food and fibre needs of an increasingly urbanised society (Quinn, 1993). With the development of modern chemistry during and after World War II, agriculturalists often assumed a position of dominance in their struggle against a seemingly hostile natural environment, often failing to recognise the consequences of management approaches upon long-term productivity and environmental quality. Increased monoculture production of cash grain crops and greater reliance on chemical fertilisers and pesticides to maintain crop growth have resulted in two to three fold increases in grain yields and on-farm labor efficiency (Avery, 1995; Brown *et al*., 1994; Power and Papendick, l985). However, these management practices have also increased soil organic matter loss, soil erosion, and surface and ground water contamination in the USA and elsewhere (Gliessman, l984; Hallberg, l987; Reganold *et al*., l987). Motivations for shifting from input-intensive management to reduced external-input farming include concern for protecting soil, human, and animal health from the potential hazards of pesticides; concern for protection of the environment and soil resources; and a need to lower production costs in the face of stagnant farm-gate receipts (Northwest Area Foundation, 1994; Soule and Piper, 1992; U.S. Dept. of Agriculture, l980).

Recent interest in evaluating the quality and health of our soil resources has been stimulated by increasing awareness that 'soil' is a dynamic living resource whose condition is vital to both the production of food and fibre and to global balance and ecosystem function (Glanz, 1995). The thin layer of soil covering the surface of the earth represents the difference between survival and extinction for most land-based life. The quality and health of soils determine agricultural sustainability (Acton and Gregorich, 1995), environmental quality (Pierzynski *et al*., 1994), and, as a consequence of both, plant, animal, and human health (Haberern, 1992). Like water, soil is a vital natural resource essential to civilisation but, unlike water, soil is non-renewable on a human time scale (Jenny, 1980). Soils are alive and represent a unique balance between the living and the dead. Soils breathe, transform and recycle sunlight and stored energy and matter through plants and animals, and are vital to providing human food and fibre needs and in maintaining the ecosystems on which all life ultimately depends. This amazing capacity of soil results from the fact that the number of organisms contained in a teaspoon of healthy soil can exceed nine billion, one and one-half times the human population of the earth. Yet, this invaluable resource has often been degraded in the name of progress; as a means to the end of meeting the increasing 'needs' of humanity.

Developing *sustainable* agricultural management systems is complicated by the need to consider their utility to humans, their efficiency of resource use, and their ability to maintain a favourable balance with the environment that is favourable both to humans and most other species (Harwood, 1990). We are challenged to develop management systems which balance the needs and priorities for production of food and fibre with those for a safe and clean environment. Assessment of soil quality is invaluable in determining the sustainability of land management systems. Some index of soil quality is needed to identify problem production areas, make realistic estimates of food production, monitor changes in sustainability and environmental quality as related to agricultural management, and to assist government agencies in formulating and evaluating sustainable agricultural and land-use policies (Granatstein and Bezdicek, 1992). In the USA, the importance of soil quality in maintaining the balance between environmental and production concerns was reflected by one conclusion of a recent National Academy of Science report that, "Protecting soil quality, like protecting air and water quality, should be a fundamental goal of national environmental policy" (National Research Council, 1993). A recent call for development of a soil health index was stimulated by the perception that human health and welfare is associated with the quality and health of soils (Haberern, 1992). However, defining and assessing soil quality or health is complicated by the need to consider the multiple functions of soil in maintaining productivity and environmental well-being and to integrate the physical, chemical, and biological soil attributes which define those functions (Papendick and Parr, 1992; Rodale Institute, 1991). Most people recognise that maintaining the health and quality of soil should be a major goal of a "sustainable" society. The major question in many minds, however, is what constitutes a healthy or quality soil and how might it best be managed?

Measuring Soil Quality And Health - The Use Of Indicators

The quality of soil is largely defined by soil function and represents a composite of its physical, chemical, and biological properties that: (i) provide a medium for plant growth and biological activity; (ii) regulate and partition water flow and storage in the environment; and (iii) serves as an environmental buffer in the formation and destruction of environmentally hazardous compounds (Larson and Pierce, 1994). Soil serves as a medium for plant growth by providing physical support, water, essential nutrients, and oxygen for roots. The suitability of soil for sustaining plant growth and biological activity is a function of physical properties (porosity, water holding capacity, structure, and tilth) and chemical properties (nutrient supplying ability, pH, salt content, etc.). Many of the soil's biological, physical, and chemical properties are a function of soil organic matter content (Rovira, 1993). Soil plays a key role in completing the cycling of major elements required by biological systems, decomposing organic wastes, and detoxifying certain hazardous compounds. The key role played by soils in recycling organic materials into carbon dioxide and water and degrading synthetic compounds foreign to the soil is brought about by microbial decomposition and chemical reactions. The ability of a soil to store and transmit water is a major factor regulating water availability to plants and transport of environmental pollutants to surface and groundwater.

Much like air or water, the quality of soil has a profound effect on the health and productivity of a given ecosystem and the environments related to it. However, unlike air or water for which we have quality standards, the definition and quantification of soil quality is complicated by the fact that it is not directly consumed by humans and animals as are air and water. Soil quality is often thought of as an abstract characteristic of soils which can not be defined because it depends on external factors such as land use and soil management practices, ecosystem and environmental interactions, socioeconomic and political priorities, and so on. Perceptions of what constitutes a "good" soil vary depending on individual priorities for soil function and intended land use. However, to manage and maintain our soils in an acceptable state for future generations, soil quality and health must be defined, and the definition must be broad enough to encompass the many functions of soil. The terms soil quality and soil health are often used interchangeably in the scientific literature and popular press with scientists, in general, preferring soil quality and producers preferring soil health (Harris and Bezdicek, 1994). Some prefer the term soil health because it portrays soil as a living, dynamic organism that functions holistically rather than as an inanimate mixture of sand, silt, and clay. Others prefer the term soil quality and descriptors of its innate quantifiable physical, chemical, and biological characteristics. Efforts to define the concept of soil quality and soil health have produced a polarisation of attitudes concerning these terms. On the one hand are those, typically speaking from outside agriculture, who view maintenance of soil health as an absolute moral imperative -- critical to our very survival as a species. On the other hand is the attitude, perhaps ironically expressed most adamantly by academics, that the term is a misnomer -- a viewpoint seated, in part, in fear that the concept requires value judgments which go beyond scientific or technical fact. The producers, and therefore society's management of the soil, are caught in the middle of these opposing views and the communication failures that result. In this paper the terms soil quality and soil health will be used synonymously. However, the term soil health is preferred in that it more clearly portrays the idea of soil as a living dynamic organism that functions in a holistic way depending on its condition or state rather than as an inanimate object whose value depends on its innate characteristics and intended use. With consideration of the aforementioned factors, **soil health** can be defined as **the continued capacity of soil to function as a vital living system, within ecosystem and land-use boundaries, to sustain biological productivity, promote the quality of air and water environments, and maintain plant, animal, and human health** (Doran *et al*., 1996)**.** The challenge we face, however, is in quantitatively defining the state of soil health and its assessment using measurable properties or parameters. Unlike human health, the magnitude of critical indicators of soil health ranges considerably over dimensions of time and space.

Assessing the health or quality of soil can be likened to a medical examination for humans where certain measurements are taken as basic indicators of system function. Larson and Pierce (1991) proposed that a minimum data set be adopted for assessing the health of world soils, and that standardised methodologies and procedures be established to assess changes in soil quality. The need for basic soil quality and health indicators is reflected in the question commonly posed by farmers, researchers, and conservationists: "What measurements should I make to evaluate the effects of management on the ability of soil to function now and in the future?" Too often scientists confine their interests and efforts to the discipline with which they are most familiar. Microbiologists often limit their studies to soil microbial populations, having little or no regard for soil physical or chemical characteristics which define the limits of microbial activity, or that of plants or other life forms. Approaches in assessing soil quality and health must be holistic, involving integration of all parts of the soil system, and not reductionistic in segregating and measuring only the function of individual parts. The indicators chosen must also be measurable by as many people as possible, especially managers of the land, and not limited to a select cadre of agricultural and environmental research scientists. These indicators should define the major ecological processes in soil and ensure that measurements made reflect conditions as they actually exist in the field under a given management system. They should relate to major ecosystem functions such as C and N cycling (Visser and Parkinson, 1992) and be components of computer models which emulate ecosystem function. Some indicators, such as soil bulk density, must be measured in the field so that laboratory results for soil organic matter and nutrient content can be converted to actual field conditions at time of sampling. Starting with the minimum data set proposed by Larson and Pierce (1991), we developed a list of basic soil properties (Table 1) which meets the aforementioned requirements of indicators for screening soil quality and health. Appropriate use of such indicators will depend to a large extent on how well the relevance of these indicators is interpreted with respect to consideration of the ecosystem of which they are part. Thus, interpretation of the meaning of soil biological indicators apart from soil physical and chemical properties is of little value and, with respect to assessment of soil quality or health, can actually be misleading.

Value Of Qualitative/Descriptive Assessments

The concept of soil health is in many ways producer-generated and rooted in observational field experiences which translate into descriptive properties such as its look, feel, resistance to tillage, smell, presence of biota, etc. Harris and Bezdicek (1994) conclude that farmer-derived descriptive properties for assessing soil health are valuable for: (i) defining or describing soil quality/health in meaningful terms; (ii) providing a descriptive property of soil quality/health; and (iii) providing a foundation for developing and validating an analytical component of soil health based on quantifiable chemical, physical, and biological properties that can be used as a basis for management and policy decisions. Unfortunately the potential contributions of indigenous farmer knowledge to management of soil quality/health throughout the world has not been fully utilised (Pawluk *et al*., 1992).

Use of descriptive soil information is not commonly used in scientific literature dealing with characterisation of soil quality/health. However, Arshad and Coen (1992) indicate that many soil attributes can be estimated by calibrating qualitative observations against measured values and recommend that qualitative (descriptive) information should be an essential part of soil quality monitoring programs. Visual and morphological observations in the field can be used by both producers and scientists to recognise degraded soil quality caused by: (i) loss of organic matter, reduced aggregation, low conductivity, soil crusting and sealing; (ii) water erosion, as indicated by rills, gullies, stones on the surface, exposed roots, uneven topsoil; (iii) wind erosion as indicated by ripple marks, dunes, sand against plant stems, plant damage, dust in air, etc.; (iv) salinization, as indicated by salt crust and salt-tolerant plants; (v) acidification and chemical degradation, as indicated by growth response of acid-tolerant and -intolerant plants and lack of fertiliser response; and (vi) poor drainage and structural deterioration, as indicated by standing water and poor or chlorotic plant stands.

Doran *et al*., (1994) stressed the importance of holistic management approaches which optimise the multiple functions of soil, conserve soil resources, and support strategies for promoting soil quality and health. They proposed use of the basic set of soil quality and health indicators (Table 1) to assess soil health in various agricultural management systems. However, while many of these key indicators are extremely useful to specialists (i.e. researchers, consultants, extension staff, and conservationists) many of them are beyond the expertise of the producer to measure (Hamblin, 1991). In response to this dilemma, Doran (1995) presented strategies for building soil quality and health which also included generic indicators which are measurable by and accessible to producers within the time constraints imposed by their normally hectic and unpredictable schedules (Table 2). Soil organic matter, crop appearance, and erosion were ranked by farmers in the Northern US Corn and Dairy Belt as the top three properties for describing soil health (Romig *et al*., 1995).

Conclusions

Producers and other managers of the land need practical tools and approaches to measuring the effects of management on soil quality and health which enable them to 'fine-tune' and determine the sustainability of their production approaches (Powell and Pratley, 1991). These tools may include some specific measures of soil quality as outlined in Table 1 but will likely involve more practical generic indicators such as water use efficiency, crop yield and growth characteristics, input costs, soil loss from wind/water, soil structure, water storage and uptake, organic matter levels, and nutrient levels in soils, water, and farm products. On-farm assessment of soil quality and health will help producers evaluate the effects of management on agricultural sustainability and permit dialogue with researchers and conservationists in interpreting management effects. Agriculture research, extension, and conservationists are challenged to develop soil quality and health standards to assess changes in sustainability which are practical and useful to producers. Successful development of practical and useful tools and standards for assessment of soil health and sustainability, however, can only be accomplished through consultation and partnership with agricultural producers who are the primary stewards of the land.

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Table 1. Proposed minimum data set of soil physical, chemical, and biological indicators for screening the condition, quality, and health of soil (after Doran *et al*., 1996; Larson and Pierce, 1991; and Doran and Parkin, 1994).

Indicators of soil condition	Relationship to soil condition and function; Rationale as a priority measurement
Physical	
Texture	Retention and transport of water and chemicals; Needed for many process models; Estimate of degree of erosion and field variability of soil types
*Depth of Soil, Topsoil, and Rooting	Estimate of productivity potential and erosion; Normalises landscape and geographic variation
*Soil Bulk Density, and Infiltration	Indicator of compaction and potential for leaching, productivity, and erosivity; Density needed to adjust soil analyses to field basis
*Water Holding Capacity (Water retention charac.)	Related to water retention, transport, and erosivity; Available water: Can be calculated from soil bulk density, texture, and soil organic matter.
Chemical	
Soil Organic Matter (Total organic C and N)	Defines soil fertility, stability, and erosion extent; Use in process models and for site normalisation
pH	Defines biological and chemical activity thresholds; Essential to process modeling
Electrical Conductivity	Defines plant and microbial activity thresholds; Presently lacking in most process models; Can serve as practical estimator of soil nitrate levels
Extractable N, P, and K	Plant available nutrients and potential for N loss; Productivity and environment quality indicators
Biological	
Microbial Biomass C & N	Microbial catalytic potential and repository for C &N; Modeling; Early warning of management effects on OM
Potentially Mineralizable N (anaerobic incubation)	Soil productivity and N supplying potential; Process modeling; Surrogate indicator of biomass N
*Soil Respiration, Water Content, and Temperature	Measure of microbial activity (in some cases plants); Process modeling; Estimate of microbial biomass activity

* In field measurements for varying crop row and topographic positions and management conditions.

Table 2. Sustainable management strategies for building soil quality and health and associated indicators which are assessable by producers and land managers.

Strategy	Indicators
Conserve Soil Organic Matter *through* Maintaining balance in C & N cycles,	Direction/change in organic matter levels with time: Organic matter potential within soil, climate, and cropping regimes; where inputs ≈ outputs.
Minimise Soil Erosion *through* Conservation tillage and increased soil cover (residue, cover crops, green fallows, etc.)	Visual signs (gullies, rills, dust, etc.); Surface soil characteristics: -Depth of topsoil -Organic matter content and texture -Infiltration rate -% Surface cover
Substitution of Renewable for Non-renewable Resources *through* Less reliance on fossil fuels and synthetic chemicals, use of conservation tillage, and greater use of natural balance and diversity (crop rotation, legume cover crops, green fallows, etc.).	Crop growth characteristics (yield, N content, colour, root patterns); Soil and water nitrate levels; Soil physical condition/compaction; Input costs and energy input/output.
Move Toward Management Systems which Coexist with rather than Dominate Natural Systems *through* Optimising productivity needs with environmental quality.	Crop growth characteristics (yield, N content, colour, vigour); Soil and water nitrate levels during year; Synchronisation of N availability with crop needs during the year.

Land management: the purpose for soil quality assessment

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Introduction

The term 'land management' is applied rather broadly in the literature and is rather ill-defined. In simple terms, management means to alter by manipulation, land is the solid portion of the earth's surface. FAO (1976), in their framework for land evaluation, broadened the concept of land to comprise all "attributes of the biosphere vertically above and below an area of the earth's surface, including those of the atmosphere, the soil and underlying geology, the hydrology, the plant and animal populations, and the results of past and present human activity, to the extent that those attributes exert a significant influence on present and future uses of the land by man". Under FAO's broader concept of land, land management is the alteration, by manipulation, of the attributes of the biosphere.

People use land for the purpose of extracting value from it. In a perfect world, the value extracted from the land is both enhanced by its management and compensated either naturally through ecosystem resilience and/or through the managed inputs themselves, in part through substitution. In the real world, land management can alter the quality of the land, often in significant ways. Changes in land due to degradation and the continuing reduction in land availability for agricultural uses has shifted the international focus from the process of land development to the development of sustainable land management systems (Dumanski *et al.*, 1991b). Since land management is sustainable only when it maintains or improves natural resource quality (specifically air, water and soil), the impact of land management on resource quality should provide a basis for evaluating sustainable land management systems (Pierce and Larson, 1993).

Since soils comprise a very important component of the biosphere, land management and soil quality are inextricably linked. Therefore, soil quality assessment is critical to sustainable land management. This paper discusses soil quality assessment in terms of its threefold purpose: (1) soil resource inventory and land evaluation (2) monitoring land condition and (3) soil quality control.

Soil resource inventory and land evaluation

Soil resource inventory, generally embodied in national soil survey programs, involves the characterisation of soils as to their inherent properties and their potential for response to managed inputs (inherent soil quality), the interpretation of soils information with respect to their suitability and limitations for use, and the spatial delineation of soil units on a map. The primary reason for initiation of soil survey in the United States was the evaluation of soil productivity, which involved a blend of qualitative and quantitative rating models (Huddleston, 1984). The assessment of inherent soil quality has been used to identify and make a comparison of promising kinds of land use, a process termed land evaluation. Land evaluation encompasses much more than soils. FAO defines land evaluation as the process of assessment of land performance when used for specified purposes, involving the execution and interpretation of surveys and studies of landforms, soils, vegetation, climate and other aspects of land in order to identify and make a comparison of promising kinds of land use in terms applicable to the objectives of the evaluation (FAO, 1976). A framework for evaluating sustainable land management systems has recently been proposed by Dumanski *et al*., (1991a).

In the United States, the inherent quality of soils is reasonably well known and quantified. A considerable knowledge base already exists on the soil resource base in the United States and other areas of the world. The USDA-NRCS have more than 10,000 soil profiles completely described (quantitatively) as part of the accelerated soil survey program. Collectively, between 100,000 and 150,000 individual soil measurements have been taken and are on record in this survey program. Additionally, the land grant universities in the U.S. may have an equal number of soil profiles described and soil measurements recorded. Most of the soils in the United States have been mapped and interpretations developed, and in many areas, this forms a basis for the determination of land values for tax assessment purposes. A reasonably well-defined set of definitions, measurement techniques, and procedures for quantifying soil attributes and processes already exists. In other words, a reasonable information base exists on the inherent quality of soil resources in many areas of the world.

This is not to imply that this aspect of soil quality assessment is complete. In practice, inherent soil quality is known more on a landscape scale and generally not known site-specifically. Site-specific management studies, where detailed spatial data on soil properties and crop yield are being obtained, often show little correlation between soil map units and spatial variability in yield and soil properties. Additionally, there are few sites where the inherent soil quality is known sufficiently to quantitatively assess long-term changes in soil quality. Inherent soil quality is critical to land evaluation and its assessment remains an important purpose of soil quality assessment. What we do not know very well is how soils change in response to management, i.e., the dynamics of soil quality is not well documented.

Monitoring

Monitoring is the regular surveillance of the condition of something. While monitoring the quality of air and water has been commonplace for the last few decades, in general, soil quality has not been monitored. Even the large scale effects of erosion on soil productivity are not well known (Pierce, 1991), prompting Lal (1987) to conclude that, in spite of billions of dollars invested in the erosion problem, we cannot say for sure what effect the loss of a unit of soil depth has on crop yield. The National Resources Inventory (NRI), a monitoring survey of over 800,000 sampling locations in the United States completed every 5 years since 1977, does not contain any data that assesses changes in soil quality during that period (Pierce and Nowak, 1996). Lack of soil quality monitoring data stem, in part, from the convincing evidence of erosion effects on soil productivity such that only the rate of soil erosion was considered important in assessing soil degradation rates worldwide. The extent to which this is true for other soil degradation processes is less known.

The dynamics of soil quality, that is how soil quality changes in response to management, is not well documented. Monitoring soil quality is an important component of soil quality assessment not addressed by soil resource inventory or land evaluation programs directed at assessing land use suitability. Changes in soil quality can be assessed in two ways: (1) by quantifying inherent soil quality and measuring its change over time or (2) by identifying indicators of soil quality and monitoring their change over time. Both methods are suitable but the use of indicators is likely to be more generally feasible since inherent productivity is difficult to quantify. While useful in describing the dynamics of soil quality, monitoring programs may have limited utility for soil quality improvement since monitoring keeps track of quality but cannot in itself change it.

A number of first principles are easily recognised relative to soil quality (Pierce and Larson, 1996). Soils vary in quality and that quality varies in space and time. Soils are characterised by attributes that range within limits and functionally interrelate. Soil quality changes in response to material and energy flows associated with external inputs, internal transformations and translocations, and external outputs. Thus, soil quality and its changes can be defined in terms of a set of attributes, in terms of kinetics and/or magnitude of internal processes and transformations, and it terms of the type, magnitude and rates of outputs. Any of these aspects of soil quality can be used to monitor changes in soil quality. The search is on for acceptable measures and procedures for quantifying soil quality and its change in response to natural and anthropogenic factors (Pierce and Larson, 1996). A number of pertinent issues must be addressed if monitoring is to have real value in assessing dynamics of soil quality. These issues include the following, presented in the order in which they should be considered.

"What are you looking for?"
"Where do you look?"
"What do you look for?"
"How do you measure it?"
"When do you measure it?"
"How do you detect real change (separate from natural variation?".
"How do you attribute change to assignable causes?"

Dr. Nicole Petite Marr, a geologist who spent her life studying the Sahara Desert, was asked how she would determine if the Sahara Desert is changing (what you are looking for). She responded by stating the first most important question is "Where do you look?" and the second most important question was "What do you look for?". To determine change in the desert, she would look not at the centre of a desert, where internal change is characteristic. Rather she would look in the transition zone of the desert to assess if the desert as a whole was changing. Then, to describe change, she would look for those definitive features that characterise the edge of the desert, avoiding ephemeral features, like vegetation patterns, which represent seasonal shifts in weather patterns more so than changes in desert movement. The analogy to monitoring soil quality changes is important, particularly since we cannot measure everything everywhere. For example, if soil salinization is of interest, look where it is known to occur and determine what measurements would best document if salinity is getting worse or improving. Issues related to soil quality indicators and measurement techniques (what to measure) and how to measure them are the subject of this symposium as well as soil quality methods books currently under development.

Regardless of how soil quality is measured, the issue remains as to how soil quality is monitored in terms of how real change in soil quality is detected. It is important to determine if a measured value is in fact indicative of real change, outside the range of natural variation, and whether the source of variation can be attributed to special causes associated with the way we have used or managed the soil. In simple terms, we do not want to attribute an observed variation in a soil quality attribute or indicator to a change in soil quality when in fact the variation is merely an expression of the natural variability associated with that attribute. Thus, we must have standards by which we evaluate soil quality measurements that include sufficient power to detect changes in soil quality at levels deemed important to sustaining or enhancing soil quality.

Once monitoring identifies a real change in soil quality, then the question remains as to the proper interpretation of that change in the suite of soil quality indicators or minimum data set (MDS) (Larson and Pierce, 1991; 1994). It is important to note that each component of a MDS provides information about the quality of soil but the collective meaning of changes (or lack of) in the components of a MDS may require special interpretation. For example, assume that a soil quality MDS consists of 5 soil attributes. Of these, two are detected as changing, the other three are determined to be within the range of natural variation and are considered stable. One possible scenario is that one soil attribute is improving and the other is degrading in quality. Such might be the case for soil organic carbon and bulk density, respectively, in soil managed under no-tillage. An increase in soil organic matter is generally considered an enhancement of soil quality. On the other hand, increased bulk density is often considered detrimental to soil quality. How changes in the quality of this hypothetical soil may be assessed represents an important area of discussion in soil quality assessment.

Soil quality control

The real issue for sustainable land management is how soil quality is achieved on the land. Our goal as scientists and managers of the land should be to sustain and improve the quality of the soil resource base. The major weakness in monitoring soil quality alone is that it is more a reactive than a pro-active approach to that end. That is, monitoring soil quality does nothing in itself to change it - the goal is to affect soil quality. Monitoring is important only when it feeds back into the management system, either to correct deficiencies or improve the system. The key to achieving soil quality on the land is in the hands of the land manager/operator. Land managers need tools that enable them to positively affect soil quality within their management systems. Well designed soil and land management systems and quality control procedures and technologies are needed to assist the land user in ensuring that the processes which regulate soil quality, as influenced by the manager's activities, are operating properly. The recent emergence of site-specific management concepts and technologies may provide the needed quality control capabilities.

The concept of soil quality control was first proposed by Pierce and Larson (1993), based on statistical quality control procedures (SQC) used in product manufacturing, and more fully developed by Pierce and Gilliland (1996). A large body of literature exists on SQC in product manufacturing (ASTM, 1992; Montgomery, 1985; Ryan, 1989). The following discussion relies heavily on these two papers and presents a brief overview of the concepts of soil quality control.

Quality control involves both monitoring and control. Monitoring is the regular surveillance of the condition of something, whereas control means to influence or regulate. In product manufacturing, the main objective of SQC is to effect product quality by controlling the processes that determine it—systematically reducing variability in the characteristics that define a good-quality product so that it meets the specifications and tolerances of the design (Montgomery, 1985). Note that quality control tools are in the hands of the worker, as that is the point in the manufacturing process where quality is determined. The analogy between product quality and soil quality is practical, because it allows the use of an extensive set of techniques used in the field of SQC. Soil quality control, then, involves the three major components of SQC: experimental design, process monitoring and control, and continuous improvement. In terms of SQC, soil quality can be stated as follows: ‘for a given land use, soil quality will be sustained or improved if the management system is well designed relative to the intended goals (quality of design) and if the components of the system conform to specifications and tolerances that the design requires (quality of conformance)’. Thus, soil quality control must include the design of management systems that do not degrade soil quality (i.e., are inherently sustainable) and the development of process control procedures that ensure that the processes within the management systems conform to the specifications and tolerances of that design. Soil quality is exactly analogous to SQC, is intuitively appealing, and, most importantly, places control primarily in the hands of the land manager.

Statistical quality control is a method to help control processes. It uses simple control charts, produced by sampling a quality parameter over time, to determine if a specific process operates within the range of "natural variation". In SQC, a process is considered to be "in statistical control" if it operates within the range of natural variation and is considered to be "out-of-control" if other variations resulting from "specific causes" are present in the process. Sample means and standard deviations of a quality control parameter are plotted over time on a control chart (Fig. 1). The upper control limit (UCL) and lower control limit (LCL) are set based on estimated means and variances or are known through some other means.

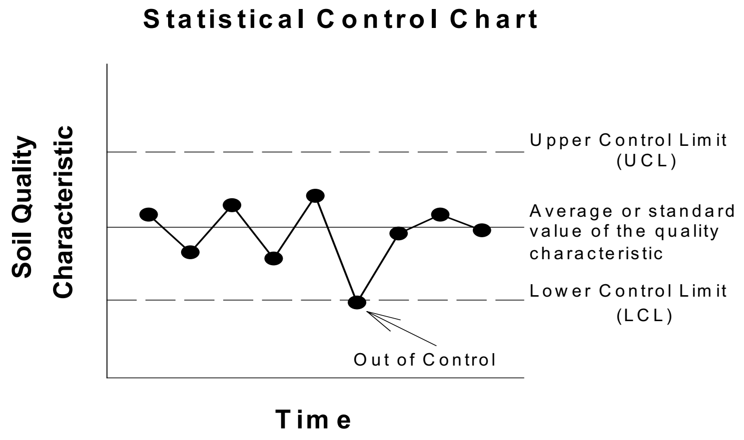

Figure 1. Illustration of a control chart for use in soil quality assessment (from Pierce and Gilliland, 1996).

There are several aspects of SQC that apply to soil quality control. The first deals with the use of control charts to monitor soil attributes or soil quality indicators and assess if soil quality is stable in response to the current management system. This statistical process-control approach indicates only that the process is in control or not but does not in itself indicate how to bring the process back to an in-control state. If the control chart indicates that special causes of variation are present, then they should be identified and removed (if possible) to bring the process into control. Problem-solving skills, intimate knowledge of the process and the gathering of relevant information help in the identification of special causes. A second aspect of SQC applicable to soil-quality control concerns the identification of key variables influencing each soil quality parameter of interest, accomplished through research on the fundamental mechanisms of the process. Research involving designed experiments and computer simulation models can contribute to this basic understanding. A third aspect is the charting of the key variables and their control and adjustment to make desired changes in soil quality attributes, which is analogous to the engineering control of a chemical process through the monitoring and adjustment of critical variables.

Statistical process control encompasses a large set of techniques and ideas for dealing with data that vary in time. One technique involves the plotting of means and standard deviations of a quantitative variable over time. Typically, the measurements come in subgroups that are close (local) in time, and it is the means,$\bar{x}_i$, and standard deviations, s_i, of the subgroups that are plotted. These statistics provide local estimates of the mean and standard deviation of the variable being driven by the process. The action rules that determine whether the process is in-control or not are functions applied to the data in these charts.

There are two applications of SQC to soil quality. One is its use in monitoring programs where a set of soil attributes, a soil quality minimum data set (MDS), is charted over time. The control limits for each quality parameter would be based on the charted values or on values determined by experts or from previous experiments. The goal, for example, could be to maintain or enhance soil organic matter content at some level (in-control). We envision that each parameter constituting a soil quality MDS would be charted independently, with appropriate rules or tests applied to the interpretation of each chart. Each parameter's control chart would be interpreted separately or in light of information on other parameters, because each chart provides different but possibly correlated information about the state of soil quality. This procedure would allow a simple, easy-to-use, yet quantitative evaluation of the impact of a particular land use or soil management practice on soil quality. The problem is that, while these charts may detect a change in soil quality, it tells nothing about the process that created the change.

The other, perhaps more important, application of SQC lies in the process-control domain of soil quality, which is generally called engineering control. In this application, the goal is still soil quality, but the approach focuses on the process that regulates quality rather than simply monitoring a set of soil quality parameters. Consider soil organic matter, but this time think in terms of the processes that regulate organic-matter content in soil. Recall that SQC involves design and process control as major components. Thus, the first matter of concern is whether or not the design of the management practice can in fact even produce the desired level of organic matter. If the design is wrong, the desired output can never be achieved. If the system design is correct, then the important questions relate to whether operational components of the system are working within the design specifications and tolerances. If the processes that create the outcome are not in control, then the desired output may not be achieved. In SQC, if the design is correct and the manufacturing process is stable (in-control), then the quality of the product is good. Thus, for a properly designed management system, the key to good soil quality is process control.

The objective of engineering control is to identify the key variables controlling the process and chart those variables as in Fig. 1. The goal might be to achieve a specific amount of crop cover or crop residue cover on the soil surface after tillage. The key control variables would likely be associated with the tillage tool components that regulate how much crop residue is buried (e.g., operating depth, speed, implement angle or number). As posed by Pierce and Larson (1993), simply informing the farmer after planting that crop residue cover on the field does not meet erosion-control guidelines is too late to affect the process that created that condition. Adequate residue cover could be achieved if the key variables were charted and adjustments were made to bring the process back into control during the tillage operation. An important aspect of this approach is that it places the responsibility for soil quality in the hands of the land manager, which is the only way to really cause a change in soil quality.

It may seem that system design and engineering control are not practical in agricultural management systems. However, emerging technologies associated with site-specific management are, in fact, capable of achieving this level of design and control, including very accurate location control (e.g., global positioning systems, GPS), variable rate application equipment, sensors for both control and performance evaluation (e.g., yield monitors), and are now readily available (Larson and Robert, 1991; Robert *et al*., 1993,1995; Schueller, 1992). The potential for real-time control is rapidly emerging and may be the best means of achieving good soil quality. While monitoring will continue to be a focus in soil-quality assessment, it is soil-quality control that will affect the soil resource base. Both site-specific management and soil quality control have the same goal - to do the right thing, in the right place, at the right time, and in the right way. Therefore, site-specific management may be the key to achieving soil quality on the land.

Conclusions

The purpose of land management is to extract value from the land. It follows, that the ultimate goal of soil quality assessment, in whatever form, is the design and management of sustainable land management systems. Sustainable land management requires soil resource inventory and land evaluation, monitoring of soil quality, and full utilisation of soil quality control methods and procedures by land managers. The key to soil quality is in the hands of the land manager/operator. Soil quality assessment, however, is of little value if it does not incite an action on the land.

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Assessment of soil quality for effluent disposal

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Introduction

The living soil is the medium in which dead organic matter returned to the land is converted to simple, non-toxic, inorganic compounds, including water, SO_4^{++}, NO_3^-, CO_2, and mineral salts of calcium, potassium, magnesium and sodium. It often is also a medium capable of immobilising and detoxifying inorganic contaminants such as heavy metals. Consequently, there is an increasing trend in many countries to use the soil for disposing of waste water, such as raw or treated sewage, effluent from factories and effluent from septic tank systems, rather than discharge such waste waters directly into rivers, lakes or the sea.

In effluent disposal on land, rather than being the wastes themselves, the waste waters are the carriers of organic or inorganic wastes. However, in any assessment of the quality of the soil for waste disposal, we must evaluate the ability of the soil, in reality of the entire geographical site being assessed, to cope with the volume of water being applied per unit time, as well as the soil's ability to degrade or immobilise the dissolved and suspended materials in the effluent. For those solutes which are and remain mobile in the soil, that is in the soil water phase, the evaluation must also include the balance between inputs and outputs. In general, such an evaluation consists of:

a) a water balance assessment;
b) a salt balance assessment;
c) an assessment of the soil's ability and rate for degrading added organics, usually expressed as BOD, COD or TOC; and
d) an assessment of the soil's ability and capacity to immobilise and store other non-degradable contaminants, e.g. phosphate or heavy metals.

We will now consider separately the assessment requirements for disposal of raw or treated sewage, factory effluents and effluent from domestic septic tank systems. This is necessary because in the first two cases one deals with very large daily flows, while in the third case only small daily flows are involved. In the case of sewage coming from a municipal collection system there can be a great diversity of dissolved and suspended contaminants, while in the case of factory effluents and certainly in the case of domestic waste water, the dissolved and suspended wastes are normally limited in diversity.

The quality(ies) of the soil that govern its suitability is(are) intensive properties. It will be seen in this paper that extensive properties, like the area of soil available for effluent disposal, can sometimes make up for limitations in quality. Alternatively, the end use may be slightly changed or the mode of effluent application may be altered, and finally, the soil may be modified to make it more suited to the goal of effluent disposal. Quantity may compensate for quality. However, the costs of a disposal scheme are affected by these changes or the need to acquire more land.

Disposal of sewage

Three main kinds of land treatment processes for sewage, raw or treated, can be distinguished: slow rate infiltration, rapid infiltration and overland flow (termed "grass filtration" by Melbourne Water in the Werribee Sewage Farm). They have different objectives as illustrated in Table 1 below.

In Victoria the most common system is the slow rate infiltration system, presumably due to the fact that many of the State's soils have a low permeability and due to the complications that can be caused by a rising ground water table under the disposal site, which may lead to waterlogging, salinity or both. It is not uncommon for disposal sites to have also geohydrological limitations caused by the presence of aquicludes, aquifers with low hydraulic permeability or ground water tables with very low hydraulic gradients to rivers and other bodies of open water acting as sinks. We are not aware of the existence of any rapid rate infiltration systems. As has been mentioned before, Melbourne Water practices overland flow (grass filtration) in some areas of the Werribee Sewage Farm.

Table 1. Comparison of land treatment systems for disposal of sewage (USEPA, 1983).

	Slow rate infiltration	**Rapid infiltration**	**Overland flow**
Objectives			
1.	Treatment of waste water	Ground water recharge	To achieve secondary effluent quality for screened raw waste water
2.	Economic return from use of water and nutrients	Recovery of renovated water by wells and underdrains and reuse	To achieve high levels of N, BOD and SS removals
3.	Water conservation	Recharge of surface streams receiving ground water	
4.	Preservation and enlargement of greenbelts and open space	Temporary storage of renovated water in an aquifer	
Design Features			
Application techniques	Sprinkler or surface[a]	Usually surface	Sprinkler or surface
Annual loading rate, m	0.5-6.0	6-125	3-20
Field area required. ha[b] for 1 ML/day flow	6-74	0.8-6	1.7-11.6
Typical weekly loading rate, mm	13-100	100-240	60-400[c]
Minimum preapplica-tion treatment provided in the United States	Primary sedimentation[d]	Primary sedimentation[e]	Grit removal and comminution[e]
Disposition of applied waste water	Evapotranspiration and percolation	Mainly percolation	Surface runoff and evapotranspiration, some percolation
Need for vegetation	Required	Optional	Required
Site Characteristics			
Slope gradient, %	< 20% on cultivated land; <40% on non-cultivated land	Not critical; excessive grades require much earthwork	Finish slopes 2-8%[f]
Soil permeability, mm/day	mod, slow - mod, rapid 37-366	rapid (sands, sandy loams): > 366	slow (clays, silt, soils with impermeable barriers: < 37
Depth to ground water	0.6-1 m (minimum)[g]	1 m during flood cycle[g] 1.5-3 m during drying cycle	Not critical[h]
Climatic restrictions	Storage often needed for cold weather and during heavy rains	None	Storage usually needed for cold weather

a. Includes ridge-and-furrow and border strip;
b. Field area not including buffer zones, ditches or roads;
c. Range includes raw waste water to secondary effluents, higher rates for higher level pretreatment;
d. Restricted public access, and crops not for direct human consumption;
e. Restricted public access;
f. Steeper grades may be feasible at reduced hydraulic loadings;
g. Underdrains can be used to maintain this level at sites with high ground water table;
h. Impact on ground water should be considered for more permeable soils.

In the following section we will only consider the slow rate infiltration system.

Water balance

The evaluation of the water balance deals with the function of the soil to regulate water, i.e. to allow infiltration of water applied to the soil surface, to store water, to allow percolation of water in excess of the storage capacity, and for the function of an aquifer below the site to remove water laterally to a sink, i.e. a geohydrological assessment. This evaluation must begin by taking into account the expected water use throughout the seasons by the vegetative cover as well as the expected rainfall regime at the subject location and its variability over long periods.

There are four main and well-known methods for predicting plant water requirements to obtain a reference plant evapotranspiration (Eto) for a given climatic condition at a given site (Doorenbos and Pruitt, 1992). These are the Blaney-Criddle method, the Radiation method, the Penman method and the Pan Evaporation method. The parameters needed to employ these methods are tabulated in Table 2.

Table 2. Parameters needed for calculation of predicted evapotranspiration (Eto)

Method	Parameters	Formulae
Blaney-Criddle	Mean daily air temperature in ºC over the month considered; % total annual daylight hours during period considered; relative humidity (minimum daytime), sunshine hours, daytime wind	Eto = c[p(0.46T + 8)] mm/day in month considered T = mean daily temp. ºC over the month p = mean daily % of total annual daytime hours (from Table of values) c = adjustment factor depending on min. rel. humidity, sunshine hours and daytime wind estimates
Radiation	Measured air temperature, sunshine, cloudiness or radiation, general knowledge of humidity and wind	Eto = c(W.Rs) mm/day over period being considered Rs = solar radiation in equivalent evaporation in mm/day W = weighting factor depending on temperature and altitude c = adjustment factor depending on mean humidity and daytime wind conditions
Penman	Measured temperature, humidity, wind and sunshine duration or radiation	Eto = c[W.Rn + (1-W).f(u).(ea-ed)] W = temperature-related weighting factor Rn = net radiation as equiv. evaporation in mm/day f(u) = wind-related function (ea-ed) = difference between saturation vapour pressure at mean air temp. and mean actual vapour pressure of the air in mbar c = adjustment factor to compensate for effect of day and night weather conditions
Pan Evaporation	Pan evaporation data from either Class A Standard Pan or Colorado sunken pan	Eto = Kp.Epan mm/day, Epan = measured pan evaporation in mm/day as the mean daily value over the period considered Kp = pan coefficient

Care must be taken not to confuse the reference crop evapotranspiration, Eto, with pan evaporation, Eo, and actual evapotranspiration, Et. Reference crop evapotranspiration is often referred to as potential evapotranspiration in the case of a fully developed leaf canopy and full cover on the ground, the actual evapotranspiration being dependent on the stage of canopy development of the vegetative cover.

Many consultants in Victoria simply multiply the monthly Eo values for the nearest Class A Pan, or the Class A Pan situated at a locality most typical of the subject site, by a factor of 1.0, 0.8, 0.75, 0.6 or less, depending on their optimism or instincts or whether it is grass or trees that are irrigated, to derive the predicted actual water use by the vegetation of an irrigated site. The factor is usually referred to as the crop factor. Work done by the

CSIRO Division of Atmospheric Physics at Aspendale, Victoria, tends to be the basis for choosing likely appropriate crop factors (McIlroy and Angus, 1964; Dilley and Shepherd, 1972).

Having determined the likely evapotranspiration for each month during a year by the vegetation to be irrigated, in Victoria generally pasture or woodlots, the further development of a water balance requires that monthly rainfall is subtracted from these values. In months in which there is a water deficit, the deficit can be compensated for by application of waste water. However, other factors must be considered as well in establishing a complete water balance equation of all inputs and outputs. Also, it is necessary to evaluate the salinity of the irrigant because a leaching component is needed to remove all added salts from the root zone. Where the nitrogen level of the irrigant is high, it may be necessary to design the irrigation system to restrict the application of waste water in order to enable fuller uptake of N by the vegetation (and smaller losses to the ground water).

Kaddous, Stubbs and Morgans (1986) on the other hand used the Penman Equation to calculate a predicted potential evapotranspiration rate for an experiment in which secondary treated effluent was used for irrigating vegetables growing on a loamy sand soil at the Vegetable Research Station, Frankston. Since this was a research project, they made quite extensive assessments of the effect of the application of this effluent on the soils, its composition, the uptake of nutrients by the vegetables and the leaching and drainage requirements of a sustainable system.

The water balance can be written as (Hoffman, 1990. In: Tanji (Ed.)):

$$Ds = Dr + Dg + Di - De - Dt - Dd$$

where D = depth of water, and the suffixes stand for, respectively:
s = storage in the soil
r = rainfall
g = upward capillary flow from ground water
i = irrigation
e = evaporation
t = transpiration
d = drainage.
In this equation, lateral runoff is neglected as a term.

As the salt concentration of the waste water increases, it is necessary to design for an increased deep drainage term, Dd. This is usually called the leaching requirement, LR.

Hofmann's equation can also be used to describe a salt balance by multiplying all the liquid flow components with their appropriate salt concentrations (C), adding all the salts originating from fertiliser application and soil weathering, and subtracting all the salts that have precipitated in solid form or were removed in the crop.

$$Ss = DrCr + DgCg + DiCi + Sm + Sf - DdCd - Sp - Sc$$

where the suffixes have the same meaning as in the previous equation, and the new terms are:

Sm = salt dissolved from minerals in the soil
Sf = salt added in the applied fertiliser
Sp = salt precipitated, and
Sc = salt removed in the harvested crop.

Since water uptake is generally maximal in the topsoil, where most of the roots are, and decreases with depth, the highest increase in salt concentration occurs in the topsoil, but the highest absolute salinity occurs at the base of the root zone. The magnitude of the leaching requirement therefore depends on the salinity of the irrigated effluent and the maximum salinity of the soil water that can be tolerated by the vegetation in question at the base of its root zone.

Sustainability of irrigation requires:

$$DiCi + DrCr - DdCd = 0$$

and

$$(Sm + Sf) - (Sp + Sc) = 0$$

From these conditions a simple expression of the leaching requirement can be derived:

$$LR = Dd/Da = Ca/Cd = ECa/ECd$$

where a = average for all the water applied, rainfall plus irrigated effluent,
EC = electrical conductivity.

Ayers and Westcot (1989) recommend the use of the Rhoades (1974) and Rhoades and Merrill (1976) equation for calculating leaching requirement:

$$LR = ECw / [5\ ECe - ECw]$$

where: LR = minimum leaching requirement needed to control salts within the tolerance (expressed as ECe) of the crop with ordinary surface methods of irrigation, expressed as a fraction of the irrigation water to be applied;

ECw = salinity of the applied irrigation water in dS/m; if rainfall is included in the water received by the crop, the average ECw must be calculated from the amount of effluent required by the crop after deducting the rainfall, and the salinity of both;

ECe = average soil salinity tolerated by the crop as measured on soil saturation extract, for which tables of values for a range of field crops, vegetables, fruit trees and forage crops are presented in their report.

Ayers and Westcot (1989) also provide a graphical means of deriving a leaching fraction.

If it is acceptable for the crop, pasture or trees to grow at less than 100% yield potential, then one can select higher salinities for the water exiting the root zone at its bottom, and consequently higher salinities throughout the root zone. The Yield Potential Tables in Ayers and Westcot (1989) list the critical salinities for both ECe and ECw at 100%, 90%, 75%, 50% and 0% for all the plant species listed. Choosing a lower potential yield enables one to reduce the leaching fraction. It thus becomes a tool in irrigation management providing alternative strategies if the geohydrological conditions at the site require the minimisation of ground water recharge.

To complete the water balance, one frequently assumes that the salinity of rainwater is 0, so that the average salinity of all the water received by the crop is reduced proportionally. The actual amount of water, AW, to be applied to satisfy both crop demand and the leaching requirement is found:

$$AW = ET / (1-LR)$$

if rainfall is insignificant and can be ignored, and

$$AW = (ET - Dr) / (1 - LR)$$

if rainfall is significant.

On sloping sites, the percentage runoff should be estimated. Runoff is a function of slope gradient, surface roughness and density of the vegetative cover, as well as the antecedent wetness of the surface soil. There are empirical methods for this, for example Burton (1965).

Salt balance

As is clear from the above, the salt balance of a site irrigated with effluent is in equilibrium when the water balance has been established following the method shown above. Computer models are available for working out salt and water balances, for example SWIM by CSIRO, TeTrans by the U.S. Salinity Laboratory in Riverside, California, and Watsuit developed by J.D. Rhoades of the U.S. Salinity Laboratory.

Having solved the water and salt balance for a proposed effluent disposal scheme, one can then assess the site, including the soil, to determine if the area is capable of handling the extra water and salt inputs, and what, if anything, must be done to modify the design or the site, and how to manage it, to enable the scheme to go ahead. The USEPA (1983, 1984) and earlier manuals going back to 1975, as well as Pettygrove and Takashi Asano (1985) give guidelines for such site assessments.

Nitrogen balance

The USEPA (1981) provides a calculation model for calculating the allowable annual hydraulic loading for effluents high in nitrogen to be used for irrigation in areas where potable ground water aquifers must be protected. The parameters in the model include:

Lw(N) = allowable annual hydraulic loading rate based on N limits, cm/yr
Pr = precipitation rate, cm/yr
ET = evapotranspiration rate, cm/yr
U = nitrogen uptake by crop, kg/ha.yr (values selected from Tables)
Cn = nitrogen concentration in applied waste water, mg/L
Cp = phosphate concentration in applied waste water, mg/L
f = fraction of applied nitrogen removed by denitrification and volatilisation (values empirically obtained by monitoring several existing slow rate infiltration systems in the United States).

The model is stated in the form of:

$$Lw(N) = [\ Cp\ (Pr - ET) + U.10\ ] / [(1-f)\ Cn\ -\ Cp]$$

The computer model developed by Max Thomas, while an officer of the Victorian Environment protection Authority, is the first local design system that takes in the nitrogen balance, as well as the water balance and a leaching fraction to remove unwanted salts for pastures or tree plantations. It is a major step forward from basing decisions on a matrix approach to land capability.

BOD and suspended solids removal

Since in slow rate infiltration systems the effluent is added to the surface of the land, oxygen has free access to the applied effluent as well as to the upper layers of the soil. Dissolved and suspended organics are rapidly degraded in this environment. Consequently, BOD removal is normally not a limiting factor, nor is the removal of suspended solids. Removal rates of 98-99% of added BOD are normally achieved. If the effluent has already been pretreated to a standard of 20 mg/L of BOD, the subsequent renovation in the soil essentially removes all the remainder.

Phosphorus removal

Most soils are capable of adsorbing and/or precipitating phosphorus, depending on clay content, concentration of “active” aluminium, iron and calcium compounds, and on the soil pH. The phosphorus sorption capacity of soils is often very large, but it is finite. On coarse sandy soils in the coastal plain of Perth, phosphorus accessions from septic tank effluent disposal soak pits to the ground water was becoming a problem after several years of operation (Whelan *et al.*, 1979). These authors concluded that in the older disposal systems phosphate was released to the ground water at the same rate as it was added to the soak pits, since the sorption capacity of the sand was fully saturated.

However, these sandy coastal plain soils are an extreme example. All the slow rate infiltration systems with which we are familiar are situated on clay soils, which will have a vastly larger sorptive capacity. The USEPA makes a reference to a predictive test for actual phosphorus retention by soils.

Crop uptake of P can remove phosphorus in the range of 20-60 kg/ha.yr (USEPA, 1981). Empirical data obtained at eight United States slow rate infiltration systems showed that removal rates for Total Phosphate were always in the range of 98-99%, with one exception of 76% at Camarillo, California. At these eight locations, the soluble PO_4 concentration in the background ground water varied between 0.02 and 3.0 mg/L, with a geometrical mean value of 0.09 mg/L.

The USEPA Manual referred to here (USEPA, 1981) does not provide a calculation model for a water balance based on a phosphorus balance, although a reference is made to an empirical model to predict the life of a slow rate infiltration system based on a finite, and time-dependent P sorption in the soil (Enfield and Bledsoe, 1975). Presumably, it is only under rare circumstances that a phosphorus balance is critical.

Heavy metal adsorption

Municipal waste water containing significant loadings of heavy metals will cause a rise of heavy metal content in the soil, especially the topsoil, as has been documented for the Werribee Sewage Farm (Johnson *et al*., 1974; Evans *et al*., undated, later than 1978). On this farm pastures on heavy clay soils with slightly acid to alkaline reaction had been irrigated with sewage for up to 73 years at the time Johnson *et al*., (1974) investigated the soils. Taking total soil lead concentrations as an example, they found that in the upper 2.5 cm the total Pb concentration was up to six times higher than in a control (non-irrigated) soil (44 mg/kg), but at 25-45 cm depth there was no great difference between the irrigated and non-irrigated soil. Similarly, cadmium had increased more than 3-fold in the upper 2.5 cm from the control (0.17 mg/kg), and only slightly at 25-45 cm depth. Soil phosphate showed a similar trend.

Evans *et al*., (1978?) show heavy metal concentration profiles in the soils of Werribee which mostly illustrate the tendency for the soil to immobilise the heavy metals in the top 20 or 30 cm.

General remarks on slow rate infiltration systems

We have seen that in the assessment of soil quality for effluent disposal by slow rate infiltration (irrigation) the water balance and the salt balance must be solved simultaneously, and that a disposal system cannot be sustainable unless the salt balance of the root zone ensures that all added salts are removed by deep drainage. Ensuring that there is a sustainable nitrogen balance is a secondary concern. Phosphorus accumulation is generally not a problem in many soils, except that it can become a problem to the selected vegetation type. Apparently, some species of tree do not grow well when over supplied with P.

Heavy metals are generally adsorbed quite strongly in the upper soil layer, say to a depth of 20-30 cm. Their solubility in the soil water is usually too low to be taken up and to cause a toxicological reaction from plants growing on the soils.

Also, it has been shown that if the soil quality for effluent disposal is somewhat deficient, the deficiencies can often be compensated for by utilising a larger land area or managing the irrigation system in a more appropriate manner.

Disposal of factory effluent

The calculation of water and salt balances in these cases are identical to the method shown above, but in the case of factories special consideration must be given to the composition of the effluent.

For example, a wool scouring operation may produce effluent with an exceptional high concentration of potassium salts and a very high pH. Abattoirs often produce effluent with very high concentrations of sodium chloride salt. Tanneries used to produce effluent with high concentrations of chromium salts. Electroplating industries used to discharge high concentrations of a range of heavy metals as well as cyanide. Dairies have effluent which creates a high salt load as the milk, which contains some salt, is collected from a very large "catchment" and concentrated in a small area. Their effluent may also have a high BOD as well as suspended organic particles which can cause some clogging of fine soil pores.

Overland flow systems (grass filtration)

A water balance and salt balance is not required for this mode of disposal, but obviously the rate of application of effluent must be high enough to bring about overland flow to the bottom of the irrigation bay, and not too high to prevent the filtration process and the bacterial degradation processes. The USEPA (1981) provides design parameters including a method for determining hydraulic loading rates for overland flow systems. USEPA (1984) provides a model for calculating optimum bay lengths for the removal of BOD, but the model needs to be calibrated against local conditions within the bays.

Also, the length of the flow path must be adequate to bring about the removal of pollutants to a satisfactory degree. Scott and Fulton (undated, probably after 1976) describe the performance of the grass filtration system at Werribee. Their bays had a maximum length of 250 m. They found that removal of BOD, Suspended Solids and Heavy Metals was good. On the other hand, nitrogen and phosphorus removal was limited.

Overland flow systems are typically used when the soils have low permeability or where there are layers at depth with a low permeability. Scott and Fulton (1976?) state that the clay soils in their experiment had a permeability of around 1mm/day.

Disposal of septic tank effluent from domestic installations

There are several methods available for disposal of such effluent. They include:

- Conventional absorption trenches;
- Combination absorption/evapotranspiration trenches;
- Mounded effluent disposal systems;
- Subsurface irrigation systems;
- Surface irrigation trickle systems;
- Sealed evaporation beds; and
- Sandfilters followed by off-site discharge.

Sandfilters followed by off-site discharge are systems which are independent of soil quality within an allotment served by a septic tank. Sealed evaporation beds have a major disadvantage in that they accumulate salts as water is transpired by the vegetation. Ultimately they have to be flushed and pumped out, or else the vegetation will die. They are also independent of the quality of the soil. Therefore, these systems will not be discussed further.

Mounded systems are constructed on imported suitable soil, if the soil at the locality is either very shallow over creviced rock, has low permeability, or has a high seasonal water table. In all other respects they are similar to absorption trenches.

Water balance and salt balance

Since these domestic effluent disposal systems are small there is normally no great concern about recharge causing a significant rise of the local ground water tables and attendant salinity. Excess water arriving in an effluent disposal field can be re-distributed to the soil around it if the permeability of the subsoil is rather low, or percolate downwards to the ground water if the permeability of the subsoil is moderate to high. Any salt in the effluent is removed as the effluent spreads sideways or downwards. Winter rains then take care of the leaching.

However, a water balance has to operate in the trench system, or else it will overflow. Effluent being stored (or ponded) in a trench causes a bacterial slime layer to form on the submerged soil interface, which acts as a hydraulic barrier. On the trench side of the slime layer the effluent is at atmospheric or at positive hydrostatic pressure - the head of water in the trench. On the soil side the soil moisture is at a negative pressure or matric suction, under normal conditions in a draining soil. The pressure difference causes the effluent to flow from the trench into the surrounding soil in all directions where there is a hydraulic gradient.

Extensive research in the United States and similar research activity in Victoria (Brouwer, 1982; Brouwer and Bugeja, 1983) has shown that there appears to be a statistical relationship between the long term effluent infiltration rate or long term absorption rate (LTAR) through the submerged trench surface into the unsaturated soil behind it and the permeability of the soil determined in a field test using clean water. For the more permeable soils the LTAR is a very small fraction of the measured soil permeability, but for the least permeable soils the LTAR tends to be about the same magnitude or a little smaller than measured soil permeability.

This statistical relationship consists of a scatter diagram through which a best fit line can be drawn, or below which a conservative envelope can be sketched. The resulting diagram can then be used for predicting the size of the trench system, i.e. the magnitude of the infiltrating surface a trench system must have, to allow the safe infiltration of a specified average daily loading of effluent. It has become the design curve in the Victorian Code of Septic Tank Practice (EPA, 1990) as in Figure A4.1.

Brouwer (1982, 1983) also developed a model which can be used to design the size of a combination absorption/evapotranspiration system, for a site where there is a quantifiable or assessable amount of runoff from a sloping site (using Burton’s Table, 1965), a certain effective rainfall, pan evaporation, and deep percolation. To achieve this, he had to use all available data on effluent plus rainfall inputs and measured outputs, including the regime of ponding of effluent in the trenches, for all the disposal fields that were monitored. Harmonising the data, he was able to develop a mathematical description of the water balance in such effluent disposal fields throughout the twelve months of the year. As pan evaporation data are relatively scarce compared to rainfall data, Brouwer also developed a statistical relationship between pan evaporation and annual rainfall for a range of meteorological stations in Victoria. This relationship enabled him to extend the model to locations with up to 900 mm average annual rainfall.

This model has become the basis for the design curve for the combination absorption/evapotranspiration system in the Code of Septic Tank Practice as in Figure A4.2. This design curve is a conservative curve as it is based on the performance of disposal fields under prolonged wet conditions, which approximate the 1 in 10 year high rainfall.

By taking into account the potential storage volume available in the voids between the screenings used to fill an absorption trench, or the space under the RELN drain (self-supporting durable fibreglass or plastic arching), Brouwer was also able to develop a calculation model to design a trench system that could cope with 3 to 5 months in which the sum of the effluent output components was smaller than the sum of the inputs. During this time, the level of ponding of effluent in the trench increased, but without overflowing the trench.

Nutrient balances

The nutrients added from a domestic septic tank system tend to be nitrogen and phosphorus mainly. Most of these nutrients are added to the soil in small quantities and in many cases they have not proved to be a problem. Where the soils are highly permeable and have a low sorptive capacity, nitrogen and phosphorus can travel a long distance from the disposal field. The coastal plain soils of Perth have already been mentioned as such a case.

On rural residential allotments, especially those subdivided from old farm land, septic systems tend to release smaller quantities of nutrients to the environment than was the case under agricultural exploitation and fertiliser use.

Brouwer and Bugeja (1983) describe a small (13 ha) subcatchment at Mount Macedon Township where they monitored the nutrient fluxes and concentrations at several sampling points along a small stream. There were 17 dwellings in the subcatchment, of which two were used only on weekends, but the remainder were occupied all the time. The export of nitrogen and phosphorus from this subcatchment was far smaller than the inputs through the human wastes. Total P in surface water never exceeded 0.09 mg/L and Total Kjeldahl Nitrogen was generally below 1.4 mg/L. These were low concentrations and do not cause concern.

Recently, Gerritse *et al*., (1995) carried out a more detailed study of catchments in unsewered mixed rural and residential areas on the Darling Plateau near Perth, and also found that stream concentrations of nitrate were much lower than expected from the rates of input. They concluded that at least 80% of the nitrogen leaching from domestic septic tank systems was lost within a distance of 10 m from the leach drain. Phosphate was strongly adsorbed by the soils, and dissolved phosphate concentrations in streams was also low and not related to land use.

Thus, it appears that in many cases septic tank systems are not contributing to stream pollution, except, perhaps, when they are failing and overflowing. This underlines the need for proper design and sizing, taking into account the properties of the soil in which they are to be established.

Inevitably, however, the soil in and around a disposal field will become enriched with phosphate. To some extent this can be dispersed by lawn mowing and removal of the clippings, etc.

Conclusions

Effluent disposal on land cannot be done in a manner that has no impact on that land or the surroundings whatsoever. One has to make a judgement whether the functionality of the soil is largely being protected, or, if a sacrifice has to be made, whether the loss of functionality of an area of land more than offsets the loss of functionality of other parts of our environment.

In carrying out the investigations on which these judgements must rest it is essential that a holistic perspective is taken and that all on-site and off-site processes are taken into account.
Soil scientists with a good background knowledge of general earth sciences, including pedology, can play a vital role in these investigations and decisions.

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Tillage Effects On Soil Quality

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The US Department of Agriculture has been involved in soil quality for 60 years, through its Natural Resource Conservation Service (formerly Soil Conservation Service) and Agriculture Research Service, but generally under the name of "conservation farming". The focus was primarily on minimisation of soil erosion and soil compaction. With the more recent worldwide emphasis on soil quality, these agencies are beginning to examine all aspects of the soil resource and its fitness to function within its surroundings.

This paper will discuss the effects of tillage on soil quality, by examining its impact on the basic soil functions. The five basic functions are generally thought to be: a) Sustaining biologic activity, diversity, and productivity; b) Regulating and partitioning water and solute flow; c) Filtering, buffering, degrading, immobilising, and detoxifying organic and inorganic substances; d) Storing and cycling nutrients and other elements; and e) Providing support for plant, animals, and human life. The tillage effects on these functions will be from the perspective of south eastern US soils. These highly weathered soils are inherently infertile and highly dispersible since their mineralogical suite tends to be quartz and kaolinite. This not only hampers their buffering, filtering, and nutrient cycling functions, but the physical and chemical forces responsible for structure and aggregation are reduced. Therefore, much of the burden for carrying on these functions is reliant upon the organic fraction. Unfortunately, nearly year-round biologic activity allows for rapid decomposition rates which makes crop residues difficult to maintain.

Tillage Effects On Basic Soil Functions

Since quality is so dependent on the soil biology, the effects of tillage on the organic fraction of these soils is magnified. A 10 year study on no-tillage (NT) versus conventional tillage (CT) in the Appalachian Plateau of North Alabama showed an increase in the upper 10 cm in soil carbon from 0.6% to over 1 % with NT (Wood *et al*., 1992). Soil organic matter is an indicator for several of the basic soil functions. This feature relates to more microbial activity, possibly increased biodiversity, improvement in water and solute flow from increased aggregation , and improved CEC for buffering and nutrient cycling. The improvements in soil physical properties reduce erosion, abate traffic problems and, therefore, improve the support function of soil quality. Soil carbon also benefits these poorly structured soils by increasing another indicator, earthworms. Hendrix *et al*., (1992) found a 1 % increase in soil carbon translating to a nearly 4 fold increase in earthworms. Not only does the soil carbon have an influence on worm numbers, the worms in turn help increase porosity and infiltration. Although total porosity changed very little (56.3% to 59.9%), the infiltration rate changed significantly (0.89 to 2.79cm min^{-1}), indicating a change in pore size distribution partly attributable to earthworms. Under conventional tillage these changes do not occur and the basic functions of water flow, biodiversity, nutrient cycling, and support have little chance of improving.

Improvements can also be accomplished with sod rotations. Five years of bahiagrass sod increased subsoil porosity in a south eastern US Coastal Plain soil by doubling the number of pores, with the most significant changes in the larger pores (>1mm) (Reeves *et al*., 1993). Sod prior to tillage more than doubled cotton root penetration below the tilled zone when compared to continuous tillage and deep tillage (Elkins *et al*., 1977). Without seeding a sod, the effects of tillage on these highly weathered soils can be long lasting even when left fallow. Reeves (personal communication, 1996) found a Coastal Plain soil left fallow for 10 years to still have a severely compacted zone below the plough layer with indentions in this zone from a chisel plough from the last attempt to break the compaction.

Is No-Tillage The Answer?

The detrimental effects conventional tillage obviously impose; coupled with the highly touted benefits on no-tillage, make it appear reasonable that the solution to enhancing quality in these soils is conversion to no-tillage. United States farm policy states practices leaving 30% residue cover must be employed in order to stay in compliance with conservation provisions. Cotton growers in north Alabama realising the need to conserve the soil resource and stay in compliance have begun to try conservation tillage. This is a major step for these landowners which staunchly prefer to stick to the conventional practices that proved successful in the past. Many still burn residues prior to spring tillage as a form of weed control and invert the soil with a mouldboard plough after harvest. Winter cover crops are rarely used because of the belief they are too difficult to plant in and the soil warms too slowly in the spring for continuous cotton. A federal cotton program and the economics of cotton versus other crops discourages rotations. Cotton is a very low residue producing crop and any form of tillage still tends to reduce residue cover to less than 30%, therefore no-tillage farming becomes the logical choice.

Under adequate growing conditions, no-till yields are slightly lower but comparable to conventional tillage for the first two to three years. At which time yield begins to decline noticeably. Under dry conditions, yield can be 20% to 50% lower. A five year study by Burmester *et al*., (1993) shows NT cotton yields 10% lower than CT. A wheat cover produces yields which are only 5% lower, which is economically acceptable. This reduction is especially troubling when one of the advantages of NT is improved moisture capacity. The addition of a wheat cover crop eases the yield decline, even though this addition may deplete some moisture reserves. Examination of some plants shows the cotton tap root making a 90 degree at the 5 to 8 cm depth, indicating the presence of a restricting layer. The plants are only able to efficiently utilise the upper 8 cm of soil, thus explaining the yield decline in dry years.

Soil cores were taken from the row middles in some North Alabama fields and the morphology was described. The 5 to 8 cm depth had fine platy structure. Some of the larger horizontal planes are readily seen, but on close inspection with the naked eye, up to 50 planes can often be seen. Cores from lower depths, undisturbed sites, and tilled sites have the expected blocky structure. Roots have to follow these planes until a weak spot is found. This translates to about 5 cm of rooting depth and thus the droughty conditions due to this farming practice. Penetrometer readings were taken to quantify soil strength to determine if the resistance is sufficient to stop cotton roots. A limiting value of 2 Mpa as determined by Taylor and Gardner (1963). Resistance across the 1m row was determined with a tractor mounted penetrometer. Sufficient resistance to cotton roots was found at 2cm under wheel traffic and 5cm in the planted row middles. The compacted layer not only limits roots, but slows water movement enough, that erosion is as much a hazard with NT as CT. In some cases it may be worse because the random roughness from tillage is absent.

Alternative Approaches

Obviously, straight conversion from conventional tillage to a no-tillage system requires careful planning in the cotton region of north Alabama. The highly weathered, dispersible nature of these soils and the historically intense farming practices may require a slow transition from tillage and the use of less disruptive tillages with varied cropping systems.

Other Tillage Practices like chisel ploughing, ridge tillage, mulch tillage, in-row subsoiling, and strip tillage may provide the means to begin conditioning the soil for reduced tillage systems. The chisel plough is good for disrupting shallow hard pans, but on the north Alabama soils it tends to leave large clods which interfere with planting and seedling emergence. Mulch tillage has become popular in this area because it combines the chisel with a disk harrow. This solves the clodding problem and helps smooth eroded spots in the field. However, the mixing that occurs tends to enhance residue degradation, so in a continuous cotton system the soil building is reduced. Under ridge till systems, ridges are built and annually planted so there is less total tillage of the soil and traffic is controlled. Similarly, strip tillage spatially disrupts less land area by opening narrow tilled areas for planting leaving as much as 75% of the area between rows untouched while controlling traffic. Reeves *et al*., 1990 found that traffic with or without tillage can produce a compacted zone in the upper 10cm capable of restricting cotton roots. Also, by controlling traffic, traffic pads may begin to develop and equipment can move through more easily, even under wet conditions. A very promising alternative for these soil types is in-row subsoiling. It provides little residue disruption while alleviating the shallow compaction problems. Since the compaction generally occurs in the upper 10cm, soil strength studies by R.L. Raper and E.C. Burt of the National Soil Dynamics Lab have shown 18cm subsoiling gives just as good results as the 33cm treatment . It requires 2.5 times less energy and therefore can be accomplished by smaller tractors .

A more biological approach to improving soil quality in developing a NT system is to use cover crops and crop rotations. Rotations are probably the best system to use with no-till cotton, however as indicated before the cotton program discourages this practice with the potential penalty of losing acreage allotted for cotton. The current Farm Bill may solve this road block. However, growers adopting cotton-corn rotations report average to increased yields over CT regardless of climatic conditions. Even with tillage, cover crops can improve infiltration by increasing pore sizes and disrupting pan development in the winter months (Elkins *et al*., 1977). The added residues from the cover crop are also a much needed boost for low residue crops like cotton. This practice has been hard to sell to growers since they believe it delays planting time by keeping the soil cooler. Also heavy residue from wheat is more difficult to plant in and the wheat must be killed prior to planting. However, a wheat cover with NT cotton on these soils was found to reduce soil strength below the critical level of 2MPa. Currently researchers are working with other cover crops such as black oats, which does not produce as much residue as wheat, and using some climatic models to see if the cold soil argument is valid or can planting time be delayed. Hopefully, benefits from cover crop practices found to improve soil quality in NT corn may also be true with cotton. Reeves *et al*., (1993), determined several indicators of the water transfer functions have been improved in both the heavy clay soils of the Appalachian Plateau as well as the sandier soils of the coastal Plain. After five years of NT corn with a clover cover, hydraulic conductivity more than doubled in Coastal Plain, as well as Appalachian Plateau soils. Bulk density was slightly decreased, although statistically insignificant, it was nonetheless a decrease. Water stable aggregates in the upper 6 cm increased from 47% to 57%, with the surface 3cm improving from 41% to 55%.

Narrow row and ultra-narrow cotton is a farming system that can be used in all tillage methods. The row widths are reduced from the traditional 1m to less than 30cm. This reduces the amount of erosion in-season, row middles are closed earlier thereby reducing weed competition and the need to spray or cultivate, thus reducing traffic in the field. Even under conventional tillage, less traffic reduces compaction and elimination of weed control cultivation reduces the destruction of soil physical properties. However, it still fails to produce enough residue, so cover crops are generally recommended. It tends to produce a higher quality lint, but the stripper-pickers required for harvest need some improvement in removing trash.

Conserving Gains

What should we do after gains are made in soil quality and how much can we improve a drastically disturbed soil. During the construction of a highway in North Alabama, 1 to 3 metres of soil material was removed for construction. After nearly 30 years of fescue sod planted in this sterile soil parent material, soil carbon in the upper 3cm has reached a level of 2.66%. Subsequently, a portion of the field was tilled using a mouldboard plough and CO_2 measured immediately after turning. Escaping CO2 was measured with a field tent apparatus and found to be nearly 60 g m-2, compared to less than 10 in the untilled sod. This indicates much of the gains from 30 years of sod would be lost in a very short period by ploughing. After one season of cotton, samples were taken in late fall after the soil was tilled again. Some reduction in the surface 3 cm, 2.66% total C to 2.19% was determined, but gains in the tilled 3-8cm and 8-13cm depths indicate it to be the result of mixing. The upper 13 cm have essentially the same amount of carbon. However, the soil colour does show some differences with the surface changing from 5YR 3/2 to 5YR 3/3 and 4/3. It may be that the organic fraction has changed forms and there is a different humic/fulvic acid ratio. Also, the single years residue from the cotton may have periodically maintained total C levels and the coming year may show the more expected result. In 30 years sod was able to produce a pretty decent surface soil and yields were somewhat acceptable considering the history of the site. Despite these early results, it must be stated that once gains in soil quality are made, diligent efforts in maintaining the resource are necessary. Researchers in soil quality need to develop the decision aids, with respect to tillage, for the growers so they can maintain economic and soil health.

Conclusions

To conclude some thoughts on tillage effects on soil quality, No-tillage systems in the highly weathered, intensely farmed soils of the south east require special consideration in improving a soil's health or quality. We may need to use a gradual conversion from conventional methods. This process can be accomplished by less disruptive tillages, controlling traffic, and using cover crops and rotations.

Gains produced from this conversion must be carefully monitored and maintained in order to have lasting soil quality.

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Soil and management for grain production

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Short Abstract

Background

I am a grain grower from the red brown soils of southern NSW. These soils are highly acid, easily erodible yet fairly productive given good management. Lucerne drives our farming systems.

Is soil a medium to prop up a growing plant or is it a **live, healthy living mass** undergoing constant change through crop and pasture phases depending on the dictates of weather conditions. As far as knowledge allows us to do at this stage, land management should evolve addressing subsections of soil units uniquely.

Figure 1 shows the measurements used to monitor pasture production. In planning a major soil use change to increase the profitability of an enterprise, in this case increased wool production per hectare, one would expect certain trade offs such as lower grain production, soil degradation and acidification among others. However, the opposite was found to occur and after a time lapse of 4-5 years soil health as we measured it improved. Grain yield showed signs of improvement, stocking rates improved significantly, weeds disappeared, with improved pasture runoff was reduced and erosion was negligible, fire risk was reduced and occasional green summers occurred. The only negative effect observed was a rapid decline of pH, however, liming can pay through farm productivity improvement.

Another shortfall was lack of good benchmarks for soil indicators, such as:
- organic carbon
- sulphur
- syzine
- available P
- Nitrogen
- Microflora

Though we now have many of these measurements they are still poorly understood, and we have not been able to say without doubt which factor caused the change.

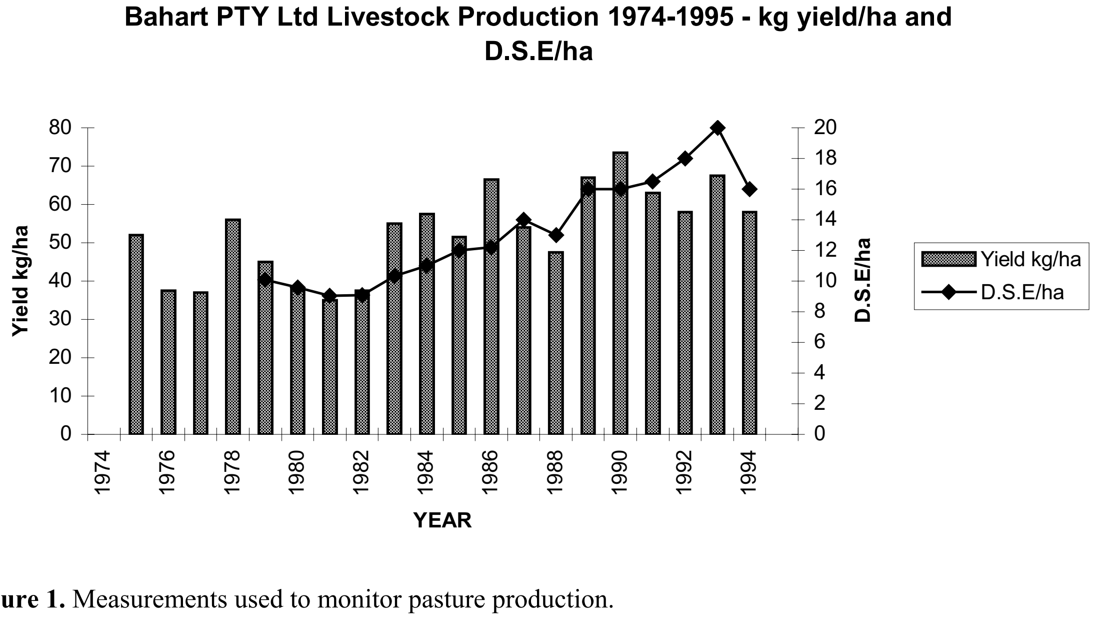
Bahart PTY Ltd Livestock Production 1974-1995 - kg yield/ha and D.S.E/ha

Figure 1. Measurements used to monitor pasture production.

Summary

1. Land management as it is today, using perennial legume pastures as the driver of a Whole Farm system, **is sustainable and can help to improve soil health**.
2. Land management incorporating crop residues on a continuous scale **is not sustainable**.
3. Land management using zero tillage methods is **soil sustainable** yet is **not environmentally sustainable**.

For good soil health a mix of the three is required

The outstanding issues are:

- A much deeper understanding of the soil processes
- Soil surface interaction of crop residues
- Tillage methodology to enhance structure development
- Soil monitoring capability packages.

Health Bench Marks by regional soil types.
The key restraint to this development is the lack of links between soil science, plant physiology and alleopathogens. Soil related issues of grain growers are ranked low amongst soil scientists, while we realised a much higher profile of soil related work is currently required by LRDC/Murray-Darling Commission etc **soil is the basis of every farm.**

Soil quality for dryland pastures

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Background

Dryland, temperate pastures of south-eastern Australia lie within the 500mm and 750mm isohyets that extend from western Victoria to northern NSW, and border the Great Dividing Range to the south and southeast. Rainfall is evenly distributed throughout the year in the southern NSW region and is winter dominant in north-eastern to southern Victorian region. The entire south-eastern region receives significant, sporadic summer rainfall (Milton Moore, 1973). Soils are predominantly duplex and are strongly acid, ranging in $pH_{(Ca)}$ from 4 to 5. Where soil pH declines below 4.5, aluminium toxicity becomes a problem (Kennedy, 1986).

Grazing management and sowing and fertiliser regimes have changed the botanical composition of dryland pastures from native perennial pastures to annual pastures of subterranean clover, volunteer annual grasses and weeds. Declining soil quality has accompanied this transition as indicated by the poor performance of sown perennial grasses in some areas, the failure of the drought-tolerant phalaris to persist and a lime response by the acid/aluminium tolerant species, cocksfoot (Ridley, pers comm).

The most important soil quality issues for dryland pastures are:
(i) Acid and acidifying soils
(ii) Inefficient water and nutrient use by annual, subterranean clover and grass pastures
(iii) Soil constraints to the growth and stability of desirable pasture species, particularly P deficiency.

The purpose of this presentation is two-fold. It outlines a multidisciplinary approach for assessing soil quality in a dryland pasture system and it examines the general usefulness of bioindicators to define soil quality. An industry-supported research program will be used as a "case study" to illustrate how practical management strategies of pasture manipulation and liming can change soil quality and how this change is being quantified. Because results are preliminary, emphasis will be placed on the approach rather than on conclusions.

The case study

This case study is an attempt to assess soil quality under dryland pastures using a multidiscliplinary approach. It is supported by three key Industry funding bodies, the Meat Research Corporation (MRC), the Australian Wool Research and Promotion Organisation of the International Wool Secretariate (AWRAP/IWS) and the Land and Water Resources Research and Development Corporation (LWRRDC). These bodies recognised that research needed to focus on (i) defining the mechanisms of soil quality decline, and (ii) assessing the effect of ameliorative strategies such as liming and changing pasture composition on this decline. Two hypotheses form the basis of the research effort. These are:
(i) The existence of highly acid soils and a pasture composition dominated by subterranean clover and annual grasses means that water and nitrogen (NO_3^--N) use is poor. Accumulation of NO_3^--N due to net mineralisation over summer, followed by significant autumn rainfall, results in nitrate leaching, a major cause of acidification.
(ii) Increasing the phalaris and cocksfoot component of the pasture improves water and NO_3^--N utilisation. This, in turn, reduces accessions of water and NO_3^--N to the groundwater and acidification of the surface soil.

The experimental design incorporates the "best" management option, represented by a limed perennial (phalaris, cocksfoot,subterranean clover) pasture (**PP+L**), with the "worst" option represented by an unlimed annual (subterranean clover, annual ryegrass) pasture (**AP-L**). Adequate rates of P, S, Mo and K fertilisers are applied to both treatments and the pastures are grazed by merino hoggett weaners in a three paddock rotation system with a 2.5 week grazing period. The site is located at Book Book , 50km south-east of Wagga Wagga, NSW, on a red podzolic acid duplex soil with annual average rainfall of 650mm. Evaluation of soil quality at the experimental site at Book Book outlines a multidiscliplinary approach (Table 1.). The protocol was designed by a team which is coordinated by Prof. R.White, and includes R. Simpson, P. Chalk, F.Dunin, L.Heng, R.Fisher, A.Ridley, D. Chen, J.Evans, L. Castlemans and K.Evans.

Table 1. Framework for Evaluation of Pasture Soils at Book Book (NSW).

Function	Attribute	Indicator for attribute	Method for attribute
To accept, hold and release water (and nitrate)	Deep drainage	Rainfall, evapo-transpiration, runoff (surface and interflow)	Tipping bucket (rainfall and runoff); Priestley-Taylor model (evapotranspiration)
	Nitrate loss	Solution Nitrate in run-off (surface and interflow)	Suction cup samplers and colourimetric analysis
	Earthworm activity	Earthworm abundance and species	Transect line of sampling points ($0.1m^2$) and identification
To accept, hold and release energy (C,N)	Organic matter	Organic carbon	Modified Walkley-Black
	Labile organic matter	Microbial biomass	Chloroform fumigation-extraction method (ninhydrin-reactive N)
	Nitrogen	Total N NH_4^+-N, NO_3^--N NH_3 volatilisation Denitrification N_2 fixation Microbial nitrification potential	Kjeldahl digestion KCL extraction/colorimetric analysis Oxalate absorption Acetylene Block Natural abundance (^{15}N enrichment) Short-term nitrification activity
	Earthworm activity	Earthworm abundance and species	Transect line of sampling points ($0.1m^2$) and identification
To maintain a suitable biotic habitat	Earthworm activity	Earthworm abundance and species	Transect line of sampling points ($0.1m^2$) and identification
	Microbial populations	Microbial biomass	Chloroform fumigation-extraction method (ninhydrin-reactive N)
	"Specialist" bacteria	Microbial nitrification potential	Short-term nitrification activity
To respond to management	Lime application	pH	pH meter
	Rotational grazing by sheep	Liveweight, wool production	Mass
	Pasture manipulation	Dry matter production Botanical composition	Falling disc meter BOTANAL standard transect

Table 2 illustrates how deep drainage and solution nitrate levels are reduced under the "best" option compared to the "worst" option. Use of perennial species and liming to pH $5.5_{(Ca)}$ to improve the soil chemical environment for growth of the drought-tolerant phalaris, reduced surface runoff and increased the soil water deficit at the start of the growing season. Longer-term effects on re-acidification cannot, as yet, be determined.

Table 2. Factors influencing the ability of soil to accept, hold, and release water and nitrate. Preliminary data from R. White, L. Heng, F. Dunin, and A. Ridley (April and July 1995).

Attribute	Key indicators for attribute	Advantage of PP+L (compared to AP-L)
Deep drainage (below 120cm)	Surface run-off and interflow	28% (27mm) less deep drainage 16% less surface run-off (23mm) and interflow (3mm)
	Solution nitrate	37% (10-15mg N/L) lower in May/June

All three soil biological parameters reflect the soils ability to process energy and to provide a biotic habitat. Soil microbial biomass as a proportion of the organic C provides a useful measure of organic matter dynamics by indicating whether organic matter is increasing (aggrading phase) or decreasing (degrading phase) (Gregorich *et al.*, 1994). The higher ratios in the uppermost 5 cm soil layer in limed pastures regardless of pasture composition, suggests that maintaining the soil pH at $5.5_{(Ca)}$ by lime addition, promotes organic matter build-up (Table 3.). The increase in absolute values also indicates that liming improves the soil chemical habitat of microorganisms.

Table 3. Factors influencing the ability of soil to accept, hold and release energy and to maintain a suitable biotic habitat. Preliminary data from P. Mele, J. Hirth and G. Morrison (Autumn 1994 and Spring 1995 for SNA and microbial biomass and Winter '94 and '95 for earthworms)

Attribute	Key indicators for Attribute	Advantage of PP+L (compared to AP-L)
Organic matter and Labile organic matter	Microbial biomass C/Organic C	0-5cm: L+>L- (autumn '94, '95; spring '95) 5-10cm: L+>L- (autumn and spring '95)
Nitrogen	Nitrification (SNA)	0-5cm: PP>AP (spring'94) PP(-L)>AP(+/-L)(autumn '95) 5-10cm: PP+L=AP-L
Earthworm activity	Earthworm numbers Earthworm species richness	0-10cm: AP>PP (winter'94) 0-10cm: 3 (2 natives)

NB. All data, particularly earthworms and SNA were effected by season with little activity in 1994, the drought period.

The short-term nitrification assay reflects the soils ability to release NO_3^--N from ammonium N (NH_4^+-N) by the action of nitrifying bacteria (Bramley and White, 1989). This process is regulated by soil pH as nitrifying bacteria function optimally at $pH_{(water)}$ 7.5-8 (Bock *et al.*, 1986) . Theoretically, if a significant lime-induced increase in nitrification is recorded, and if pastures cannot utilise the extra NO_3^--N produced, then liming may be less effective in the long-term. Short-term (1 to 2 years) lime-induced increases in nitrification have been measured at a dryland pasture site in north-eastern Victoria on a sandy, acid soil. This is not evident in the case study (Table 3.). The absence of a lime response may indicate that the response was missed, that the upward adjustment of soil pH to 5.5 may not have been sufficient to increase activity, or that the nitrifying population has adapted to the prevailing lower soil pH (Bramley and White, 1989). Evidence of the latter situation is supported by the depression in activity in soils of limed perennial pasture (autumn 1995). Instead, soil conditions under perennial pastures promoted activity in spring 1994 and autumn 1995.

Earthworm activity (abundance and species richness) can impact upon the three key soil processes listed in Table 1. Burrow formation has been associated with improved water infiltration in conservation cropping soils in north-eastern Victoria (Carter *et al.,* 1994) and hence solute infiltration, whilst the fragmentation of plant material increases the availability of organic matter for microbial mineralisation (Lee, 1985). In addition, the presence and abundance of earthworms is indicative of organic matter quantity and quality (Lee, 1985). The overriding regulatory effect of moisture is evident at the local field moisture scale where higher numbers were found in the wetter soils under annual pastures (winter 1994) (Table 3) and on a regional rainfall distribution scale, where average densities of $71m^{-2}$ and $87m^{-2}$ (winter 1994 and 1995), are relatively low when compared to $163m^{-2}$ from a survey of north-eastern VIC and southern NSW (Mele, 1991). This is supported by Baker (1994), who showed that earthworm numbers are extremely low in regions receiving less than approximately 630mm; Book Book receives approximately 650mm.

Choice of biological parameters to assess soil quality under pastures.

In the case study, the choice of biological parameters was based on a number of inter-related factors:

(i) The ease and cost of measurement for seasonal collection

(ii) Prior knowledge based on cropping systems

(iii) The desire to focus on a specific microbial process that is an integral component of nitrate leaching and acidification, ie. nitrate production by nitrification

(iv) Lack of available alternative options

The choice of parameters to assess soil quality is problematic. A real dilemma relates to the sensitivity versus the scope of the parameter, in that generally the greater the sensitivity of the parameter, the more limited the scope in terms of end-user application. A selection of some of the current options are listed in the Table 4.

Table 4. The scope of biological parameters for assessing soil quality.

"Land-user friendly"	"Lab-user friendly"
Cotton strip assay	Microbial biomass/CO_2 respiration or Total C

Earthworm counts/biomass/species	Abundance of nematodes and microarthropods
	Soil enzymes
	*Carbon management index
	Microbial community structure-biodiversity (FAME)
Mid-infra-red spectroscopy	Mid-infra-red spectroscopy

* carbon management index= C pool size index x Lability index (Blair *et al*., 1995)

“Land-user friendly” bioindicators must be inexpensive, robust, and straightforward for field use. They must also provide the land-user with a decision support tool ie. to either persuade farmers to modify pasture management practice or to affirm this practice. Three methods are listed in this category. The cotton strip assay (CSA) provides a field-based assessment of microbial activity (Williamson, 1994; Pankhurst *et al*., 1995a). The sensitivity and hence interpretive power of this method requires strict attention to depth of insertion, adequate and constant moisture levels and the recording of temperature over the period of burial (K. King, pers comm). In addition, this assay must be validated against more definitive microbial assays such as CO_2 respiration. Preliminary trials in pasture soils suggests a limited application where chemical or physical disruption are extreme, ie.as in fertiliser rate trials (K. King, pers comm).

Earthworm activity may only be useful as a bioindicator in higher rainfall regions (above 600mm) (Baker, 1 994). The numerical dominance of introduced species coupled with a distribution that is not ubiquitous and low species richness and biodiversity, pose major restrictions on the widespread adoption of this parameter by land-users (Mele *et al*., 1993). Nonetheless, in areas receiving >600mm, the presence of certain earthworm species, including the poorly researched natives may still provide a useful indication of soil quality improvement by virtue of their impact on major soil processes particularly their ability to bury surface-applied lime in pasture soils (Baker *et al*., 1993) .

Mid infra-red (IR) spectroscopy, though developmental (CSIRO Division of Soils), appears to be a promising and versatile field-based tool for monitoring soil quality. It measures a range of soil mineralogical properties and predicts with a high degree of accuracy a range of other soil properties including %C content, cation exchange capacity and pH_{ca} (Janik and Skjemstad, 1995). As with the CSA, its sensitivity as a microbiological monitoring tool relies on validation with "lab-user friendly" parameters. Preliminary evidence from soil from a trial site at Tarlee, SA shows significant correlations between mid IR spectra and soil microbial biomass C, particulate organic matter C, and soil moisture status (B. Doube and L. Janik, unpublished results). The relationship between mid-IR soil analysis and GC-FAME (gas chromatography of Fatty Acid Methyl Esters) soil analysis has not been established. Mid-IR spectral analysis of soils can also been done rapidly and inexpensively, especially if a portable spectrophotometer were to be used (ca. $5 per soil sample).

"Lab-user friendly" options must also be utilised and developed because they directly and definitively quantify soil quality characteristics. Approaches are needed that do not require the isolation or extraction of whole organisms nor rely on some measure of their activity. A technique that may be useful in this regard is GC-FAME. Extraction of lipids from microorganisms, their conversion via alkaline methanolysis to fatty acid methyl esters (FAMEs) and their chromatography, has been developed by Microbial ID, Inc., (MIDI), Newark, DE, USA, as a rapid and highly successful identification method for identifying bacteria, actinomycetes and fungi from soil. Here the extracted FAMEs come from the whole community of organisms in the sample and can provide a “snap-shot” profile of the composition of that community. These FAME profiles are very complex, but they can be analysed and compared using principal component and dendrogram analysis (Cavigelli *et al*., 1995). Individual fatty acids within the profiles can also be identified (“signature fatty acids”) which may allow for the detection of specific organisms or functional groups of organisms (eg. sulfate-reducing bacteria or protozoa) within the community. Using this methodology, soils with different cropping histories can be distinguished by their FAME profiles (Zelles *et al*., 1992; Pankhurst *et al*., 1995b). The capacity to differentiate soils using GC-FAME is robust, ie. it is not subject to minor variations associated with sudden fluctuations in the populations of organisms in response to changing environmental conditions, and there is a positive correlation between the total ‘peak area’ of soil FAME profiles and the soil microbial biomass (Pankhurst *et al*., 1995b). A major plus for FAME analysis of soil samples is that it can be performed on small air-dried samples (1-5 g), rapidly and inexpensively (currently $20-$25 per sample). However, the technology needs to be widely tested and whilst it appears to give a good objective measure of the nature of a soil organisms community in qualitative and quantitative terms, the relationship between FAME analysis and other indicators of soil quality needs to be examined. This will establish whether the technique could be used as an objective bioindicator of soil quality.

How can soil bioindicators be linked with soil quality in dryland pastures?

To define relationships between soil bioindicators and soil quality, several issues need to be addressed:

(i) The type of "quality" being assessed ie. pasture composition, production etc.

(ii) Biological reference/baseline values. Is the treatment control adequate or is a comparison with a "native" or undisturbed soil more meaningful for predictive indicators?
(iii) Spatial thresholds related to climate and specific land-use. Habitation limits of soil fauna (earthworms, nematodes and microarthropods) must be defined in terms of abundance and species.
(iv) The inherent quality of biological parameter. Values obtained for a bioindicator eg. microbial biomass activity or arthropod abundance, do not reflect changes or differences in the composition or "functional biodiversity" of the organisms involved; this may be important for long-term sustainability of the system. For example, two soils may have similar microbial biomass, but in one soil this may be the result of only a few dominant organisms whilst in the other it may be the result of several million different organisms; do these soils have the same quality?
Outcome-focussed basic research will help resolve these issues to provide useful tools for assessing soil fitness for pasture and livestock production.

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Soil quality under dairy pastures

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Introduction

The New Zealand dairy industry is currently enjoying 'prosperous' times along with buoyant prospects for both the short and medium term. Present day financial returns to dairy farmers far exceed those received by other pastoralists. As a consequence, there are an increasing number of 'dry-stock' farmers converting to dairying. In addition, there is a monetary incentive for existing dairy units to increase production. This is often achieved by increasing inputs and/or stocking rates. The rise in the number of dairy farms and the increase in the intensity of this land use is causing widespread concern. This paper will consider those concerns which relate to the soil resource.

Dairy farming as practised in New Zealand (and Australia) is, in many ways, quite distinctive. Therefore, this paper will focus on these farms and the manner in which some of their especial features influence soil quality. The characteristics of New Zealand dairy farm management which benefit soil quality will be considered alongside those aspects which result in a reduction in the overall fertility of soils. The ramifications of a deterioration in soil quality for plant, animal, and ecosystem health will be discussed before listing some management practices for the enhancement of soil quality. Finally, an attempt will be made to draw some connections between soil quality under dairy pasture and the socioeconomic and political aspirations of New Zealand 'society'.

Soil quality under dairy pastures - some positive aspects

Plant communities on New Zealand dairy farms are comprised, almost exclusively, of perennial grass and clover species. Unlike those dairy systems where annual crops form a large proportion of the cows diet, New Zealand dairy farms grow only a small quantity of forage crops. Therefore, only a very small area of dairying land is cultivated each year and even then it is often, primarily, for pasture 'renewal'. (By loosening surface soil which is likely to have been compacted by animal traffic, this cultivation may benefit soil structure).

The benefits of perennial pastures to soil quality are well understood and documented. In fact, soils under permanent pasture are often viewed as being paradigmatic of 'good' quality. In some studies, it is assumed, either explicitly or implicitly, that soil under pasture is representative of the pristine or optimum condition and may therefore be used as a benchmark against which soil quality under other land use s (eg. arable) can be contrasted. The advantages of permanent pasture for soil quality are four-fold; soil structure and macro-organisms are spared the adverse effects of tillage; the quantity of organic matter is relatively large and stable; the input of nitrogen due to fixation by legumes and; the advantages that accrue due to the fibrous and prolific morphology of pasture roots. In turn, the organic matter content has implications for a host of soil properties and processes including, structure stability, nutrient cycling and microorganism activity.

Relative to arable farmers and orchardists, dairy farmers use small quantities of pesticide and herbicide. In a survey of dairy and arable farmers in the Manawatu region of New Zealand, only 15% of dairy farmer respondents applied more than 100 litres annum^{-1} of agrichemicals, compared with 65% of arable farmer respondents (Horne and Laird, 1997).

Compared with other pastoral land users in New Zealand, dairy farmers apply generous quantities of fertiliser and, where necessary, lime. Traditionally, fertiliser policies have been based around potassic-superphosphate blends, spread at rates between 300-700 kg ha^{-1} annum^{-1} normally in spring or autumn, and on the tactical application of nitrogen fertiliser mostly in late winter. Routine soil nutrient analyses suggest that on many high producing dairy farms, these fertiliser applications have increased the availability of the macronutrients, phosphorus, sulphur and potassium, to levels which might be thought of as 'near optimum' for pasture growth. Or, in other words, given present day pasture species, significant responses in growth to larger applications of fertilisers containing these particular nutrients are unlikely. Soil macro- and microorganisms have also benefited from the enhancement of this aspect of soil quality.

In New Zealand, animal excreta plays an important role in nutrient cycles. Some nutrients will be transferred, via excreta, from soil under pasture to non-productive areas such as races, and the yards at the dairy shed. However, this inefficiency is small compared to the transfer of nutrients which takes place when crops are cut, transported and fed to cows indoors as practised elsewhere. The recycling of nutrients through excreta spread ‘evenly’ across the entire farm by grazing cows should be more advantageous to ‘whole farm’ nutrient budgets than the application of the waste material, collected from feeding barns, to the fields immediately surrounding these facilities.

In summary, compared to many aspects of the soil quality found under numerous arable and orcharding land uses in New Zealand, and on dairy farms elsewhere in the world, many facets of soil quality and its management on New Zealand dairy farms are commendable.

Soil quality under dairy pastures - some negative aspects

Year-round *in-situ* grazing of pasture by cows contributes to the profitability of New Zealand dairy production systems and some positive aspects of soil quality. Unfortunately, this practise is also problematic to the quality of many soils, and surface and ground waters.

During the winter-spring period all but the very coarsest textured soils frequently have high moisture contents due to imperfect drainage and/or intense or prolonged winter-spring rainfall events. Grazing cows in wet conditions gives rise to severe surface soil structure degradation commonly known as ‘pugging’ or ‘treading’. A reduction in the quality of surface soil structure is likely to reduce water infiltration rates, oxygen diffusion rates, plant root activity, micro and macro organism activity, the utilisation of pasture by grazing cows, subsequent pasture regrowth rates, and animal comfort (Horne, 1992).

Grazing dairy cows on pastures year-round also has interesting implications for the nitrogen cycle in these soils. Nitrogen is lost from the soil system as both a gas and leachate. The quantities of N_2, N_2O and NO produced in soils is receiving increasing attention because of their suspected role in ‘greenhouse warming’ and ozone layer depletion. Most studies in New Zealand have suggested that losses of nitrogen under dairy pastures due to denitrification are small (Tillman 1995). More problematic is the effect of leaching on the quality on surface and ground waters. A number of studies have measured leaching losses of between 35 and 88 kg N ha^{-1} $annum^{-1}$ under grazed pasture in the absence of nitrogen fertiliser (Table 1.). Leaching of nitrate from under animal urine deposits will account for a sizeable proportion of this total. Tillman (1995) has suggested that the impact of dairy farming on nitrate concentrations in ground water will depend on a number of factors, including the extent of dilution provided by rainfall and/or recharge of the ground water by water from areas which are not intensively farmed, such as mountain ranges. He also makes the disconcerting point that it may take considerable time (eg approximately 25 years) for nitrate to reach the ground water (at a shallow depth of 10 m) and be detected, and therefore, there will be an equal length of time before any improvement in land management to reduce nitrogen leaching will have an effect on ground water quality. Already in New Zealand there are regions where the concentration of nitrate nitrogen in the ground water exceeds the limit of 11.2 g m^{-3} set by the NZ. Ministry of Health for potable water. Given this, the increase in stocking rate on many farms and the spread of the dairy farming land use is somewhat troubling.

The use of nitrogen fertiliser on New Zealand dairy farms has escalated in recent years. While it is difficult to quantify the magnitude of this increase, it is apparent that there are now a small, but increasing, number of farmers applying nitrogen at rates in excess of 200 to 400 kg N ha^{-1} $annum^{-1}$. There are widespread and growing concerns about the final fate of this applied nitrogen. Measurements of the quantity of nitrate leached under grazed pastures, fertilised with nitrogen, have reported a wide range of results (Table 1.), with the effect of fertiliser nitrogen on the amount of nitrate leached depending on a number of factors including: fertiliser type or form, the timing of application, grazing management, and stocking rate. Fertiliser is not the only medium by which nitrogen is imported onto the farm; many feedstuffs purchased to supplement the cows diet will contain nitrogen. Another important consideration is that both nitrogen fertiliser and feed supplements are often used for the express purpose of increasing stocking rates.

The application of large quantities of fertiliser was listed above as a merit of dairy farm management. However, as was pointed out, fertiliser policies on most farms have concentrated on a select few macronutrients. The problems with this strategy are two fold. Firstly, if applied in excessive amounts there is the risk that these nutrients will be lost from the root zone, either through leaching (potassium and sulphur) or via surface runoff (phosphorus). Secondly, undue emphasis on a few nutrients often means that other nutrients essential to plant and animal nutrition, including trace elements, are neglected. This point is borne out by the need for farmers to routinely administer oral drench containing minerals to supplement those obtained by the cow from a pasture diet (eg. magnesium).

Table 1. Effect of N fertiliser on nitrate leaching in New Zealand pastures
After Bolan and Podila, 1996.

Fertiliser(kg N ha^{-1} yr^{-1})	**Leaching losses**		**Reference**
	(kg N ha^{-1} yr^{-1})	% added N	
0, 172	88, 193	61	Steele et al., (1984)
0	42		Field et al., (1985)
0, 110, 450	73, 101, 222	25 - 33	
50	17	34	Heng et al., (1991)
0, 120	35, 43	7	Magesan et al., (1994)
0, 400	7, 41	9	Ruz (1991)
0, 200, 400	45, 60 , 120	8, 19	Ledgard (1995)

Nitrogen fixation by legumes and applications of some fertilisers such as urea, ammonium sulphate and diammonium phosphate result in the acidification of soils; decreases in pH will be more rapid in soils with low buffering capacities. However, given the relative ease and inexpensiveness with which soil pH can be modified, soil acidity should not present a major problem to the management of soil quality on New Zealand dairy farms.

The most appropriate method for the disposal of effluent generated when cows are confined on artificial surfaces (eg. the milking shed and yards, and 'stand-off' areas) is one of the most topical issues confronting dairy farmers, those who set policy for environmental management and administrators. On most farms, effluent is currently treated in a series of aerobic and anaerobic ponds before being discharged as a point source form of pollution often directly into surface waters. There is a push by local government officials to clearly establish 'disposal to land' as the preferred method of effluent treatment. Irrigation of this effluent will have implications for soil quality; if well managed, land disposal should increase the nutrient status of soils, however, if poorly managed, soils may become saturated, compacted and the source of large concentrations of mobile solutes.

In summary, there are undoubtedly a number of innate soil characteristics and dairy farm management practices which contribute to a reduction in soil quality and/or pollute the environment.

The effect of soil quality on pasture quality and animal health

Soil quality has a direct effect on both the quantity and the nutritional value of the pasture grown on New Zealand dairy farms. As mentioned above, soil macronutrient contents on most dairy farms are maintained at levels sufficient to enable high annual yields of pasture. Unfortunately, in winter and spring, when grazing frequently occurs on wet soil with low bearing strength, it is often not possible for cows to harvest this pasture because the passage of hooves either buries or muddies the sward, rendering it unpalatable (pugging and treading damage). Utilisation of pasture by cows grazing on wet soils can be commonly 30-50% less than for grazing in dry conditions (Horne, 1992). Likewise, subsequent to the grazing of wet soils, pasture regrowth rates may be reduced by 30-50% because of the damage inflicted on the plants. Severe damage to surface soil and the pasture sward during the grazing of wet soils may also result in the exposure of bare soil which may be colonised by lower quality grass species and weeds.

The nutritive value of pasture to dairy cows is mostly determined by the concentration of energy, protein and minerals; vitamins and water are seldom limiting. The ability of pasture to supply these nutritional requirements will vary according to the season (Wilson *et al* . 1995). Soil quality and its management will be a factor in these variations. At times, the concentration of some minerals in pasture may be either too high or too low for good cow nutrition eg. average magnesium and calcium concentrations in pastures in spring are often lower than cow requirements (Wilson *et al*., 1995). There are also complex interactions between the 'uptakes' of various nutrients by both the plant and animal. For example, high levels of potassium in pastures are associated with low levels of magnesium, calcium and sodium, and high levels of potassium and sodium in the rumen upset calcium homeostasis. The application of potassium and nitrogen fertilisers in spring will exacerbate seasonal changes in the mineral composition and may cause grass tetany in cows (Wilson *et al*., 1995). Nitrogen fertiliser addition may also result in an increase in the amount of crude protein ingested by cows and problems with nitrate toxicity. Current fertiliser policies do not pay adequate attention to the trace element requirements of either animals or pasture.

At times, the intake of pasture may be insufficient to meet either cow energy or mineral requirements. Pasture allowances which are deficient in either energy or minerals essential to cow nutrition give rise to metabolic diseases (eg. hypocalcaemia, hypomagnesaemia), or subclinical effects on performance, unless this diet is supplemented. In addition, under-nourished cows will have longer anoestrus.

Increases in the incidences of mastitis and lameness are also commonly associated with wet conditions.

In summary, a reduction in soil quality will have an adverse impact on pasture quantity and quality, and on cow health.

Management practises to improve soil quality

There is obviously not space here for a comprehensive treatment of management practices for improved soil quality but a few important practices would seem to arise logically out of the above discussion. Firstly, there needs to be a better match between soil type and the intensity of dairying. Damage to surface soil and pasture during wet periods must be minimised through installation and maintenance of artificial drainage systems where required and/or the adoption of strategies for removing cows from paddocks in wet conditions. There is also a need to devise fertiliser policies which take full account of the range of plant and cow nutrient requirements, in tandem with fertiliser programs which minimise the pollution of surface and ground waters by nutrients which are either leached from the soil or runoff its surface. It is suggested that such policies can only be formulated on the basis of information furnished by analysis of samples taken from each component within the ecosystem ie. surface and ground waters, drainage, soil, pasture, cow, and possibly milk. If there is some sense in which plant and animal performance might be said to integrate aspects of soil quality, and if in the final analysis soil quality is most important for ecosystem health then this should be acknowledged in the composition of so-called ‘minimum data sets’ which, to date, have included only soil parameters.

Soil quality under dairy pasture - the big picture

There are a number of larger issues confronting the dairy industry and wider society. While these issues, obviously, encompass considerations much broader than just soil quality, the effects of dairy farming on the soil resource will feature prominently, perhaps predominantly, in deliberations on these questions. Pre-eminently, there is the question, ‘are current practices and trends in dairy farming sustainable’? Should dairy farming be allowed to intensify to any greater extent and/or should it be allowed to spread to soils where intensive dairying might be deemed a ‘marginal’ use? Does the fact that the dairy industry currently generates relatively large amounts of export sales give it a privileged position; is New Zealand financially dependent on profitable dairy production systems? If so, will New Zealanders have to accept a deterioration in some aspects of their natural environment in order to maintain their current ‘standard of living’. Is there scope to mitigate some of the adverse impacts of dairying on ecosystem heath by spreading the ‘national’ herd across the countryside at certain times of the year? This would necessitate greater coordination or integration between dairy farms and other land uses eg. the common practise of grazing non-lactating cows on sheep and beef farms in winter. Interestingly, Howse (1995) predicts that “provision of supplementary feed to dairy farmers will become an industry in its own right”.

There are also a number of beyond ‘farm gate’ issues to consider. Internationally, New Zealand is widely seen as relatively “clean and green”. Many of New Zealand’s products enjoy a competitive advantage in the marketplace because there are an increasing number of consumers who are ‘environmentally aware’ and who discriminate between brands accordingly ie. they favour food which originates from an unpolluted countryside, is perceived to be produced in a low input system, has ‘natural’ taste and nutritional value, and has not been sprayed with large amount of pesticides etc. Indeed, there have been overt attempted to label and market products in just such a manner. There is increasing concern that this claim to be ‘clean and green’ would not stand up to close scrutiny. Relatedly, there is the risk that, in order to protect indigenous agricultural industries in this new age of liberalised worldwide trade, countries will impose non-tariff barriers on New Zealand products citing environmental degradation.

The final issue which encompasses much of the above discussion is how will society in general, and politicians in particular, formulate and administer polices which govern land management. Given that ‘property rights’ are a bulwark of New Zealand culture, dairy farmers are unlikely to take kindly to being told what they can and cannot do on and to their soil, particularly if restrictions penalise them financially. Although New Zealand has legislation (The Resource Management Act) which prescribes the framework that ‘managers’ of the ‘wider’ environment are to work within, the legal status of soil quality *per se* has not yet been considered.

Conclusions

New Zealand dairy production systems are illustrative of how soil quality impacts on animal, plant, and ecosystem health. Soil quality under dairy pasture may be superior, in many regards, to that observed under other land uses both in New Zealand and elsewhere in the world. This notwithstanding, many current dairy farm management practises pose a risk to soil quality. Arguably, there are already some symptoms of declining soil quality which become most acute at times of unfavourable climatic conditions when these dairy production systems lack the resilience to buffer the effects of ‘unseasonal’ weather. Perhaps the most pressing issues for farmers in the mid 1990s as they seek to manage soil quality is the interaction between soil management and animal welfare and nutrition and the effect of land use practises on water quality.

The New Zealand dairy industry will face some difficult issues in the future; some arising out of its role as a major player in the New Zealand economy, some to do with its role as custodian of much of our most productive soil resource and some to do with its role as responsible citizen in the wider rural landscape. It is imperative that these difficult times are negotiated in the secure knowledge that the land is in good health.

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Soil Quality For Orchards On Duplex Soils

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In the irrigated fruit industries of south-eastern Australia yields are far lower than potential. Orchardists must achieve high yields to remain viable and clearly the highest yields come from the highest quality soils. Fruit trees in the area yield 30 t ha^{-1} on average and the best orchards yield 60 t ha^{-1}. The potential, calculated from levels of solar energy and from the best experimental yields is, over 150 t ha^{-1}. In fact, a fruit yield of 180 t ha^{-1} has been achieved in samples of trees in south-eastern Australia and higher overseas. The highest producing orchard soils, Class I, in south-eastern Australia have developed on the sandier levees of prior streams. In California, Class I soils occur on recent alluvial fans and in The Netherlands on recent deposits of the lower Rhine (for example, see Stromberg, 1962). Even in these three areas, best orchard yields are far below potential.

The attributes of soils for orchard production are water supply, aeration, low mechanical resistance, optimum temperature, nutrients and no toxins. The limits for each of these are well known (Olsson and Cockroft, 1980). Table 1 sets out each optimum and range. The table also gives typical data for duplex soils in south-eastern Australia. These orchard soils usually have a loam A horizon to about 150 mm, with a medium to light clay B horizon underlain by a more permeable C horizon below 600 mm (Skene and Poutsma, 1962). The A horizon contains sufficient fine sand and silt to become hardsetting when low in organic matter. The B horizon nearly always contains more than 50% clay and is often sodic so that hydraulic conductivities are usually less than 10 mm d^{-1}, penetrometer resistances are above 3 MPa and aeration porosities are commonly less than 2% (Olsson *et al.,* 1995). Roots grow poorly in these soils, with root concentrations rapidly declining with depth in the B horizon, from about 10 cm cm^{-3} in the A horizon to less than 1 cm cm^{-3} by 500 mm depth (Cockroft and Wallbrink, 1966). Richards and Cockroft (1974) argue that the rapidbuild up of mechanical resistance in both horizons as the soil dries is a major cause of poor root growth and function. All orchardists irrigate their trees, provide nutrients, ensure surface drainage and keep their soils free of toxins such as salt. It is clear from the above that poor soil structure is the main process affecting tree yields. The activities of the tree roots are reduced by the high mechanical resistance of the soil and, we suggest, by low water storage and the low flux of water and nutrients to the root surface.

Table 1. Optima and limits of soil physical attributes and typical levels in orchards

Attribute	Optimum	Limit for roots	Level in orchards
Water suction (MPa)	< 0.05	> 1.5	0 - 50
Air-filled porosity (% at 10 kPa suction)	> 15	< 2	2-15
Mechanical resistance (probe, MPa)	< 0.5	3	1-6
Temperature (°C)	18-28	30-35	2-50
Volume (mm depth)	500	750	150

Assumed soil is free of toxins and that nutrient supply is based on leaf analyses. After Richards and Cockroft (1974).

To improve these soils in terms of their function of fruit production, we require a new system of soil preparation and subsequent soil management. Current soil management involves irrigation, no cultivation, chemical weed control, traffic confined to lanes between the tree rows, surface drainage and appropriate fertilisers. The orchardist applies fertilisers according to leaf analyses and where necessary, controls salinity by underground pipe drains or by pumping water from aquifers.

The aim of the new system is to achieve the optimum levels of soil attributes given in Table 1. This means a major alteration of soil structure from one that is hard, massive and impermeable to soft, loose and porous; the new structure should be developed to a depth of 500 mm (Greenland, 1981). Clearly, the new structure must be maintained as such.

The indicators of these attributes can be assessed in the field:

- Hardness according to the scale given by Butler (1955) as the force required to shear a 20 mm piece between thumb and fingers on a scale from force 1 that is just perceptible to force 5 that is beyond the strength of the fingers.
- Penetrometer resistance with a hand held penetrometer first with the soil wet, then dry.
- Coalescence by estimating the percentage of soil aggregates that are welded to each other at points of contact (Cockroft *et al.,* 1996).
- Macroporosity by counting the number of visible pores on a fresh undisturbed face (Cockroft, 1969).

In this way we can assess the structure of any soil in terms of how soft, loose and porous it is. We can increase precision with the attributes by measuring soil strength, aggregate size distribution and pore size distribution in the normal way in the laboratory.

We have developed a new system of soil preparation and management for orchards in which all soil attributes are improved and yields are increased. In preparing an area of land for orchard planting we start with a soil survey. The survey includes an assessment of land capability from Class I to VI, the depth to a more permeable C horizon, dispersion and slaking indices, pH and slope of land surface. The grower must apply gypsum if the soil is sodic, lime if acid, and grow grasses if it slakes. Calcic soils can be deep tilled to form a friable mass of fragments less than 20 mm in diameter because the calcic soil will loosen by brittle failure in contrast to plastic failure if sodic. But this can be achieved only when the soil water content is just drier than the Plastic Limit, that is it can be rolled into a rod 3 mm in diameter but only with difficulty. If it is too dry the soil loosens to powder and clods and if too wet, to a plastic mass.

The deep tillage, to 500 mm, is best done with rigid tine rippers operated as described by Spoor and Godwin (1978). The point of the ripper ruptures the soil around it and the tip and shank of the tine further fragment the soil as they force it around them. Thus, the tine should have a wide tip (greater than 50 mm) and wings each about 300 mm wide welded to the back of the tip; these increase the volume loosened and create the maximum amount of brittle failure. The tip and wings should be at an angle of 20 degrees to horizontal so that they fail the soil to the surface and not locally around the tine to form a slot. The tines should be spaced at 0.75 times the depth of working to ensure the soil between them is loosened.

Operation of the implement is critical. It is important not to penetrate the tine deeper than a critical depth at which the overburden and cohesion of the soil above prevents proper loosening. Several runs are needed, each deeper than the one before. When working in wet clayey subsoils the operator must drive slowly to prevent high pressures developing in front of the tine that cause plastic failure. He must avoid recompacting the loosened soil.

The deep tillage is confined to one to two metre each side of the future rows of trees. The two metre strip between becomes the traffic lane; but first the orchardist must cultivate this strip and form the loose soil up into beds. All future traffic is confined to the traffic lanes. This hilling into beds ensures that all the surface soil is used by the tree and none for traffic, it ensures rapid drainage of surface water and it acts as a guide to equipment operators in the orchard to drive in the traffic lanes.

The bedded soil is now loose to almost 750 mm depth and could be prone to excessive intake of water in wet years. However, the system protects the trees from waterlogging by providing good surface run off, by the permeable subsoil that takes away the transient excessive water, by the grower avoiding late irrigations, by ensuring no accessions to the water table and by growing a ryegrass cover crop in the autumn and winter.

The rye grass is part of the process of stabilising the loose soil. Nearly all soils, especially subsoils, slump after they are loosened, during wetting and drying cycles. Usually the soil hardens and penetrometer resistances increase back to close to the original 4 MPa. The soil loses its loose structure and becomes massive again. However, some macropores created by the deep tillage remain and new macropores are formed by earthworms and roots. The soil thus retains a high hydraulic conductivity so that irrigation water penetrates readily, the soil drains well and roots can grow somewhat deeper (Taylor and Olsson, 1987).

The fruit grower can reduce the amount of this slumping and hardening by standard methods of structure stabilising. The grower must build up organic matter to stabilise microaggregates and macroaggregates; he ensures its build up by concentrating leaf fall, prunings and weed slashings on the bed and especially by growing rye grass on the bed in autumn and winter. The initial cultivation and deep tillage must be done when the soil is moist rather than dry, to avoid powder within the bed when it is first set up. Then he must ensure good drainage, since soil at zero soil water suction is extremely fragile and often collapses under its own weight. The method of irrigation is very important; flood irrigation causes the most slumping whilst slow spray irrigation the least. Slow wetting reduces slaking and in addition, prevents the soil water suction from reaching zero during irrigation. Also important is the stabilisation produced by roots - the trees' own roots in spring and summer and the roots of cover crops growing on the bed in autumn and winter. Roots bind loose soil into aggregates, stabilise those aggregates by growing through them, increase the porosity and stability of the fragments formed by tillage, host fungi and other microorganisms that are important in stabilisation, produce exudates that bond soil particles, and provide organic matter. Grass roots are the best of all in doing these things because of their very large numbers per unit volume of soil. The best structure develops when the soil has plenty of dynamic root activity as in grassland. Oades and Waters (1991) describe these processes in building soil structure.

Once the soil preparation is finished the grower plants his trees in the bed and embarks on his program of soil management. The system described here ensures yields much higher than previous systems, continued soil improvement, low cost and simple operations. He must spray the winter cover crop in spring with a herbicide to avoid it competing with the trees. The dead cover crop then forms a mulch for the summer to reduce soil temperatures, provide organic matter and suppress weeds. Traffic on the beds is avoided. The grower no longer cultivates. He irrigates with sprinklers that apply water at less than 6 mm h^{-1}, evenly along the bed. He applies weed sprays as needed but not after late summer so that the winter cover crop will volunteer and become well established before the winter cold. Table 2 summarises the preparation and management inputs needed to develop and maintain the five physical attributes.

Table 2. Summary of inputs in the new system of soil management to maintain soil attributes near optima

Attribute	**Preparation and maintenance**
Water suction	Frequent irrigation. Adequate macroporosity. Adequate water holding capacity. Minimum evaporation.
Air-filled porosity	Adequate macroporosity. Drainage of excess water (surface run off, permeable subsoil, no water table, cover crop). Careful irrigation.
Mechanical resistance	Beds set up with soft, loose soil. Adequate macropores. No clods. No traffic on beds. Slow wetting. Good drainage. Cover crop roots.
Temperature	Summer mulch of dead cover crop. Shading by trees.
Volume	Soil loosened to 500 mm. Surface soil hilled. Separation from traffic. No cutting of roots by cultivator.

With this new system of soil preparation and management average yields in commercial orchards have increased by 50%, even though the trees are still immature.

These yields are still considerably below potential and we have identified several problems remaining in reaching the optima for the five attributes listed in the tables. The most obvious is the increase in mechanical resistance to the root; we have been only partially successful in preventing the build up of soil strength. We have also measured a low volume of storage pores (30 to 0.2 μm in diameter) of less than 10% of the soil volume. This lack of storage pores also restricts rates of water and nutrient flow to the root surface.

We can make four conclusions from this example of soil improvement.

- The two most tangible orchard outcomes are the possibility of doubling yields and the quick adoption of the new system by growers.
- Soil structure has become a dominant issue in intensive cropping.
- Soil structure can be markedly improved to a soft, loose and porous state.
- Maintenance of the ideal structure appears possible because we have instances of soil remaining loose long term.

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Soil And Land Management For Cotton Production

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Cotton Growing in Australia

Cotton is grown on about 250,000 ha in eastern Australia, in a belt stretching from Hillston, NSW to Emeral, QLD. Cotton is a woody, tap rooted perennial plant but is grown as an annual crop. About 90% of Australian Cotton is produced by flood irrigation on medium to heavy grey or black cracking clay soils.

Changes in Soil Management

The main changes which have occurred in the management of cotton soils over the last 20 years have been an overall reduction in tillage, and widespread adoption of controlled traffic permanent bed farming systems. The industry-funded research has also changed its focus over that time. In 1975, the focus was on Nitrogen rates, irrigation timing, soil tests and basic physical aspects. In 1995, the research has a multi-disciplinary approach including engineering for controlled traffic, micro/macrofauna behaviour, salinity and zonal tillage concepts. The Cooperative Research Centre (CRC) approach to research has been a great boost for producers, giving research a practical focus, and bringing scientists from different disciplines and institutions together. The outcomes from all industry-funded soils research, as well as grower experiences, are used in the SoilPAK manual, which is a decision-support system for irrigated cotton production on cracking clay soils.

Operations Calendar with Reference to Management of Soil/Land Quality

To how soil/land management issues are considered in day-to-day operations management, a yearly cycle is presented below:

Harvest

- Restrict compaction to defined traffic zone (controlled traffic) - match picker to tractor sets, guidance system, weight of picker.
- Disease transfer - disinfect equipment which has travelled from other farms/infected paddocks.

Cotton Stalk Disposal

- Retention of stable root channels for next crop's root growth, water infiltration - "Eliminator", slash and bury, or pull/rake and burn (less preferable)
- Breakdown of woody stubble for ease of handling, disease control, nutrient/OM cycling - mulch as finely as possible, incorporate (breakdown bacteria/fungi compete with crop pathogens, aiding in control). Rake and burn has not lowered disease levels, may cause nutritional problems, atmospheric/social problems.
- Control *Helicoverpa* pupae for resistance management - "Eliminator" discs, pullers, esp. "Sundance".
- Controlled traffic - retain existing wheel/crop zones

Soil Pit Observation (May occur before stalk disposal)

- Used to assess soil structure and health as objectively as possible, and to make decisions about the future management of the field. Involves decisions on crop to be grown and how to achieve best possible soil conditions for that crop, given a range of possible starting conditions. Use of SoilPAK manual and score useful especially for industry newcomers and when practices or conditions depart from "normal".

Reform Beds

- Controlled traffic - same sets as other operations, guidance systems may help straight lines. Narrow tracks will help restrict compaction to wheeltracks where it IS an advantage - allows timely operations at reduced horsepower. Wider equipment favoured to reduce percentage of wheeled furrows. Time operations to optimum soil moisture to reduce compaction.
- Aeration of root zone - hills or wide "camel humped" beds formed to ensure good drainage of surface soil after irrigation or rainfall.
- Water infiltration/holding capacity - beds shoulders may be sheared to undo compaction from picker wheels, improve infiltration. Bed reforming carried out ASAP to allow rainfall capture and storage in profile, flexibility in cropping options. Bed configuration (wide beds/ single hills, 1m/34"/30")

matched to soil type and farm layout to ensure efficient water application (fast, low waterlogging, low tailwater)

- Seed environment - trash is concentrated in seed zone giving improved structure (soil/seed contact), and care taken not to bring sodic subsoils up into seed zone.
- Soil Strength and Root Growth - if root-limiting compaction present in plant zone and stable vertical channels are few, remedial tillage (eg middle-busting) may be performed - only if soil moisture is suitable for tillage. Permanent beds allow successive row crops to repair compaction through wetting/drying cycles.

Soil Tests - P, K, Zn, S

- Used to establish requirement for additional nutrients. P application becoming widespread, K and Zn used in specific areas.
- *Weed Control*

Controlled traffic, moisture conservation - weed control over winter achieved with knockdown herbicides (aerial or light ground rig).

Fertiliser Application

- Denitrification - can cause large losses of early applied nitrogen, so nitrogen application not done too early and is split during the season to reduce chance of loss. Inhibitors may help, but they may harm beneficial soil microorganisms.
- Water infiltration/holding - "bent shank" ameliorates some shoulder compaction, and assists water infiltration.
- Root growth - is less restricted in non-wheeltracks, so N is applied here (may be in a wide bed) to assist uptake. Toxicity hazard to young roots dictates that N is placed suitably.
- Excess N - may cause problems in cotton crop, has potential to leach to groundwater, runoff to rivers. rate is chosen according to research results and models (in SoilPAK, Agfacts). Test strips left unfertilised to allow September soil tests to refine rates.
- P/K/Zn/S may be applied at same operation (banded in plant line for efficient uptake). Airseeder on tractor, NH3 tank on rig (or vice-versa) means less passes over the field, less fuel/labour/repairs.

Pre-emergent herbicide Application

- Surface soil structure/erosion - effective residual herbicides can reduce the need for mechanical tillage post-plant, thus reducing susceptibility to erosion, and structural decline. If finer tilth is required for seedbed, this operation may achieve it (Lillistons, etc), but if not, the herbicides may be surface applied and incorporated by irrigation/rain.

Pre-irrigation

- Seed/seedling environment - provides adequate moisture for germination. May be preferable to watering-up to avoid waterlogging seed, especially if rain follows sowing. Provides profile of moisture for developing seedling at the time when it is most susceptible to damage from post-plant irrigation (first 60 days).

Nitrate Test on Nil Strips

- Surface and groundwater quality - refining N rates reduces possibility of excess N flowing to groundwater or surface streams where it may alter nutrient balance. Adequate N assists crop to achieve maximum yield per Megalitre of water.

Planting

- Plant pathogens - disease-resistant varieties and fungicidal seed dressings help in countering these.
- Soil pests - in-furrow insecticides may be required.
- VAM - stater fertilisers may be applied if low VAM levels are indicated.
- Controlled Traffic - guidance systems may be used, or most skilled operators used to ensure that plants lines are located properly for controlled traffic system throughout season.
- Seed environment - Planting begins when soil temperature is adequate to ensure germination within 7 days. Bed architecture/orientation, soil type, and stubble cover/content may affect temperature. Harrows or moisture seekers may be used to locate seed in adequate moisture. Double disc openers common for good control of depth and alignment of seeds.

Inter-Row Cultivation

- Surface Structure/erosion - cultivations may be limited to 1, followed by directed knockdown or residual sprays. Aims to reduce regermination of weeds, erosion, pesticide transport (in eroded sediment).
- Controlled Traffic - Guidance systems used, narrow wheels, lighter implements and tractors.

Side-Dress Nitrogen (Water-run)

- Denitrification - split timing of application reduces effects of denitrification.
- Root growth/nutrient uptake - water-run application places N in the dry soil (ie where roots have been active), thus ensuring good uptake. Efficient in terms of machinery/manpower.
- Surface water quality - recirculation of tailwater prevents losses of N to waterways.

Irrigation

- Soil structure/aeration/water holding capacity - flood irrigation efficient on cracking clays. Fast infiltration before cracks seal. Reduces time that surface soil is anaerobic. Irrigation water quality may need to be considered, especially if using bore water - may require blending with river water if high in salts.
- Water use efficiency/erosion/evaporation - scheduling of irrigation by Neutron Probe, Capacitance Probe, Pressure Bomb etc to water at optimum interval. Makes best use of shrinking/swelling properties. Proper design and development of fields and irrigation system increases efficiency. Design factors include field slope, row length, water flows, row spacing and configuration. Stubble cover, polymers may be used to reduce sediment transport/erosion
- Surface water quality - recirculation of tailwater prevents accession of pesticides/nutrients to waterways.

Pesticide Application

- Total pesticide load - Intense scouting, thresholds and IPM approach minimise applications. Aerial application is most timely, also reducing total applications by maximising efficacy of each spray.
- Off-target transport (soil, water, air, stock, humans etc) - sensitive locations may require specialised application techniques (aerial or ground rig), special timing for wind direction, or particular pesticide selection. Bt cotton should help reduce total load on environment.
- Soil structure (compaction) - aerial application avoids damage. For ground rigs choose light rigs with narrow tyres, fit spray swath to controlled traffic system.

Crop Rotation After Harvest

- Soil Microbiology - alternate crops (eg Graminae) may be used to reduce load of some pathogens. Sacrificial, green manure or short winter crops may be used to maintain VAM levels if required.
- Soil Structure - wetting-drying cycles of rotation crops may biologically repair structural damage, especially after wet harvest. Fibrous root systems are especially good at this. Stable vertical macropores are promoted by leaving the cotton roots to decay in place, and also by the rotation crop's roots. All rotation crop operations including harvesting done on controlled traffic system - has required equipment modification.
- Insecticide resistance - Heliothis pupae over-wintering after cotton must be destroyed to reduce carryover of resistance to next season. This can be achieved by proper design and operation of rotation crop sowing equipment or land preparation equipment for back-to-back cotton.
- Soil Organic Matter Levels - OM levels typically low in cracking clays. Surface structure (seedbed) improvement greatly enhanced by retention of crop residues rather than burning/deep ploughing. Greatest benefit appears to be physical rather than chemical.

Future Directions

- Sacrificial/Cover crops - increasing interest for OM, moisture retention, erosion control benefits. Limitations to overcome are equipment design/availability, and weed control.
- Compaction - requirement for wider, lighter equipment to improve efficiency while limiting compaction. Tracked tractors, pickers etc will be crucial to this. Tracks need to be long and narrow, not short and wide. Picking equipment the biggest limitation at present.

- Denitrification - an efficient denitrification inhibitor would increase efficiency of applied N use, and reduce total application. Limitations to overcome are adverse effects on beneficial microflora, and price.
- Meso/macrofauna - A great benefit is envisaged in increasing populations of worms, etc. Limitations are effects of tillage, fertilisers and pesticides on populations - little is understood about these at the grower level, most information appears to be myths or conventional wisdom.
- Zonal Tillage - Becoming understood as a concept, but not in practice yet. Limitations are mainly equipment.
- Note the importance of engineering solutions in all these desired directions - we have not been as good at managing engineering R&D as we have in areas such as plant breeding/insect control.

Soil Components Of Yield Decline In Sugar Cane

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Abstract

With a few notable exceptions e.g. root diseases, little is known about the soil components of yield decline in sugar cane and for much of the history of the industry soil health has been largely ignored. This is now changing with the main thrust of the Yield Decline Joint Venture being to identify, understand, and overcome/manage the soil related factors that are instrumental in the productivity plateau. In this paper an historical approach is taken to explaining the development of yield decline and ideas are put forward as to how it may be overcome. It is suggested that the long established practice of productivity improvement through plant improvement and the use of chemicals must change if the industry is to approach long term sustainability. The Joint Venture is attempting to examine the farming system as a whole and not merely focusing on isolated components.

Introduction

The Australian Sugar Industry has been on a productivity plateau for the past 25 years (SRDC, 1995). The reasons for the productivity plateau are unknown but is believed to be due to a combination of factors that are related to climate, soil, management, and industry development (Anon, 1991). Yield decline, which is defined as the loss of productive capacity of sugar cane growing soil under long term monoculture, is a component of the productivity plateau. The phenomenon occurs in all sugar growing areas in Australia and at this stage the cause/causes are unknown. Current thinking is that the causes of yield decline are complex and are due to a number of soil related factors being out of balance in the current farming system. Yield decline has been variously estimated to cost the Australian sugar industry up to $400 M per year.

A Joint Venture involving the Bureau of Sugar Experiment Stations, CSIRO Division of Soils, Queensland Department of Primary Industries, and the Sugar Research and Development Corporation was established in 1993 to research and develop solutions to the problem of yield decline.

The Sugar Cane Farming System

The sugar cane farming system is probably the most intensive monoculture of any agricultural cropping system. The monocultural system has developed for a number of reasons including the need to be close to sugar mills due to high transport costs, the assignment system, and the lack of alternative enterprises as profitable as sugar cane (Courtenay, 1978). In modern times the system revolves around a plant and normally four to five ratoon crops before the root stock is ploughed out and, in most situations, a maximum of a six month fallow (either bare, as weeds, or a sown legume) is applied before the cycle is repeated. In many situations plough out/re-plant is now practiced resulting in virtually no fallow period. Importantly, the intensity of the monoculture has been increased in the last 30 years with the lifting of regulations that forced fallowing. Farmers were forced to fallow 25% of their assigned land each year until 1964 when the restriction was reduced to 15%. In 1975, the restriction was lifted completely (Wegener, 1985).

In addition, the intensity of production in the monocultural system has continued to increase with industry development. Inorganic fertilizers, insecticides, and herbicides have been used extensively as the economics of sugar cane production has largely been adequate to readily cover costs. In particular, the heavy use of some of the major elements in high analysis mixtures e.g. phosphorus, has produced very high soil levels resulting in an unbalanced nutritional composition in many sugar cane soils. Further, until the last decade the industry was largely based on burnt cane harvesting so virtually no organic matter was returned to the system. The advent of green cane harvesting and trash retention has been a major innovation in recent years and the benefits of such a system in terms of organic matter improvement, soil health, and erosion control are now starting to emerge (Wood 1985,1991; Spain and Hodgen, 1994; Prove *et al*., 1986). Further, in terms of soil physical properties, heavy machinery is used, often under wet conditions, to harvest and transport the cane, resulting in substantial soil compaction (Braunack and Hurney, 1996).

Taken as a whole the sugar cane farming system has been exploitive of soil resources and there is little doubt that the plateauing of yields over the last 25 years can, at least in part, be attributed to a dominant focus on productivity improvement through plant improvement. For example, breeding programs are estimated to provide potential productivity increases of 1% per year (Roach and Daniels, 1987; Bull *et al.*, 1993; Chapman, 1996) so it could be expected that a 25% improvement in productivity should have been realised over the past 25 years. This has not occurred, and although it is most unlikely to have been entirely due to a reduction in the productive capacity of sugar cane growing soils (yield decline), as expansion onto poorer soils and other industry changes are likely to have had some adverse effects, there appears little doubt that soil related factors are involved. As with many agricultural production systems scant attention has been paid to the management and maintenance of the soil resource.

Historical Aspects

Yield decline is an issue that has vexed the sugar industry almost since it's establishment in Australia (Maxwell, 1900), although the term itself has only been invoked in more recent times. However, what we now know as a productivity plateau was apparent in some sugar cane growing areas as early as the turn of the century (Bell, 1935, 1938). For example, during the 40 year period from 1898 to 1937 the average yield of sugar cane in the Bundaberg - Gin Gin district was around 37 t/ha with 10 year averages being 36.5, 38.3, 36, and 39.7 t/ha (Bell, 1938). In discussing this data Bell observed .... "During this period much new land has been brought under cultivation, the use of artificial fertilizers has developed from nothing to a highly important farm practice, while new and better varieties have been grown. Yet the yield of cane has barely held it's own, and one might well ask why it has not progressed"........ and further........ "In short, the native fertility is being rapidly lost as a result of growing continuously a crop which is a gross feeder and which requires that constant cultivation which brings about fertility depletion and soil erosion; the soil is becoming ***dead"***

Given that the sugar industry is again on a productivity plateau, as it was 60 years ago, one could be excused for asking whether we have actually learnt anything. We probably have but we haven't as yet developed the resource and perseverance to fully apply what we have learnt to our system and manage it in the optimum manner. In many instances we are still looking for the quick solutions that have overcome our past productivity problems.

The Current Status of Yield Decline

The recent history of yield decline dates back to 1967 when northern Poor Root Syndrome was recognised as a problem in sugar cane on Queensland's wet tropical coast (Egan *et al*., 1984). Subsequent studies into a range of possible causes eventually isolated the root pathogen *Pachymetra chaunorhiza,* which, when controlled by the use of resistant sugar cane varieties, led to yield increases of up to 40% (Magarey, 1993). However, even greater responses (>100%) were obtained when soil from the same site was fumigated with methyl bromide, suggesting that factors other than *Pachymetra* were involved (Croft *et al*., 1984). Further, when *Pachymetra* susceptible and resistant sugar cane varieties were grown on fumigated and unfumigated soil at the same site, the resistant variety outyielded the susceptible variety but still showed a 36% yield response to fumigation (A.P.Hurney, unpublished data). More recently it has been established that substantial sugar cane yield responses to fumigation can be measured in all sugar growing areas of Queensland, whether *Pachymetra* is present or not (Magarey and Croft, 1995). Further, yield increases in response to fumigation of sugar cane land is largely specific to sugar cane; other monocotyledon species (maize, sorghum) are only slightly responsive while dicotyledons are unresponsive (Garside *et al*., 1995). Consequently, yield increases in response to fumigation are not simply an artefact of the fumigation process but an effect of improving the soil environment for sugar cane growth. Further, yield increases have also been shown in comparisons between old and new sugar cane land (Garside and Nable, 1996) and when the monoculture is broken by other species for periods of time (Chinloy and Hogg, 1968).

Recent Research Initiatives in Yield Decline

The Bureau of Sugar Experiment Stations (BSES) has had a dedicated program to research yield decline for the past 25 years. This program initially investigated a whole range of agronomic, nutritional, entomological, and pathological issues as possible causes of the original Poor Root

Syndrome that occurred in north Queensland (Egan *et al*., *1*984). The discovery of *Pachymetra chaunorhiza* (Croft and Magarey, 1984) along with major responses to fumigation (Croft *et al*., *1*984) had clearly indicated that root pathogens were involved and there was little doubt that their expression was favoured by the long term monoculture.

Subsequent research by BSES has concentrated on the further isolation of pathogenic fungi responsible for yield decline with limited success (Magarey *et al*., *1*995). Although there seems little doubt that root pathogens are involved, given the continued response to fumigation, the approach that assumes root pathogens are the primary cause of yield decline has been questioned. Indeed it has been suggested that a build up of root pathogens may simply be the ultimate expression of other factors being out of balance in the farming system (Garside, 1995). It is this concern that led to the establishment of the Yield Decline Joint Venture.

Joint Venture Approach to Researching Yield Decline

The Joint Venture started with the premise that yield decline was a complex issue associated with a number of factors being out of balance in the farming system and that these factors and their relative importance was likely to vary in response to soils and environment. Further, only two pieces of previous evidence were fully accepted - yield decline was associated with the long term monoculture and root pathogens were certainly involved. Consequently, the Joint Venture is attempting to consider all aspects of the farming system in approach to the yield decline problem. A three phase approach is being implemented based around ***identifying, understanding*** and ***overcoming/managing*** the problem.

At present the research is still largely in the ***identifying*** phase with a major focus on studying differences in soil chemical, physical, and biological properties and their effect on sugar cane growth in: paired old and new land sites, new land after it is first planted to and continues to grow cane (rundown studies), and old land after it has grown rotation species for different periods of time. The next phase will involve more detailed studies to better ***understand*** the impact of factors that emerge from this ***identification*** phase.

In order to fully capitalise in future studies on specific factors a project to understand the growth and function of sugar cane root systems was initiated early in the program, as roots are the important link between the harvestable product (tops) and the source of factors reducing potential productivity and sustainability (soil).

Progress to Date

Most of the results currently available have emerged from the paired sites which were intensively monitored in 1993/94. The rotation studies commenced in 1994 and have not as yet returned to sugar cane, while rundown studies are only just commencing.

As expected there was very little consistency between paired sites across environments except that crop growth, in terms of stalk development, was less on older land. Whether, this was reflected in ultimate yield depended on a number of factors associated with the growing conditions (Garside and Nable, 1996). However, some general trends emerged in soil properties that indicated old land was more degraded in terms of acidification, soil structure, and organic components. In general old land was shown to be more acid, have lower CEC, more aluminium and manganese, less copper and zinc (Bramley *et al*., *1*996) less microbial biomass (Holt, 1996), greater soil strength, lower infiltration and water holding capacity (Ford and Bristow, 1995a,b), and more root pathogens (Magarey, *unpub. data)*. More specific research programs are being developed based on these findings.

Conclusions

The Joint Venture, and consequently the farming systems approach to understanding the issue of yield decline is in it's infancy. Yield decline is a significant problem for the sugar industry with an estimated cost of up to $400 M per year. Single issue approaches have dominated the research effort on yield decline issues in the past and although they have produced some spectacular short term productivity improvements they have not managed to erase yield decline as an issue. Further, with the possible exception of green cane harvesting, the approaches have done little to maintain the productivity of the basic soil resource. It appears then that the major investment the industry has made in varietal improvement over the past 25 years has failed to realise a productivity increase. It may, however, have arrested a productivity decrease. However, the failure to realise a productivity improvement is a clear reminder that all components of the system are important and should be treated accordingly. Hopefully, the important factors causing yield decline will emerge from the approach now being taken and the management of these in conjunction with varietal improvement will result in a productive and sustainable sugar cane farming system.

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Rebuilding soil quality in rehabilitated land

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Introduction

This paper will focus on current approaches to rebuilding soil quality in land reconstructed after mining and on future directions for research to improve those approaches. The area of land that is reconstructed and rehabilitated after mining each year in Australia is likely to exceed 10,000 ha. This reconstruction effort is usually managed by the mining company at each site. In general, the aim of rehabilitation is to construct a landform that is stable with a self-sustaining ecosystem (Bell, 1990). The vegetation community that is re-established often depends on agreements with Government on final land use, and is usually similar to that existing prior to mining.

The nature of the mining operation is an important determinant of the final soil profile that is re-created. In some operations an horizon of mineral ore may be removed. For example, bauxite mining removes the bauxite layer (from 2 to 8 m thick) in the soil profile, after topsoil and overburden layers (up to 1 m) are salvaged (Lawrie, 1984; Nichols *et al*., 1985). After mining, the topsoil and overburdens are then replaced on the newly-exposed clay horizon. This contrasts with mineral sand mining where after salvaging topsoil, a complete profile is removed (usually tens of metres deep), the small percentage of mineral is extracted, and the mixed profile replaced and topsoil respread (Brooks and Bell, 1984; Jefferies *et al*., 1991). As a result of the mineral extraction process or during replacement of the material, sand and clay components are often separated. Therefore, discreet layers, particularly of clay 'slimes' may be found in the reconstructed soil profile.

Open cut mining for coal or metals such as gold and nickel, results in excavation of greater depths of material, a high proportion of which is 'waste', containing little or none of the target commodity. In open-cut coal mining, the waste or overburden is commonly of sedimentary origin (Hannan and Bell, 1993). Whereas in gold or nickel mines this waste material ranges from near-surface oxidised material through to fresh rock. Consequently at any one open-cut mine site there can be a variety of waste materials, differing in mineralogical, chemical and physical characteristics. At these sites there should be potential to manage the waste dumping sequence, to optimise the chemical and physical fertility of the final reconstructed profile.

Wastes or 'tailings' from mineral processing represent a further important rehabilitation challenge. These finely ground tailings are deposited as a slurry in large impoundments, creating deep, relatively uniform profiles. The chemical and physical characteristics of these materials varies at each site according to the ore type and the processing method.

Soil quality is the key factor in stable and sustainable restoration of land disturbed by mining. The capacity of the land manager to create a soil profile that is chemically and physically stable and that is capable of supporting plant growth is important and depends on an understanding of the properties of the materials available.

The quality of soil can be measured in terms of physical, chemical and biological fertility, each of which is crucial to plant productivity. The productivity of the re-established vegetation drives the rate of re-establishment of ecosystem processes, such as soil nutrient cycling. The challenge for land rehabilitation managers is not only to build a quality soil but also to demonstrate that to the satisfaction of overseeing authorities.

Achieving physical and chemical fertility

Rebuilding a soil profile may be as gross as managing a waste dumping sequence at an open-cut mine, or as detailed as manipulating the content and behaviour of clays in mineral sand tailings. The target may be to recreate the pre-mining soil profile and vegetation, alternatively, a different plant community may need to be established to suit the new soil. Each of these processes depend on a thorough knowledge of the key components of soil fertility.

The physical fertility of soil is reflected in its capacity to form a seedbed, its penetrability to roots, water infiltration, water holding capacity and availability to plants, and its resistance to erosion. Many or all of these specific factors will be covered in more detail elsewhere in these proceedings, as will the capacity of the soil to supply essential nutrients. An added factor which must be considered in reconstructed profiles is presence of chemical toxicities either from the mineral extraction process or released as a result of weathering or acid generation (Hannan and Bell, 1993).

The potential to influence the final physical fertility of the soil profile depends on the mining process. In bauxite mining the components of the profile are fixed, and the requirement is to optimise their performance. The principle approach is deep ripping to reduce compaction either inherent in the clay subsoil or caused by heavy machinery traffic. This process allows increased water infiltration and storage and root penetration (Nichols *et al*., 1985).

In mineral sands mining there is generally little opportunity to manage the sequence of deposition of the mixed and slurried soil profile. Although at some operations it may be possible to exert some level of coarse control on the proportion of clays and sand in the surface layers. Layering of clays and sands will occur during the deposition and settling process. These clay layers have the potential to form a relatively impermeable barrier in the soil profile which reduces water movement and root penetration. Future research is required to focus on mineralogical characterisation of these clay materials in order to optimise their management. Some clays such as those containing smectite have the capacity to crack and initiate the processes of soil formation while others such as kaolin-dominated materials remain as a potential barrier in the soil. It may be practical to amend these less reactive clays with calcium and to ensure a productive soil profile.

In tailings deposits from mineral processing of finely-ground ore, the chemical environment is frequently hostile for plant growth (Meecham and Bell, 1977; Barrett *et al*., 1992; Bell *et al*., 1994) particularly in terms of pH and salinity. Amelioration of these hostile elements in surface layers to allow the establishment of plants is a priority. Increased understanding of the movement of contaminants such as salt in these materials and into subsequent surface capping materials, together with patterns of reductions in sodium content (Wong, 1990) in response to ameliorants such as gypsum remain a priority.

After open-cut mining, the physical quality of the soil surface on a waste dump is amenable to control because the profile is literally being rebuilt and there is an opportunity to 'choose' the materials and their sequence of deposition. However, in practice most soil profiles are re-built according to a mining schedule, not according to the principles of soil science. It is our aim through research and extension to build some planning into the dumping sequence, to ensure that material with optimum physical and chemical fertility becomes the final surface.

Restoring biological fertility

The cycling of nutrients in soil and their acquisition by plants is mediated through the soil microbial population. Restoring this biological component of soil fertility should be an important aim of mine rehabilitation. This has two aspects, firstly, managing topsoils to optimise the survival of beneficial micro-organisms, soil animals and seeds. Secondly, if topsoil is unavailable or severely degraded, then inoculation with key symbiotic micro-organisms may be warranted.

Leguminous plant species play an important role in successful rehabilitation of reconstructed land through their capacity to fix nitrogen. An effective symbiosis of legumes with the nitrogen-fixing bacteria depends on the capacity of the bacteria to survive and infect the plant roots in the particular soil material. The soil chemical environment, particularly soil pH, is crucial to the survival of rhizobia (Robson and Loneragan, 1970).

Rhizobia appear to survive well in disturbed topsoil, even in the absence of host plants but are vulnerable to anaerobic conditions deep in stockpiled soils (Jasper, 1994a). Introduction of rhizobia for native plant species is technically feasible, but not widely practised. This is due partly to the ability of these nitrogen-fixing bacteria to spread as a result of dust, soil or animal movement. Infrequent use of inoculation with rhizobia in the mine industry also reflects the relatively imprecise sowing process at many sites, where seed may not be physically buried and seed germination may be delayed until adequate rainfall is received. Survival of rhizobia in a conventional seed-coating process is likely to be poor under these conditions.

Inoculation with rhizobia is particularly applicable for soil materials where chemical conditions differ substantially from that which local rhizobia may be adapted to, or where a legume is to be grown that is not native to the area and does not associate with locally-occurring rhizobia. Selection of adapted, effective rhizobia and the development of an appropriate inoculation process should enhance the early growth of leguminous species.

Unlike rhizobia, vesicular-arbuscular (VA) mycorrhizal fungi do not easily spread into adjacent soils**.** In addition, these fungi are obligate symbionts which makes it difficult to produce an inoculant in sufficient quantities for field use over large areas (Jasper, 1994b). Therefore, the first priority in rehabilitating mine soils should be to manage topsoil to ensure the survival of these and other beneficial soil micro-organisms. However, where good quality topsoil is unavailable or where chemical conditions in the soil to be rehabilitated are substantially different then inoculation with selected effective fungal strains may be justifiable (Jasper, 1994b). The challenge is to develop a practical procedure to introduce these fungi on the large scale required by the mining industry, where areas of up to 450 ha may be revegetated annually. Research in this area is continuing, with a focus on a dry inoculum that can be introduced into the soil, for example during a deep ripping operation (Jasper, 1994b).

Ectomycorrhizal fungi survive poorly in topsoils salvaged during mining. Further, the species of ectomycorrhizal fungi that thrive in newly-rehabilitated soils are not necessarily those that dominated in the pre-mining topsoils. To balance this, fungi which are suited to disturbed environments are able to rapidly re-invade (Gardner and Malajczuk, 1988). A succession of species of ectomycorrhizal fungi has been observed in rehabilitated soils, reflecting the changes in soil conditions with increasing age of rehabilitation (Gardner and Malajczuk, 1988). Inoculation with some ectomycorrhizal fungi is possible for seedlings produced in a nursery environment (Kuek, 1992; Grove and Le Tacon, 1993), but is only likely to be justifiable if fungi are required that are adapted to soil conditions which differ substantially from adjacent undisturbed soils.

Measuring soil quality and rehabilitation success

Rebuilding a quality soil is a challenge — equally important is proving that it has been achieved to the satisfaction of governments and the community. Consequently, developing and validating indicators of restoration success is currently of major interest (Tacey and Treloar, 1994). Ecosystem development is a long-term process, therefore early indicators of recovery which can be used to predict long-term sustainability are essential.

One area of current research at The University of Western Australia is focusing on quantifying nutrient cycling processes in rehabilitated soils, including soil microbial biomass and activity. Nutrient uptake and plant growth reflect initial soil fertility, while the resulting litter fall and decomposition enhance soil structure and water-holding capacity. Our research to date in rehabilitated bauxite mines suggests that soil microbial biomass is a useful, easily-measured, early indicator of plant productivity. Through this research, we aim to develop generic indices of nutrient cycling and soil formation and contribute to guidelines for the assessment of sustainability of mine sites throughout Australia.

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A global program to develop land quality indicators at district, national and global scales

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Abstract

The development of land quality indicators (LQI's) for evaluation and monitoring of land resource changes due to human-induced land use pressures was initiated by the World Bank in 1993. This initiative came from the World Bank's own internal concerns for the growing degradation of vital land resources needed for food, fibre and other primary industries by the increasing world population, particularly in developing countries. The preliminary work involved two consultative regional workshops (Colombia and Kenya) and a co-ordination workshop in Washington. A discussion paper has been published to set the framework and approach that will be used. Other international institutions have endorsed the need for such an activity and have added support over the past year. These include FAO, UNDP and UNEP. Many developing countries see the benefit both in building better monitoring and information analysing services (capacity building), and improving their inventories on the current condition and future needs for land resources.

The program is expected to achieve a set of standardised LQIs that can be used by decision-makers, appropriate to the needs of tropical, sub-tropical and temperate regions. A set of targets and thresholds will be developed for LQIs describing the state indicators. A meta-database on land related information will be set up on internet and the World Wide Web, and as stand-alone systems. This meta-database will provide documentation as to what is stored where, and its quality, reliability and mode of access. Emphasis will be on land suitable for cultivation and forestry, biological production potential, current land management technologies and monitoring provisions.

The trends in land quality occurring in agro-ecological zones at district, national and global levels will be the eventual output. The program is therefore targeted very specifically at achieving universally accepted indicators that are relevant at several scales by decision makers. The framework being used implies that human activities, including land management changes caused by population increases, exert pressure on the land resource that result in changes to land quality (state), and that these in turn provide reactions (responses) that can be used to rectify the land quality change. Finally the program will assist in improving the overall capacity of developing countries to monitor and manage their land resources for the future by making computing, statistical, remote sensing, and other monitoring technologies available and training personnel in their use.

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[1] Christian Pieri was unable to attend the symposium, his paper was presented by proxy by Ann Hamblin of CRC Soil & Land Management, Adelaide. Only the abstract is presented here.

Indicators Of Catchment Health : Towards A Conditionally Stable System

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Abstract

In addressing the question of where soil quality fits into catchment management it is argued that a holistic paradigm is needed. Catchments consist of a spatially variable set of biophysical factors of which soils are a part. Catchments also contain users and the functioning and health of catchments are often set by societal values rather than biophysical limits. This often leads to degradation or an unstable system. A conditionally stable system, with defined limits and a simple way to measure trends towards or away from stability may be the appropriate paradigm. An indicator approach that can be used by the catchment users is outlined. This approach depends on defining the condition of the catchment and monitoring trends in key but easily measured attributes (indicators).

Introduction

The management of catchments for sustainable multiple use requires a knowledge of both the biophysical resource base and the societal values associated with its use. Soil quality is only one of many factors to be considered in a catchment context. The biophysical base includes climate, soil quality, water quality, terrain characteristics and vegetation functional properties, particularly water use. Thus whilst a catchment boundary is readily defined, the entities that comprise a catchment and the flows and fluxes that occur between the entities are less easily quantified. Societal values include water quality and quantity, agriculturally productive soils, forest productivity, recreation, fishing and so on. Societal values decide most of the functional aspects in a catchment through land uses. Thus to manage a catchment to bring about a desired change requires trade-offs between many biophysical and socioeconomic constraints. Defining the economic output from a catchment is relatively simple. However, spatially combining soil properties with hydrology, ecology, climate and terrain attributes to predict water quality and quantity for management purposes is much more difficult. So what paradigm do we adopt given that there is presently no coherent theory to apply to catchment management? What questions are we asking in considering soil quality in catchment management ?

An equilibrium postulate for the desired catchment state appears to be a good starting point in developing a unifying theory of catchment behaviour in relation to management. A compelling reason to develop this line is that each of the major disciplines involved in catchment management contains an equilibrium concept that goes back to the beginnings of the discipline. The concept that soils evolve and age depending on climate, vegetation and weathering to a quasi-equilibrium state has been expressed by Jenny (1941) and Stark (1978). Progressive plant succession to a climax state has developed as a central ecological concept (Clements, 1916). In hydrology the concept of an equilibrium condition is well established. A hydrologic equilibrium / ecological optimality theory has been proposed by Eagleson (1982, 1994) and recently reviewed by Hatton, Salvucci and Wu (*in press*). Eagleson's work has largely been ignored, yet represents the endpoint of the conceptual development of a cross disciplinary equilibrium theory that could apply to catchment management. The attractiveness of Eagleson's work is that it may be possible to estimate how far a particular catchment has departed from it's initial equilibrium state and hence set limits to predict thresholds for a dysfunctional state. The main disadvantage is that the system may have changed in functional terms, and quantifying departures may be of little management value. Thus, is the equilibrium concept useful in catchment management ?

Equilibrium states beyond a climax has been demonstrated in several regions including coastal systems in Australia (Walker *et al*., 1981). It is well established that soils and landscapes age, and consequently responses of ancient soil systems to land uses can be expected to be different to young soil systems. That multiple equilibrium states can exist, and that some equilibrium points are less stable than others has been amply demonstrated by Walker and Noy-Meir (1981) and others. In the catchment context this means that systems could exist in different equilibrium states and the reaction to management could be quite different. Maintaining the stability of the equilibrium state depends on an ability to identify and manipulate the main factors involved and to evaluate how passive or active the processes are. A complicating factor is that active components may react on different time scales. Trudgell (1977) gives some useful discussion and examples of active (flow of energy and matter) and passive (when altered there is no mechanism to recover to the original state eg drainage). He concluded that *the sensitivity of a state of a system to fluctuations in external factors increases in proportion to the importance of these factors in maintaining that state*. Plants and soils are two external factors that can be manipulated to reach an equilibrium. Nevertheless, to manage catchments towards an equilibrium state seems unnecessarily limiting, since the state may be unstable or past land uses have ensured that a return to an equilibrium state is either biophysically impossible or economically unlikely. The idea of managing catchments towards a conditionally stable state, seems more achievable. In catchment management the conditionally stable state can be defined in terms of the inputs needed to maintain a healthy catchment, and embraces biophysical, economic and societal values. The question then becomes which factors influence the health of a catchment and how can they be manipulated to reach a conditional stable state ?

Indicators Of Catchment Health

Integrated catchment management is considered here to depend on both biophysical and societal values. Management is towards a self perpetuating and economically viable system (a healthy catchment). Sufficient information exists to indicate in broad terms how changes in vegetation and soil, through processes linked with water balance will affect the stability and productivity of catchments. Societal values, or the conditions required for an economically viable system also can be defined in broad terms. Establishing the rules for a conditionally stable catchment are definable, and although this is not the term used by catchment management groups, it is their global goal. The problem is that to achieve a “conditionally stable system” requires action on the ground, and often the action is production or externally driven (funding for remedial works), and this may not achieve the desired end-point. The first need is to define the broad goals of a catchment care initiative by agreeing on end-points based on societal values and biophysical limits. The biophysical status of the system can usually be defined in broad terms from existing information and the broad limitations to production agreed on. The next and critical step is to monitor how the catchment is coping with the production systems imposed, to find out trends in system health (conditional stability).

The need is to develop assessment techniques that can be applied by individuals or community groups at the paddock and catchment scales. One obstacle to developing better farm and catchment management options to minimise damage to catchments, has been the availability of simple methods to assess the relative environmental condition of a farm within a catchment context. Production records and product prices are compiled to keep track of financial trends. An **environmental health report card** is needed by farmers to keep track of the biophysical properties and processes that underpin and sustain farming activities. Within a specific catchment this offers the means to benchmark, monitor and evaluate trends in environmental properties and processes. Once assessed, longer term plans and staged remedial action can be implemented to restore productivity and profitability. Since biophysical processes are known to operate at a range of spatial scales (patch, paddock, farm, small catchment, large catchment and basin scales) and temporal scales (paddocks need day to day management, but a catchment may take decades to show watertable changes) planned management actions require knowledge at the scales likely to influence these processes. For example, salinisation at the patch scale can be caused by local features (a dyke, geological break, change in soil type, change in slope) as well as more substantial regional features (tree clearing replaced by annual cropping, which increases recharge and local and regional groundwater pressures). Response times to particular activities will also be different at the different scales.

The report card needs information at the management unit scale placed within a local and regional context. Because off-farm impacts as well as on-farm impacts are important we recognise the need to include the local catchment to give the spatial context. The catchment unit offers an appropriate scale for many societal values (profitability, quality of life, recreation, aesthetics and so on) to link with landscape and eco-system processes. It also links at a spatial scale with social and economic aspects which are usually in terms of a local government area (LGA). The implication from the above is that **locally collected data by landholders needs to be placed in a catchment context**. The latter data are usually collected by State or Federal agencies or with their assistance by local groups. Linkages between these data and information sources are important.

Monitoring changes in paddock or catchment condition can be expensive and is often left to various State and Federal bodies. Such sampling is rarely spatially dense enough to provide detailed information to an individual landholder or community group. **Community involvement in environmental monitoring is needed** and there are encouraging steps being taken in Australia in this direction (Alexandra *et al.*, 1996). A methodology that will be useful to detect trends and assess conditions employs **environmental indicators**. Environmental indicators are conceptually similar to the familiar economic indicators that appear daily in newspapers**. The need is for a few rather than many**. Carefully selected indicators combined with existing or expanded Commonwealth, State and community based environmental monitoring programs are envisaged as a rapid and cost effective way to develop practical ways to identify trends (improvements and declines) in natural resources resulting from farming practices.

A Brief Description Of The Indicator Approach

Indicators are measurable attributes of the environment or socioeconomic systems within a catchment area. They represent a subset of the attributes that could be measured, for example in a process model, focusing on the key easily measured attributes. They can be monitored *via* field observation, field sampling, remote sensing, or compilation of existing data. In the context of integrated catchment management, indicators are intended to enable individual farmers or catchment groups to assess the impact of farming practices on the health of their catchments. The health of catchments and the questions asked are related to societal values (productive land, water quality, soil quality etc), and because these change from place to place, one would expect indicators to vary from region to region. Nevertheless, it is possible to suggest how to assemble a core set of indicators to assess catchment health and to point out possible limitations on attributes that individual groups may want to use. The means to carry out an indicator program to aid catchment management has been outlined in a book edited by Walker and Reuter (1996) *Indicators of catchment health : a technical perspective*. The book contains technical input from scientists in CSIRO and other research agencies servicing Australia's rural industries. The following comments draw from this source.

Monitoring and assessment procedures are of little value in a stand alone mode. A set of steps are recognised from the legislative processes, community awareness, benefits analysis of monitoring, indicator development, implementation and assessment of the actions taken. The approach to an indicator program suggested by Walker and Reuter is to rate catchment condition and trends in farm and catchment health within a set of standards. These determine their relative condition and suggests areas where action is needed. The action may be remedial activity or meetings to improve awareness of issues or it may mean that more detailed study is needed to better identify the nature and source of the problem. Too often indicator approaches become bogged down in trying to identify and assess in detail all the environmental problems of an area or catchment. The result tends to be a long list of attributes that complicate collection, reduce adoption rates and in many cases confuse interpretation. Reliable interpretations for indicators, development and collection of easily collected indicators by catchment groups are two vital ingredients in linking with catchment management.

Two broad types of indicators were recognised by Walker and Reuter: **condition indicators** (these define the state of the system relative to a desired state) and **trend indicators** (measures of how the system has changed). These indicators need to be placed within the local context, and this is achieved from existing information, often maps of the distribution of soil types, geology, eroded areas etc available from agencies. Because it is necessary to consider information at both the point (paddock) and catchment scale these broad indicators are **sub-divided into on-farm and catchment indicators**. On-farm indicators are mainly soil attributes and are easily mapped. Amalgamated values or averages of paddock values can be difficult to interpret eg mean pH of several paddocks will fail to identify the one paddock that has an acid soil needing attention. Catchment indicators give overall responses (raising water table, rising stream salinity etc) or surrogate measures of complex process responses (eg area of a farm with trees yields inferences about local recharge) but not necessarily the location of "hot-spots".

The proposed indicators are shown in Table 1 and include farm productivity and financial performance, product quality, soil health, water health and catchment integrity. These indicators have been selected on the basis of a set of criteria that includes cost of collection, simple to measure, standards available etc. In the context of catchment health the ability of landholders to understand, systematically collect and interpret indicators outweighs most considerations. The criteria used to rank indicators from high (H), medium (M) to low (L) were :

1. Ease of capture (H =easy)
2. Total cost per hectare or per catchment (H = most economical or $ per ha)
3. Existence of a standard method of estimation (yes/no)
4. Interpretation criteria available - expected and threshold values (H = reliable criteria available, L = not available or variable spatially or temporally)
5. Significant at the catchment scale to estimate condition (H = directly related to catchment processes, L = indirectly related to processes)
6. Low error associated with measurement (H = low error)
7. Known response to land management or disturbances (H = well established response, L = response unclear)
8. Stable over the period of measurement (H = highly stable)
9. Trend indicators are mappable - as in property management plans (yes/no)
10. Generic rather than diagnostic (G or D)
11. Context data can be expected to be available -soils, vegetation etc maps (yes/no)

The indicators which best fit the criteria are identified and become part of the minimum set of indicators.

An example of a "report card" is given in Table 2. The data comes from a mixed farming area in the 600mm region of New South Wales. The trends are based on 5 years of data. The main environmental problems in the region relate to rising water tables and salinisation. The economics of the area revolve around current low wool prices and fluctuating but higher wheat prices. Annual systems (wheat) increase recharge and encourage the spread of salinity, and this affects both the value of the property and off-site water quality. The attractiveness of higher wheat prices is off-set by potentially costly environmental damage. The report cards show that under an annual cropping system the health of the catchment has deteriorated. Threshold values need to be established locally to set the limits below which the system is declared unstable. The perennial system shows an improving environmental situation which in the longer term should become stable. The catchment planning process should establish the most useful rotations to stabilise recharge rates, and this may involve farm forestry enterprises.

Conclusions

Soils are components of a catchment that are amenable to management. Integrated catchment management planning needs to include an understanding of the processes that integrate soils (not only with biological, climatic and atmospheric processes) but also with socioeconomic values. The factors that control the biophysical dynamics of catchments are well enough understood to underpin catchment and farm management planning. A problem exists in converting this technical knowledge into actions that are likely to sustain the overall health of catchments. The concept of aiming towards a conditionally stable system brings with it some challenges in terms of defining the limits to the system. However, the concept does blend well with the health metaphor and with relatively simple ways to empower catchment users with a means of self-assessment. The need to encourage action, and then monitor the benefits is the key to developing integrated management.

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Measuring Sustainability Of Agricultural Systems At The Farm Level

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This paper bases sustainability evaluation on the multifaceted FESLM (Framework for the Evaluation of Sustainable Land Management) developed by FAO and IBSRAM. The work reported evaluates sustainability at the on-farm level. It proposes a preliminary list of field indicators, provides examples from actual measurements and outlines a method to visually and quantitatively represent results for easy analysis and comparison.

An agricultural system is said to be sustainable at the farm level if it satisfies the farm manager's needs (over time) while conserving the natural resource. Resource conservation is handled separately from farmer satisfaction. Farmer satisfaction includes issues such as "productivity", "profitability", "stability" and social "acceptability".

Selection of field indicators is not yet complete. Initial screening for measurable and meaningful surrogates has revealed yield, net income, and frequency of crop failure as field indicators for farmer satisfaction; and soil depth, organic carbon content, and percent ground cover for resource conservation.

An indicator is said to be at a sustainable level if it exceeds a designated trigger or threshold level as given below. The thresholds are tentatively set as improvements on community averages. Those for resource conservation include an absolute minimum. Indicators are expressed as units of their respective threshold levels, where one equals the threshold.

INDICATOR	THRESHOLD LEVEL
Yield	20% more than average yield in the community
Net Income	20% better than average of the community
Frequency of crop failure	20%, or average frequency for the community whichever is lower
Soil depth	50cm or average of similar soil types in the community
Organic Carbon (OC)	1%, or average of community, whichever is higher
Permanent ground cover	15%, or average of community, whichever is higher

On this basis an agricultural system is not sustainable if the average of indicators for either farmer satisfaction or resource conservation, is less than one. The sustainability of the system can be represented in two ways:

(1) as the combined average of the ratings for farmer satisfaction and resource conservation, and
(2) as a radar polygon for farmer satisfaction and resource conservation.

This procedure for evaluating sustainability was applied to actual data from farms in Guba, Cebu. Our experience is that the procedure can be implemented easily. The results are also consistent with our expectations. The process allows the worker to compare farms or farming systems and monitor changes over time. It also allows comparison of different scenarios by altering thresholds for farmer satisfaction or adding other indicators.

Introduction

Sustainable agriculture has been equated to almost all that is good for the farmer, his farm, and the wider environment. Profitability, stability, productivity, acceptability and environmental friendliness are some of the qualities now associated with sustainable agriculture. Considering that each of these qualities is complex and can be defined in several ways, it is no surprise that the definition and measurement of sustainable agriculture has been very elusive.

There are two potential approaches for defining and measuring sustainable agriculture. One is based on the principle that the important indicators of sustainability are location specific and change with the situation prevailing on a farm. For example, in the steeplands, soil erosion has a major impact on sustainability, but in the flat lowland rice paddies, soil loss due to erosion is insignificant and may not be a useful indicator. Based on this principle, the protocol for measuring sustainability starts with a list of potential indicators from which practitioners select a subset of indicators which is felt to be appropriate for the particular farm being evaluated.

The other approach is based on the principle that the definition, and consequently the procedure for measuring sustainable agriculture, is the same regardless of the diversity of situations that prevails on different farms. Under this principle, sustainability is defined by a set of requirements that must be met by any farm, regardless of the wide differences in the prevailing situation. For example, in the steeplands and in the lowland rice paddies, described above, soil erosion is an important indicator of sustainability, accepting that this requirement is more easily met in the latter situation.

There are clear advantages and disadvantages between these two approaches to assessing sustainability. The principle of location specificity avoids the difficulty of selecting and agreeing on a common set of indicators, a task that is always controversial. In addition, it allows each practitioner the freedom to choose their own indicators, a feature that is very attractive amongst workers at the grassroots level. A major drawback with the location specific approach is the difficulty of comparing results from farms where different indicators have been selected. Here lies the strength of the second approach of constant indicators across all farms. All measurements are based on the same indicators and the results are comparable across farms and are easier to analyse for repeatability and replicability.

This paper assumes that the second principle of a common definition and set of indicators for measuring sustainability is a much more powerful and useful concept for studying sustainable agriculture. It proposes a protocol for measuring sustainability at the farm level by:

1. defining the requirements for sustainability,
2. selecting the common set of indicators,
3. specifying threshold levels,
4. transforming the indicators into a sustainability index, and
5. testing the procedure using a set of data from selected farms in the Philippines.

1. Defining The Requirements For Sustainability

At the farm level, a farming system is considered sustainable if it conserves the natural resource and continues to satisfy the needs of the farmer, the manager of the system. Any system that fails to satisfy these two requirements is bound to change significantly over the short term, and is therefore considered unsustainable.

Farmer satisfaction and resource conservation, the two requirements of sustainability, are not simple characters but are influenced by a host of factors. High yield, low labour requirement, low input cost, high profit, and stability are some of the features that are likely to enhance farmer satisfaction. Natural resource conservation, however, is usually associated with soil depth, water holding capacity, nutrient balance, organic matter content, ground cover and biological diversity.

This definition is similar to the Framework for Evaluating Sustainable Land Management (FESLM), proposed by FAO and IBSRAM. The first four 'pillars' of FESLM, productivity, stability, viability and social acceptability are the main components of farmer satisfaction. Social acceptability has more relevance at the community level parameter and is not included at the farm level. The fifth 'pillar' of FESLM, protection/conservation, is the main component of resource conservation.

2. Selecting Indicators Of Sustainability

Even with the simplified requirement for sustainability at the farm level, there are many indicators commonly mentioned. Shown in **Appendix 1** is a list of some of these indicators and the procedure for measuring them. It is clear that several indicators are closely related to each other and it is not necessary to measure all of them. Those that should be selected must possess one or more of the following features:

1. be easy to measure,
2. respond easily to change,
3. have obvious boundaries (threshold) separating sustainable from unsustainable conditions, and
4. be directly related to the two requirements for sustainability.

Using the above guidelines, the following indicators were initially selected: yield, net income and variance of profit as indicators of farmer satisfaction and soil loss, nutrient balance and organic carbon as indicators of resource conservation. However, variance of profit, soil loss, and nutrient balance were considered too difficult to measure directly and the following surrogate indicators were used instead: frequency of crop failure, soil depth and percent permanent ground cover.

Of the six indicators selected, only the last one, permanent ground cover poses a problem in terms of universality. For example, in steepland where soil conservation practices are needed, permanent ground cover serves as a useful indicator. However, in the flatlands where soil conservation may be of little importance, ground cover may not be so relevant.

3. Specifying A Trigger Or Threshold Level

The term threshold level is used to denote the boundary between sustainable and unsustainable values. Unless this threshold level is specified for each indicator, it is not possible to distinguish between sustainable and unsustainable conditions.

In this paper, the primary basis for the threshold level is the average of the community, instead of an absolute value for all situations. This seems reasonable since farmers usually judge their state of well being on the basis of their position relative to their neighbours, and since farms applying good conservation practices are expected to retain their initial resource endowment. With this procedure, it is expected that the threshold levels for communities with widely different economic and biophysical environments will also differ widely. Shown in **Table 1** are the threshold levels for the indicators used in measuring sustainability. Also shown are the formulae used to compute each threshold.

Table 1. Threshold for sustainability indicators.

Indicator	**Threshold Level**	**Threshold Formulae**
Yield (X_1)	20% more than average yield in the community	1.2 (Mean x_1)
Net Income (X_2)	20% better than average of the community	1.2 (Mean x_2)

Frequency of crop failure (X_3)	20%, or average frequency for the community, whichever is lower	0.20 when the mean of $x_3 > 0.20$, mean of x_3 otherwise.
Soil depth (X_4)	50cm, or the average of similar soil types in the community, whichever is greater.	Mean x_4 or 50cm, whichever is greater.
Organic Carbon (X_5)	1%, or average of community, whichever is higher	0.01 when mean $x_5 < 0.01$, mean x_5 otherwise
Permanent ground cover (X_6)	15%, or average of community, whichever is higher	0.15 when mean $x_6 < 0.15$, mean x_6 otherwise

4. Transforming Indicators Into A Sustainability Index: A Case Study In The Philippines

To illustrate the procedure for computing the sustainability index at the farm level, we use data from ten farms in Guba, Cebu, Philippines (**Table 2**). Guba is a farming community of about 1000 households cultivating the slopes of the mountains surrounding Cebu City. About fifteen years ago, the World Neighbours, a church based organisation, decided to introduce contour hedgerow farming into Guba in an effort to conserve the soil and related resources. Today about 60 percent of the community has adopted the new technology. Of the 10 farms given in **Table 2**, the first six are adaptors of the contour hedgerow technology while the remaining four are not. For data given in the table, yield, net income and frequency of crop failure are survey data while soil depth, organic carbon and permanent cover are measurement data.

Table 2. Sustainability Indicators for 10 farms in Guba, Cebu.

Farm N^o.	**Farmer Satisfaction**			**Resource Conservation**		
	Yield (T/ha)	**Net Income ($/ha)**	**Frequency of Crop Failure (%)**	**Soil Depth (cm)**	**OC (%)**	**Permanent Ground Cover (%)**
1	1.88	252	15	117	1.15	25
2	1.42	163	20	80	0.52	14
3	1.43	195	20	87	.72	17
4	2.02	247	30	37	.60	14
5	1.75	203	25	86	1.26	16
6	1.62	227	25	70	0.80	14
7	.88	38	20	47	1.61	7
8	.52	30	15	27	0.82	0
9	.98	116	20	100	1.74	0
10	.81	29	15	42	0.82	1
Average	1.33	150	20.5	69.3	1.06	10.8
Threshold	1.60	180	20.0	69.3	1.06	15.0

The computation of the index of sustainability for each of the ten farms is as follows:

Step 1: Specify the threshold level for each indicator following the formula given in **Table 1**. Convert all measurements into threshold units as shown in **Table 3**.

Step 2: Represent the relative sustainability of farms graphically for visual comparison **(Figure 1).** Note that the specific components that results in reduced sustainability are easily seen from these graphs.

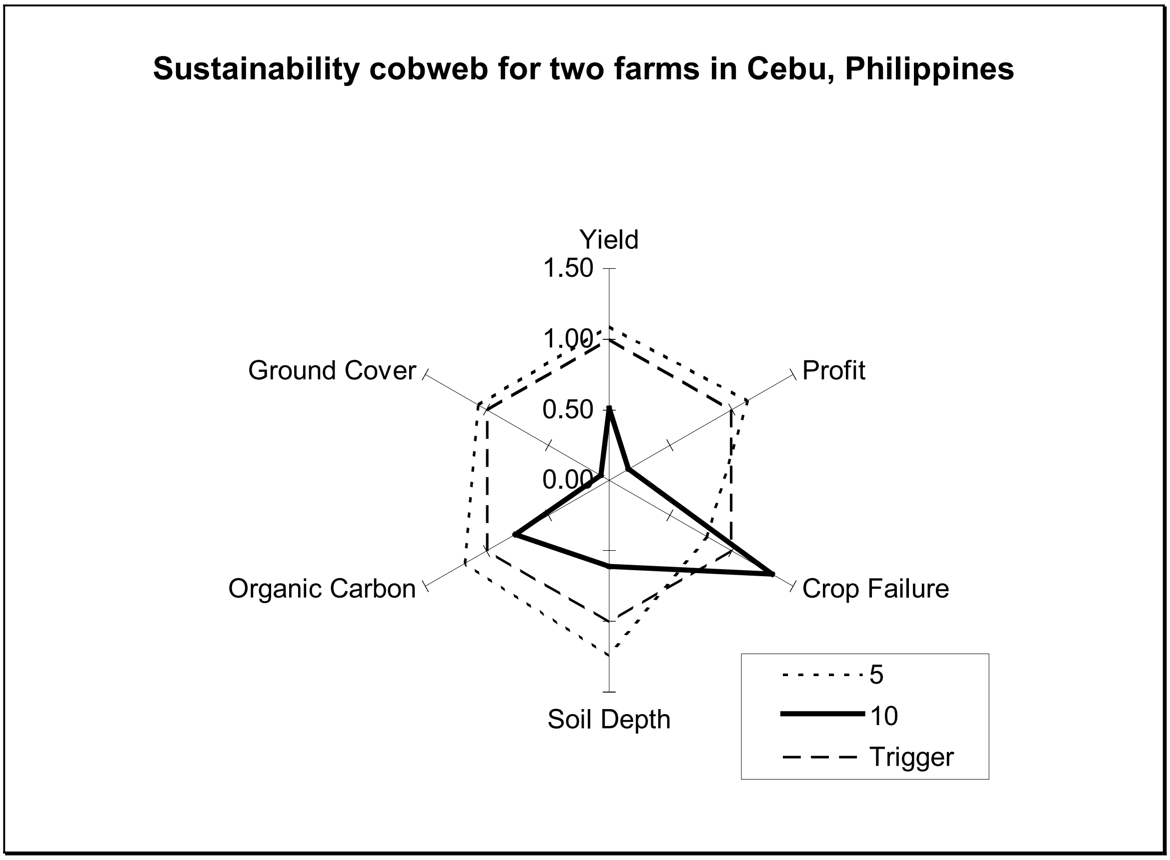

Figure 1. Radar Graph showing : (a) the threshold or trigger line, (b) the sustainability of farm number 5 with a bounded area exceeding that of the threshold even as one indicator is below threshold, and (c) the unsustainable situation in farm number ten with five out of six indicators below threshold.

Step 3: Compute the indices for farmer satisfaction and resource conservation as the average of their three respective indicators. These two averages must both be equal to or greater than 1.0 for the system to be judged sustainable. For our example, only farms N^{o}. 1 and N^{o}. 5 are judged sustainable.

Step 4: For sustainable cases, compute the average of the two indices. This average is the final index of sustainability which is equal to 1.48 for farm N^{o}. 1 and 1.08 for farm N^{o}. 5. Note that the sustainability index is computed for sustainable systems only, i.e., no index is computed for farm that are judged unsustainable. Thus, the sustainability index is always positive and greater than 1.0, the higher the value, the more sustainable the farm.

Table 3. Sustainability indices for 10 farms in Guba, Cebu.

	Farmer Satisfaction				**Resource Conservation**				
Farm N^{o}.	**Yield**	**Net Income**	**Crop Failure**	**Index**	**Depth**	**OC**	**Ground Cover**	**Index**	**Sustainability Index**
1	1.18	1.40	1.33	1.30	1.69	1.65	1.66	1.66	1.48
2	0.89	0.90	1.00	0.93	1.15	0.49	0.93	0.85	NS
3	0.89	1.08	1.00	0.99	1.25	0.68	1.13	1.02	NS
4	1.26	1.37	0.66	1.10	0.54	0.57	0.93	0.68	NS
5	1.09	1.13	0.80	1.01	1.24	1.18	1.07	1.16	1.08
6	1.01	1.26	0.80	1.02	1.01	0.75	0.93	0.89	NS
7	0.55	0.21	1.00	0.59	0.68	1.51	0.47	0.88	NS
8	0.32	0.16	1.33	0.60	0.39	0.77	0.00	0.38	NS
9	0.61	0.64	1.00	0.75	1.44	1.64	0.00	1.02	NS
10	0.51	0.16	1.33	0.67	0.61	0.77	0.07	0.48	NS

Some Notes On The Index

As a consequence of the procedure with which the index is computed, several characteristic features are worth noting. These features are discussed below:

A. *The requirements for sustainability.* An average rating of more than 1.0 for both farmer satisfaction and resource conservation is necessary for the system to be sustainable. This requirement can be met even if some indicators are below the threshold level (i.e., less than 1.0). For example, average rating for farmer satisfaction or resource conservation may exceed 1.0 even if one or more indicator has a rating of less than 1.0. This means that a deficiency in one indicator can be compensated for by excess capacity in another. For example, in farm N^{o}. 5, frequency of crop failure is below threshold, but yield and income are high enough to compensate for the deficiency. Note, however, that this ability to compensate is allowable only among indicators of the same index, (i.e., within farmer satisfaction) but not across requirements. Thus excess rating in yield or income cannot compensate for deficiencies in soil depth and organic carbon.

B. *Sustainability at the community level.* Changes in the threshold level, over time, are a key indicator of sustainability at the community level. Note that communities that upgrade their management practices should consistently improve their level of productivity and natural resource endowment, which then should be reflected in ever improving threshold levels. Thus, improving threshold level, over time, is indicative of sustainability at the community level; and conversely, a decreasing trend indicates unsustainability.

C. *The radar graph*. This graph is a good tool to immediately visualise and identify the specific component practices that result in reduced sustainability. It helps to understand the differences across farms, or over time in the same farm. Hence, overall sustainability is not just reduced to a single analogue derived from a common perspective, but becomes a useful visual tool to planning for further action.

Concern has been expressed that the approach gives equal weighting to each of the indices, whereas some workers consider some to be more important than others. The graphical representation goes some of the way to addressing this. Individual workers can see the relative contribution of each index and draw conclusions based on their personal interpretation of the importance of each.

D. *Level of index*. It should be noted that once the sustainability requirement is satisfied, a general index is computed whose value is indicative of the number of times that the threshold level is surpassed. For example, an index of one indicates that the system is at threshold level, an index of two means that the system is two times the threshold, and so on.

E. *Flexibility to accommodate additional indicators.* In terms of procedure it should be obvious that there is no difficulty in accommodating additional indicators under each of the two main pillars. Since the indices are averaged across indicators, adding more indicators should not unduly complicate the process nor the level of comparability among indices.

F. *Farmer satisfaction and Resource conservation.* The net effect of grouping indicators into two requirements for sustainability is to reduce the strictness with which farms can be judged as sustainable. The fact that there is a given level of substitutability among indicators in the same requirement group results from this reduced strictness. Note that if all the six indicators have to exceed the threshold for the system to be sustainable, then fewer farms will pass the requirement for sustainability. This is clearly illustrated by the 10 farms in Guba. Two farms are judged sustainable under the present procedure. Otherwise only one farm (farm N^{o}. 1) would pass.

Conclusion

The procedure outlined in this paper has been developed from a definition of sustainability at the farm level which provides two sets of indicators relative to farmer satisfaction and resource conservation. It has been selected for its ease in implementation both in data gathering and in data analysis. Experience in applying this procedure to farms in Guba strongly corroborates this desired simplicity. The data are easy to gather and the analysis is simple. We plan to repeat the process in another community where measurement data will be used for all indicators.

The two approaches to measuring sustainability, i.e., location specific versus constant indicators across farms, is closely related to the principle of substitutability among indicators. The location specific approach does not allow for substitution but requires that all indicators are above their respective threshold level. This is so since the indicators selected for each particular situation are those that are likely to be lower than threshold. This is why soil loss is a good indicator for steeplands where soil erosion can be high, but is not so in the flat lands where erosion is low. If all farms are to be assessed on their weakest points then this is likely to give a very pessimistic picture of sustainability.

In the constant indicator approach, however, a selected indicator is measured for all farms regardless of its likelihood or non-likelihood of violating the threshold. Indicators are selected for their own merit. Thus this approach is less targeted and more farms are likely to pass the sustainability test.

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Appendix 1. Summary of the commonly mentioned sustainability parameters.

INDICATORS FOR FARMERS SATISFACTION	MEASUREMENTS
Productivity	
Net return to land	Economic outputs, economic inputs, farm- gate prices (inc. imputed prices), using direct measurement, periodic interviews, market surveys
Net return to labor	
Total factor productivity	
Yield	kg/ha, kg/person/year
Viability	
Cash flow; discounted cash flow	As above, over time (measured or projected; interest rates on farm credit (explicit or implicit); food surveys
Flow of net benefits; net present value	
Net farm income (after farm development)	
Flow of staple food availability	
Stability	
CV of productivity measures	Measurements of inputs and outputs, costs and returns, over time for each test farm; periodic
CV of net benefits	
Diversity of enterprises	Number and kind of enterprises
Net returns in worst 20% of trials (minimum returns analysis)	Measurements of key elements (e.g., yield, output price) across a sample of farms
Acceptability	
Labour	Person days per year
Membership of community organisations	Number of organisations, type of organisations
Adoption indices	Adoption surveys examining degrees of adoption, farmer opinion, and likely constraints (e.g., tenure status) .
Farmer ratings	Opinion poll of farmers, e.g., at a field day

INDICATORS FOR RESOURCE CONSERVATION	MEASUREMENT
Soil loss (gain)	Amount of soil formed - amount of soil loss
Woody perennial population	Area of woody perennials/total farm area
Soil nutrient budget	Added nutrient vs biomass removed
Turbidity index	Suspended solids in run-off water
Erodibility index	Soil loss under controlled rainfall simulation
Ecological diversity	Shannon's index (the total number of species cultivated, collected or used on the farm)
Topography	Slope, slope length
Soil stability	Water dispersable clay
Nutrient cycling	Finn's Cycling Index (Proportion of the nutrients within the system which are recycled within the system)
Bio-resource recycling	The total number of farm-generated biological material flow within the farming system.
C:N ratio	Organic Carbon: Mineralisable Nitrogen ratio over time
Soil compaction	Soil resistance to penetration over time
Calico index	Degradation in tensile strength of a calibrated strip of buried calico over time. Surrogate measure of soil biological activity.
Ground cover	Averaged percent of soil surface covered by living or dead mulch during wet weeks (>50 mm rainfall per week)
Water stress	Crop rotation stress days per year

Abstracts to Posters

"MCALM" (Monitoring Catchment and Land Management)
A Computer based Recording, Monitoring and Management system to assist Evaluation through the use of Performance Indicators

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MCALM is a computer based component which supports the monitoring and reporting system.
MCALM is intended as a base level system which stands alone or supports other central systems.

Its purpose is to:

- enable the monitoring of, program activity, client activity and budgets.
- simplify the production of activity reports from existing or readily collected data.
- provide easy access to information required for day to day activities and to benchmark progress for Catchment Management Officer's at work centre and/or Area level.

The system is designed to enable data storage; information sharing; data filtering, manipulation, analysis and the production of reports

MCALM is programmed in Visual Basic using the MS Access Database engine.

It incorporates existing routines and modules used in the Agbase Whole Farm Planning program.

MCALM is PC based and can operate on stand alone systems.
It can also operate as an online system able to be interrogated from remote locations.
The program requires a 486 DX 2-66 with min. 8 Mb of RAM, Windows 3.1 or later (Windows 95 compatible) and at least a 200 Mb hard disk.

The program has been designed to utilise GIS. It should be able to utilise two systems. One is an AG-base, on-line visual GIS developed by Agtech to support landholders whole farm planning needs.
The second is ESRI's Arcview 2 used by DCNR.

Progress with MCALM Development

MCALM has been developed to the prototype stage in association with the Horsham based computer company "AgTech". AgTech is an Internet service provider and provides a secure connection to its clients involved in its whole farm planning consultancy.
Information derived from the consultancy may be available for use within the MCALM Program.

Effects of Storage on Topsoil Revegetation Characteristics

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At the Placer (Granny Smith) open cut gold mine in the north-eastern goldfields (Laverton [28_46'S, 122_26'E]) of Western Australia, topsoil stripped before mining has remained *in situ* for up to five years in stockpiles before re-use. Nutrient analyses of three topsoils, stored for two months, two years and five years, showed anaerobiosis in five year old material. There were significant increases in topsoil acidity and elemental sulphur, and the level of phosphorus and organic carbon decreased significantly. In topsoil stored for five years there was a decreasing trend in the amount of potassium and nitrate and increase in ammonium levels.

Storage of topsoil altered the percentage of different soil particle sizes. The proportion of topsoil particles < 0.20 mm in diameter was significantly reduced in five year old material, primarily in response to mechanical dispersion from raindrop splash and wind. A topsoil storage period of two years or more significantly reduced the number and species diversity of the seed store.

The establishment of a short and long lived leguminous plant cover was examined as a method of maintaining and (or) re-invigorating topsoil viability. Fertiliser, applied at up to 780 kg per ha, was trialled as a topsoil ameliorant. Fertiliser at 130 kg per ha benefitted seed germination, and decreased seedling mortality of three legume species, in topsoil stockpiled for between two months and five years. Fertiliser rates in excess of 130 kg per ha decreased seed germination and increased seedling mortality.

In topsoil stored for longer periods, plant establishment was detrimentally affected. Lower heights and lighter dry shoot and root biomass at harvest was recorded for plants grown in topsoil stored for five years, compared to two months or two years. Increased topsoil storage age decreased the intensity of plant root nodulation and the level of infection by VA mycorrhizal fungi. In five year old topsoil nodulation was inhibited and no VA mycorrhizal infection was observed. The application of fertiliser at 130 kg per ha or more inhibited plant root nodulation. Higher fertiliser rates up to 780 kg per ha progressively decreased the level of VA mycorrhizal infection.

Topsoil grafting was another method examined for re-invigorating long term stockpiled topsoil over rehabilitation sites, through the application of a thin surface cover of recently stripped topsoil. The germination and seedling survival of short lived species were not affected by topsoil grafting depth, or the age of underlying stockpiled topsoil. Longer lived *Acacia* species however showed higher levels of seed germination and seedling survival, with a topsoil graft in excess of 50 mm depth.

Over topsoil stockpiled for two years, a topsoil grafting depth more than 25 mm increased plant performance as measured by growth parameters. Over topsoil stored for five years a grafting depth of 50 mm or more significantly increased plant performance. Long and short lived species showed more root nodulation in topsoil stockpiled for two years, compared to five years. Deeper topsoil grafts of 75 mm and 100 mm depth, enhanced root nodulation on both two and five year old topsoils.

In a field trial at Laverton, two and five year old topsoil stockpiles were examined. Low rainfall during 1994 limited plant growth and survival. However, the establishment of short lived legume species was favoured over topsoil mounds stockpiled for two years, and longer lived *Acacia* species were more successful on the five year old stockpile. The application of fertiliser and animal droppings in the field did not lead to increased plant numbers fifteen months after seeding. A locally collected brush matting spread over topsoil mounds tended to enhance seedling establishment on the surface of storage mounds.

The Characterisation Of Cadmium In Some Soils Of The Ballarat Farming District And Its Implications With Respect To The Availability Of Cadmium For Plant Uptake

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The entry of cadmium into the food chain via agricultural processes has generated considerable concern throughout the farming and scientific community. Phosphate fertilisers contain appreciable amounts of cadmium and thus their application constitutes a likely source of cadmium in agricultural soils. It has been well established that the availability of soil cadmium for plant uptake depends primarily on its chemical and mineralogical form. The present study involved the characterisation of cadmium in some agricultural soils of the Ballarat potato growing district. Such soils are rich in iron and manganese oxides which are able to readily absorb phosphates. Thus, increasing quantities of phosphate fertiliser are applied to compensate for this phenomenon and therefore comparatively large amounts of cadmium are introduced to these soils.

The characterisation scheme adopted, permitted the extraction of cadmium associated with the major soil components; namely: water soluble, exchangeable, metal oxides, organic material and residual material. The characterisation method adopted is commonly referred to as a sequential extraction procedure and involves treatment of soil samples with increasingly stronger reagents such that each reagent(s) solublises cadmium associated with a specific soil component.

Subsoil cadmium concentrations were measured at a number of sites and the cadmium concentration in the topsoil of a virgin site was also measured.

A number of soil parameters considered to be important in regulating the distribution of cadmium throughout the soil components were measured. These parameters include:

- the concentration of inorganic and available phosphorus,
- the concentration of iron and manganese associated with their amorphous oxides,
- the concentration of the cations of calcium, magnesium and zinc,
- pH_{H20} and pH_{CaCl2} and
- electrical conductivity.

Some of the findings of the study were:

- the cadmium concentrations in the soils tested ranged from 70-200 ppb,
- the concentration of cadmium in the agricultural sites were, on average, twice that of the virgin site and three times that of the subsoil sites
- on average, more than half of the soil cadmium was associated with amorphous oxides of iron and manganese and thus were relatively unavailable for plant uptake,
- approximately 10% of the soil cadmium was found to be readily available for plant uptake,
- the average concentration of cadmium associated with the organic and residual material was 20 ppb,
- the correlations between the measured soil parameters and the cadmium concentrations were generally low and insignificant,

Agricultural processes have significantly elevated the cadmium levels of these soils but such concentrations are still well below levels considered normal for unpolluted soils.

Furrows that Trickle?

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Introduction

Irrigation of Riverina vineyards is usually by flooding with broad based furrows (8ML/ha/yr). To obtain greater control of irrigation, farmers are adopting drip systems (5ML/ha/yr). Another system is to create a small furrow either side of the vine. This 'Riverina Twin Furrow' (RTF), with quick applications should result in a reduced wetted soil volume (6ML/ha/yr). Drip is relatively expensive to install, whereas water and labour savings make drip and RTF cheaper to run than flood.

Method

Flooding in broad based furrows, Riverina Twin Furrow (RTF) and drip irrigation were evaluated on clay soil. Tensiometers were installed in a grid at 5 points perpendicular to the vine row at 5 depths, read daily from mid January 1995 to mid February 1995. Soil salinity was also analysed at each point grid. The distribution of vine roots was analysed by a qualitative scoring system from soil cores.

Results

Soil Water Potential - Flood irrigation completely wetted the soil profile. Much of the soil was too wet (<20kPa), especially close to the vine and below 50 cm. RTF wetted the entire soil profile, however only below 50 cm was too wet (<20kPa) and the middle of the inter-row was drier than with flood irrigation. Drip irrigation produced a limited soil wetting pattern. The soil was too wet (<20kPa), except at the fringes of the wetted area. There was free water directly below the emitter at 50 cm depth.

Roots - Vines under flood irrigation had a large root zone. Roots were found from the surface to 60 cm depth, below this the soil was too wet. Vines under RTF had a large root zone. Roots were found from 10-60 cm depth. Surface roots had been destroyed by cultivation. Vines under drip irrigation had a limited root zone. The roots were growing in the very wet zone but avoided the area of free water.

Soil salinity - The initial soil salinity was very different at each site. The flood irrigation site had uniform soil salinity distribution. The RTF site showed that salt was leached away from directly under the vines where the water was applied. The drip site showed a build up in soil salinity at the soil surface.

Conclusions

- Over irrigation occurred in some part of the root zone with all the irrigation systems.
- Better management is the key to better irrigation, not the irrigation system in itself.
- Each system produced a different wetting pattern and root distribution.
- Drip irrigation had a restricted wetting pattern and root zone requiring different management from the other systems.
- Riverina Twin Furrow resulted in less wetting of the middle of the inter-row which would reduce water use.
- Point application of water results in uneven soil salinity distribution

Soil Quality and Salinity of Victoria's Agricultural Soils

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Introduction

Many soil chemical properties affect soil quality and one of the most important in many areas of Victoria, is the concentration of soluble salts. A recent report on salinisation in Victoria (Allan 1994) estimates that 120,000 ha of land is affected by secondary salinity. Natural or primary salinity is estimated to affect 250,000 ha and irrigation salinity to affect 140,000 ha. This study attempts to provide an update on soil quality in terms of the salinity of surface and sub-surface soils by illustrating state-wide trends in surface soil EC and local trends in soil profile EC.

Methodology

This investigation used the same approach as in papers on soil pH and soil fertility presented in this symposium (Crawford *et al.* 1996; MacLaren *et al.* 1996). This paper reports on the mapping of electrical conductivity ($EC_{1:5}$; 1:5 soil:water) of surface soil samples (0-10, 0-15 and 0-30 cm depth) representing farmer's paddocks to show state-wide temporal and spatial trends. Local trends in soil profiles (0-1 m depth) are illustrated using soil electrical conductivity data ($EC_{1:2.5}$; 1:2.5 soil:water) from a survey (Crawford and Maheswaran 1995) based on the 1993 resampling of 54 sites from the National Soil Fertility Project (NSFP) conducted in 1968-72.

Results and Discussion

Spatial trends in surface soil EC across Victoria

Of the 15 million Ha of agricultural land in Victoria, it was estimated that the surface soil of 190,000 Ha, or 1.3 % of agricultural land, is sufficiently saline ($EC_{1:5} > 0.3$ dS m^{-1}) to cause problems for plant growth. Of these saline soils, 64 % can be classified as low level salting, 23 % as moderate salting and 13 % as severely affected (Matters and Bozon 1989). Many of the saline areas correspond with areas which Allan (1994) indicated to have been influenced by dryland salinity and irrigation salinity in inland Victoria. Coastal areas may be the result of the combined affects of low rainfall and proximity to the sea. Areas of natural salinity are probably not represented in this study since soil sampling would normally be used to assess agricultural land only.

Changes in surface soil EC across Victoria

This study highlighted the emergence of salinity problems especially in the north-western plains through to the Kyneton-Broadford district and also in the Hamilton district. Shires in these regions had significant ($P < 0.05$) increases in mean $EC_{1:5}$ of samples from 1973-83 compared to those from 1984-94. No shire showed significantly lower mean $EC_{1:5}$ over time.

Changes in surface and sub-surface EC at specific sites

The NSFP sites were selected to represent the main soil types used for dryland pasture production in the > 450 mm rainfall zone. Few sites are in the lowest parts of catchments and most are situated away from discharge areas. As such, they provide an illustration of soil quality, in terms of salinity, under typical productive dryland pastures. Most had harmlessly low salinity ($EC_{1:2.5} < 0.5$ dS m^{-1}) throughout the profile and remained so or became lower, after two decades. Exceptions were four sites where $EC_{1:2.5}$ increased. All four of these sites were in potential discharge areas situated in the lowest part of the landscape.

Conclusion

This investigation indicates that soil quality is degrading in some shires in western Victoria. However, it is also demonstrated that at specific sites, salinity or changes in salinity may be dissimilar to general district trends. This emphasises the need for farmers to assess paddocks individually.

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Soil Quality and pH of Victoria's Agricultural Soils

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Introduction and Methods

Extremes in soil alkalinity and soil acidity are aspects of poor soil quality. Acidification can degrade the quality of otherwise productive soil. Alkalinization may improve soil quality if strongly acid soils become less so, but in soils that are already alkaline, this process may be associated with poor soil structure and/or high salinity. Results from three projects are used to update knowledge of the current quality of Victoria's agricultural soils in terms of acidity and alkalinity.

Surveys in the > 450 mm zone

Two pasture surveys are used to illustrate changes in soil pH at the local level. In the first, 112 sites consisting of unlimed dryland pastures and adjacent undisturbed areas, eg. roadsides or forests, are used to illustrate changes in surface soil pH (1:5 0.01 M $CaCl_2$, 0-20 cm depth; pHc) since the land was cleared (Crawford *et al.* 1994). A second survey (Crawford and Maheswaran 1995) based on the 1993 resampling of 54 sites used in 1970-72 for the National Soil Fertility Project, is presented to show how soil pH (1:2.5 water; $pH_{2.5}$) has changed in the last 20 years.

Mapping Project

A current project is used to map soil pH (1:5 water; pHw) and identify pHw changes on a statewide basis. Data including nearest location and pHw, were digitally recorded from farmer's soil samples submitted to the State Chemistry Laboratory from 1973 to 1994 for routine testing. Spatial trends were mapped by kriging mean pHw for each location. Temporal trends were detected by splitting pHw data from each shire into two periods (1973-83 and 1984-94) and comparing means using t-tests. Data for the period 1989-94 was used to estimate the area of soils which were sufficiently acid (pHw < 5.5) or alkaline (pHw > 7.5) to adversely affect the growth of agricultural plants, ie. poor soil quality. This was based on calculating the ratio of the sum of sampled areas belonging to each pHw class in a shire, to the total sampled area in that shire, and extrapolating this ratio to the total area of the shire.

Results and Discussion

Soil pH changes since the land was cleared

Soil pH changes in the 112 sites since the land was cleared and pastures established, ranged from −1.8 to +0.6. Under subclover pastures, mean δpHc was −0.2 with 32% of sites becoming strongly acid (pHc < 4.5). In contrast, mean δpHc was +0.2 for white clover pastures with only 11% of sites becoming strongly acid.

Recent changes at specific sites: acidification

Thirty five of the 54 NSFP sites had acidified (min. $\delta pH_{2.5} = -1.2$) over the last two decades. Acidification occured at various depths throughout the sampled profile (0-1 m depth). This survey shows how rapidly soils acidify especially where all factors known to be associated with acidification are present, ie. N fertilisers, legumes, hay removal, slight to moderate initial soil pH.

Recent changes at specific sites: alkalinization

Soil alkalinization was recorded in 25 NSFP sites (max. $\delta pH_{2.5} = +1.0$) but often occured below the acidified zone. While liming, product imports and spatial separation of the N cycle are suspected to be the main causes of alkalinization in some sites, the rise and fall of alkaline water-tables may be responsible in others (R H Merry, pers. comm.).

Current state-wide trends in soil quality: acidity

It was estimated that in 2.3 million ha of agricultural land, soil quality is poor due to strong acidity. Such areas are mainly in the high rainfall regions of the state. Despite local trends observed in the surveys, it is evident that recent liming practises have ameliorated the acid state of shires on the north-eastern slopes. In contrast, acidification trends in shires of the south-west, point to the need to recognise the presence of acidification and the future need for lime in this region.

Current state-wide trends in soil quality: alkalinity

It was estimated that in 1.6 million ha, soil quality is poor due to high alkalinity. Such areas are mainly in north-western Victoria. Land adversely affected by strong alkalinity can require amelioration of nutrient deficiencies, eg. zinc deficiency in cereal crops.

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Value Adding To Radiometrics For Mapping Soil Properties

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The full value of airborne radiometric or gamma- ray data has not been exploited for mapping soil properties purposes. Research and development undertaken by Environmental Research and Information Consortium Pty Ltd (ERIC) has demonstrated that radiometrics can yield significant information about the land surface relevant to geochemical and structural analysis, soil and surface hydrology mapping. ERIC has developed procedures using TNTmips^{TM} (Map and Image Processing System) to spatially map the similarities and differences (variation) in surface patterns, including lineament mapping.

Airborne radiometric measurements have traditionally been obtained for four energy bands indicative of Total Count, Uranium, Thorium and Potassium. The emissions of gamma radiation from the land surface vary with many factors but essentially depend on the composition of radionuclides within 30 cm of the soil surface. This composition depends on the parent material and the degree of breakdown, loss and/or accession, and therefore generally reflects parent material and weathering. As soils are essentially the product of parent material and weathering the radiometric data provide an opportunity to remotely sense information relevant to soils.

The main benefits in using airborne radiometrics in mapping soils are:

- the mappings relate directly to factors important in soil development;
- mappings are independent of other variables and interpretations;
- classifications define the limits to areas that can be regarded as homogeneous;
- classifications provide indications of similarities in soil characteristics within the mapped area;
- mappings provide a basis for the stratification of field sampling; and
- the technique is highly efficient compared with traditional soil mapping techniques.

The data classification procedure has been used by ERIC to map the soils of the Jemalong/ Wyldes Plains (70 km x 50 km or 350 000 hectares) for NSW Agriculture (Gourlay, 1995) The data were from 400 m spacing airborne radiometrics provided by the Australian Geological Survey Organisation (AGSO) The Plains are a complex mix of soils formed on flood plains, prior streams, and prior lake beds; and including eluvial, aeolian and fluvial materials of different ages. The classified radiometrics provided the spatial and spectral separation of these materials into 22 soil classes (Figure 1) and the basis for field survey design. Soil samples were collected for each class and statistically interpreted for profile thickness, texture, colour, pH, Eh, EC, bulk density and dispersability. Labels were then attached to each class to provide a soils map based on significant differences (mainly for texture, thickness, pH, pe and EC) These field data for each of the 22 soil classes also enabled soil property patterns or processes to be mapped, eg. texture, pH, salinity, pe/ pH, dispersibility, etc, at each of the soil horizons over the whole region; which highlights the value of maintaining independence of data within a GIS. Other maps derived from the radiometric data included surface hydrology, landscape evolution and surface structure (basement fractures or lineaments) information.

The Jemalong/ Wyldes Plains project has clearly demonstrated the efficiency and effectiveness of this approach to soil mapping, at a cost of less than 20 cents per hectare within 50 work days. This cost could increase to a maximum of $2.00 per hectare where the data are not available and has to be specially flown, ie. at 400 metre spacings. These costs and the time taken would compare very favourably against soil mapping techniques used by Commonwealth and State agencies which are taking at least 2- 3 years to map a similar sized area, at considerably less spatial resolution.

The Centre for Land Rehabilitation at The University of Western Australia

D.A. Jasper, Centre for Land Rehabilitation, The University of Western Australia
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A Centre for Land Rehabilitation was established at The University of Western Australia in 1995. The centre is based in the Soil Science and Plant Nutrition Group within the Faculty of Agriculture. With strong links to other research centres at the University, it is a multi-disciplinary centre applying soil science, geomechanics, hydrology, soil biology, plant nutrition, plant biology, ecology and resource economics to the management of disturbed lands.

The Centre for Land Rehabilitation builds on a strong record of research and extension in land rehabilitation at The University of Western Australia. Mine rehabilitation research has included soil development and management, use of wastes from mineral processing, soil microbiology, and ecology and reproductive biology of native plants. This is complemented by extensive research in restoring and maintaining physical, chemical and biological fertility of agricultural soils.

The Centre for Land Rehabilitation has four major objectives :

- To increase understanding of **processes contributing to stable landforms and sustainable ecosystems** in mine rehabilitation
- To contribute to the development of **management strategies to restore and maintain physical, chemical, and biological fertility** in degraded agricultural soils
- To increase understanding of the **plant and soil resources of rangelands** and develop strategies for their sustainable management
- Through application of appropriate science disciplines, contribute to **rehabilitation and management of other disturbed land**s, including urban land and wetlands

The objectives of the centre will be achieved through the major activities of research, education, training and consulting:

- **Research :** Applied and basic research will be conducted to develop cost-effective solutions for rehabilitation of disturbed lands and disposal of wastes
- **Education :** Staff from the Centre will contribute to undergraduate and postgraduate courses and postgraduate research programs in land rehabilitation , for land affected by mining, agriculture, industry and urban development.
- **Training :** The practice of land rehabilitation will be advanced through practically-oriented short courses to managers and operators.
- **Consulting :** Staff from the Centre will be available to advise on management practices for disturbed land and will offer problem evaluation, literature surveys and analytical services that relate to land management objectives.

Enquiries should be directed to the Director, Dr David Jasper at the Centre for Land Rehabilitation, The University of Western Australia, Nedlands, WA, 6907.
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A Framework for Community and Agency Soil Assessment Monitoring
SAM-PLE
Soil Assessment and Monitoring, Paddock LongTerm Evaluation

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Soil quality assessment and monitoring is an issue that has received considerable attention over recent times. At present we have a number of notional frameworks and systems for assessing soils for particular end uses although few involve assessment of a soils ability to provide for a range of end uses. The soil serves many purposes and soil assessment and monitoring systems should be able to reflect an ability to quantify and qualify a soils ability to fulfil a range of purposes such as agriculture and environmental protection.

Land managers and the broader community have expectations of a soil to;

A. provide a medium for plant growth and thus provide agriculture produce and viable rural industries

B. regulate and partition the flow of water through the environment and thus allow streamflow and water for agricultural purposes

C. serve as an environmental filter for the protection of surface and ground waters (Larson and Pierce, 1991).

Understanding how land management affects the functioning of soil to provide the above three expectations is a continuing challenge and balancing a soils ability to provide for the above three expectations is a key to soil quality and minimising degradation of the environment.

Soil quality is little more than a concept unless aspects of soils related to quality can be assessed and monitored in a field situation across a wide variety of land systems and land components. The key is to use indicators that will;

1. indicate the current condition of the land
2. provide knowledge of the management and external forces applied to the land,
3. indicate the likely response of the land to the applied management and external forces.

Point 3 can be tackled in three ways, prediction based on our current knowledge, reassessment of the condition of the land at a number of temporal intervals or a combination of the two. Given our current state of knowledge, a combination of the two is likely to provide the greatest returns and can be divided into the pressure applied to the land and positive management options able to counteract the pressures.

Assessments of the land and activities/forces applied to the land need to measured at some level and due to the spatial differences in both, should be measured at points across the landscape. This has developed another major stumbling block in addition to what do we measure ie who does it and where. Given that society divests the management of large areas of land to many individuals, it should be incumbent on these managers to assess the quality of the land that they manage for more reasons than just agricultural productivity.

Soil Assessment and Monitoring - Paddock LongTerm Evaluation (SAM-PLE) is aimed at providing land managers with simplified soil assessment tests to provide them with a tool to improve decision making with respect to their soils, as well as providing longer term information for land management agencies to assess the effectiveness of current land management practices and the adoption of new land management practices. The package will collect information that relates to the ability of a soil to fulfil the broader expectations of a soil as described above. The package collects past paddock history, utilises visual estimates to describe the physical status of the soil and relies on chemical tests as provided by a commercial laboratory. A brief description of the tests involved is presented in Table 1.

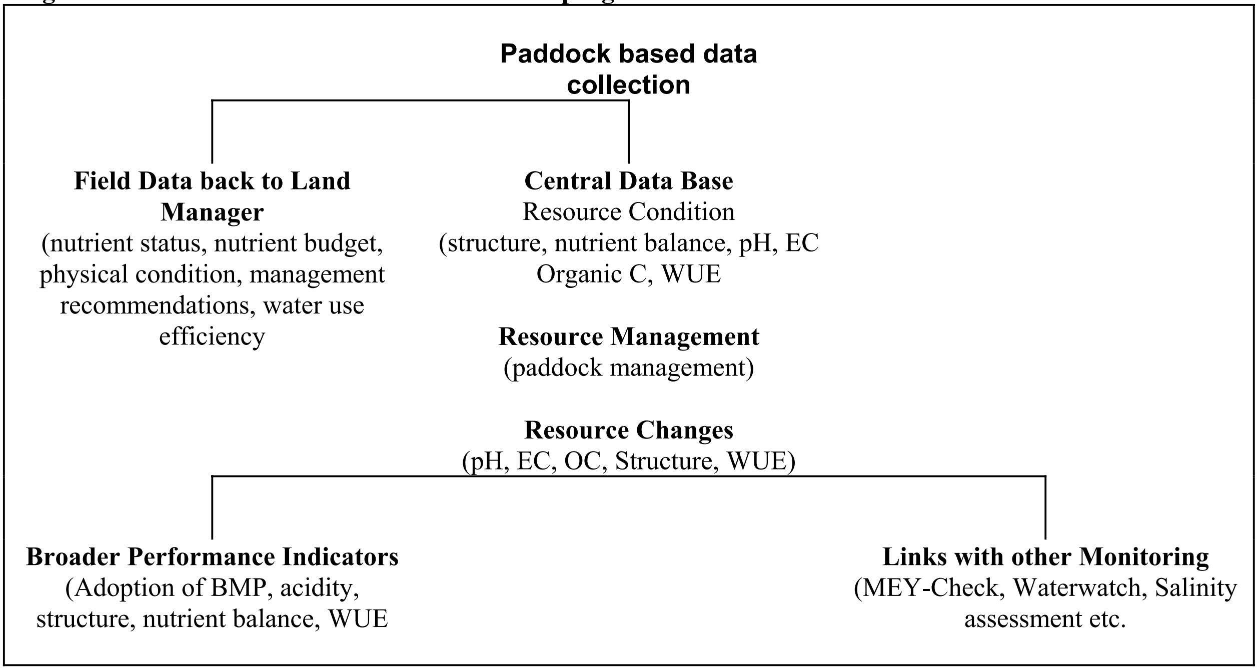
Utilising the package requires land managers to select a representative area within a paddock that will be referenced and monitored over coming years. The various tests or questions within the package are answered either from paddock records or from observations of the soil exposed by excavating a small hole. A sample of soil to 10 cm deep is collected at a range of locations within the paddock and both the soil sample and completed forms are sent to a central location for processing along with the required fee. The land manager will receive rapid field back (a number of weeks) which will include information on soil nutrient status, nutrient budgets, physical condition, past water use efficiencies and management recommendations. It is expected that land managers would reassess a paddock every 3 - 5 years to monitor changes in the resource base.

Table 1. Indicators, attributes, methods and soil expectations covered in SAM-PLE.

Indicator	Attribute	Method	Expectation
Agronomy	Crop/pasture/production	Farm record	A
Soil management	Cultivation/stubble	Farm record	A, B, C
Soil/Plant management	Fert type + quantity	Farm record	A, C
Climate	Rainfall	Farm record	A, B
Topography	Slope class	Visual estimate	B, C
Soil type	Texture/A hor. depth	Field texture, ruler	A, B, C
	Colour	Colour triangle	A, B, C
Soil structure	Crust	Photo comparison	A, B, C
	Porosity	Count	A, B
	Aggregate type	4 class description	A, B
	Aggregate stability	Simplified Emerson	A, B, C
Soil Chemical	pH, EC, N, P, Org. C	Standard Lab tests	A, C
Plant	Root distribution	Visual estimate	A, B
	Water use efficiency	Farm record	A, B

All information will be recorded on a central data for future monitoring for the land manager and the agencies (Fig. 1). All information collected would be strictly confidential but the use of the information for other sources would be a requirement of participating in the programme. This aspect is likely to provide an impediment to the widespread success of the programme although other monitoring programmes such as MEY-Check have succeeded based on a similar framework.

Figure 1. Framework for the SAM-PLE programme.



Spatial differences in the landscape can be dealt with at two levels by the SAM-PLE framework, extensive participation by people in the programme or strategic targeting of areas by agencies and community groups.
SAM-PLE is at the conceptual stage and requires validation of the tests as reliable indicators is still required.

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Cotton Strip Assay and Microbial Parameters of Soil Quality

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Introduction

A Cotton Strip Assay (CSA) has been proposed as an indicator of microbial activity in soil (Walton and Allsopp, 1977) which is one attribute of quality. The CSA is based on the rotting rate of buried cotton cloth. A few studies have attempted to establish relationships between CSA and soil microbial parameters (Smith and Maw, 1988; Williamson, 1994). This study examined the relationship between the CSA and microbial respiration.

Methods

Long-term tillage sites of NSW Agriculture trials at Warialda and Croppa Creek in NSW were used (Felton *et al.* 1995). No tillage (NT) and stubble burned (SB) treatments for wheat were selected. Soil samples were taken to 5 depths (0-25 cm, with 5 cm intervals) at the 2 sites. CO_2 evolution (RespicondIII®, Nordgren Innovations AB, Terrängvägen 3A, S-903 38 Umeå, Sweden) was measured in moistened soil (M/D=0.5) at 20^0C. Cotton strips were buried in soil in half the respiration chambers with the other half containing soil alone (controls). After 9 days, strips were removed and their loss of tensile strength was measured in a tensometer. Cotton rottenness (CR) at 9 days was calculated (Hill *et al.*, 1985) .

Results and Discussion

Microbial respiration of control soils (no strips) was highest in the top 0-5 cm layer and declined markedly with depth ($P<0.001$). NT treatments had higher respiration rates than SB ($P<0.001$) and site differences were significant ($P<0.001$) (authors unpublished). How well does the CSA reflect these differences?

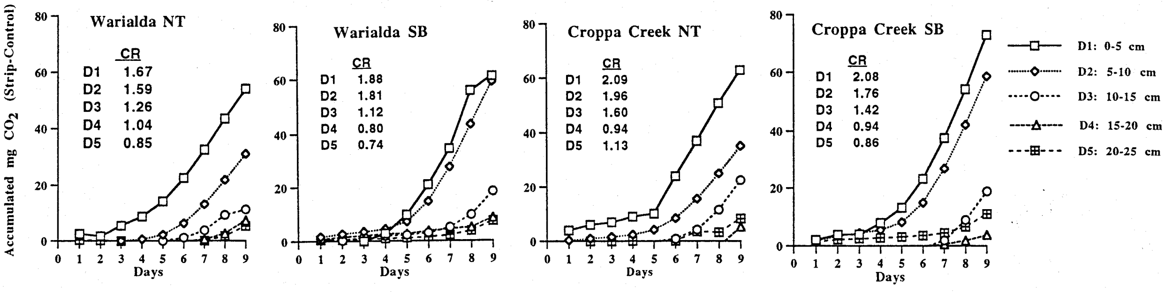

Figure 1. Cumulative respiration (mg CO_2/100 g DM soil) for soil (strips-control) and CR at 5 depths

Additional respiration, due to use of the cotton strips as a carbon substrate by microbes (soil containing strips *minus* control soil), indicates phases of colonisation and growth of microbes (Fig. 1). For all depths, there is a lag period before response in respiration. The lag time represents a period of colonisation of the strips which is shortest in surface soil where there is most microbial activity. After colonisation, a period of growth occurs as reflected by increased respiration, as carbon in the strip is utilised for microbial growth. Data for CR (Fig. 1) detected differences between sites ($P<0.001$), tillage ($P<0.06$) and depth ($P<0.001$) which were in general agreement with findings from levels of microbial respiration in control soils (see above). The linear regression ($P<0.001$) of CR against microbial respiration (strips-control) also showed that the CSA sensitively detected differences in microbial activity.

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Tools and Indicators for Sustainable Land Management : A Partnership Approach

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The Australian Centre for International Agricultural Research (ACIAR) Project No. 9435 is a partnership approach to sustainable development involving organisations in both Andhra Pradesh, India and Queensland, Australia. The Commissioned Organisation is the Queensland Department of Natural Resources (QDNR) and the Collaborating Organisation in India is the Central Research Institute for Dryland Agriculture (CRIDA). It builds upon past soil and water conservation research at ICRISAT and CRIDA and on research, modelling and extension initiatives in QDPI/QDNR.

The aim of this project is to improve long term productivity of rainfed lands in the semi-arid tropics by the improvement of water use efficiency, reduction in runoff and soil erosion, and maintenance of soil organic matter. This will be achieved by working with farmer and community groups in an integrated approach using modified soil management practices in watersheds and experiments, and simulation modelling. The project focuses on five main areas including, *identifying indigenous sustainability indicators, developing and applying action learning activities, conducting soil management experiments, evaluating social and economic impacts, and applying simulation models.*

The project will link the scientific understanding of elements of sustainability with the observations and factors that farmers take into account when making land management decisions. In recent years, there has been an array of conceptual and policy level literature to demonstrate the degree of sustainability of a variety of practices. Information on farmer-based or 'indigenous' indicators of sustainability however, is scarce. One way of influencing a farmer's willingness to change is to make available indicators that show the effect that their management practices are having on soil quality. As a result, this project will **identify sustainability indicators** that farmers use to judge the sustainability of their own management practices. A comparative analysis of indicators used by farmers will be carried out and linked to those used by researchers to identify unsustainable practices. This will aid in the development of improved extension tools to be used with farmer groups.

Participation through **action learning** is a major process of the project. With farmer participation and involvement in project experimentation and processes, more appropriate and acceptable technologies for farmers will be developed through knowledge interchange between researchers and farmers, leading to more purposeful learning and decision making for sustainable farm management.

Soil management will be evaluated using field plots and watershed experiments and the results combined with existing research data to investigate a variety of management options that are both sustainable and economically viable. Simulation models will be used to integrate data and predict responses to management practices using long term climate data.

To better understand the factors that influence farmers' decision making, the project will **evaluate the social and economic impacts** of changing to more sustainable farming systems. This will shed light on the complex interactions between social, cultural, socio-economic and technical factors impacting on adoption behaviour.

The overall output of this project will be a platform of enhanced knowledge for land management decision support leading to management systems that are more productive and more sustainable.

Processes Of Soil Structural Quality Decline Induced By Soil And Irrigation Management In Permanent Raised Soil Beds

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When judging soil quality, emphasis must be placed on those soil attributes which allow high, sustainable yields. High, sustainable yields come only from soils which meet the functional requirements of the plant roots: oxygen, water, nutrients and mechanical environment. Acknowledging these helps to develop a set of physical attributes to judge soil quality in terms of water storage, soil strength, aeration, permeability and temperature. In review, the soil should provide at least 20% storage porosity, have a resistance to a penetrometer less than 0.5 MPa and minimise the distance from a water-filled pore to a continuous air-filled pore. Thus, a loose assemblage of aggregates within the class of 0.35 to 12 mm in diameter allows unimpeded root growth through the inter-aggregate pores, developing an evenly distributed root system with reduced water stress (Tardieu *et al.*, 1992). In our experience this soil quality is not sustained using existing forms of soil and water management. Our aim, therefore, is to develop a management system that sustains soil physical quality in permanent raised soil beds used for deciduous fruit production.

Field and glasshouse experiments were established using water stable aggregates from a permanent pasture. The field study investigated the effects of soil management systems in orchards on the rate of physical fertility decline. The glasshouse study investigated the effects of both irrigation rate and aggregate size distribution. Bulk physical measurements were taken on all studies including soil strength characterisation, water release curve and vertical collapse. At periodic intervals selected samples were collected and view (x10 magnification) to estimate the degree of aggregate deformation and welding.

Despite the use of water stable aggregates to form permanent soil beds, the resultant soil structure was far from ideal in the field. The aggregates progressively welded together to a point where individual aggregates became unrecognisable. The soil strength characteristic changed as did the pore size distribution such that the soil quickly became hard after irrigation. We describe this slow decline in soil structural quality as coalescence (to come together and form one, OED). Coalescence occurred quickest with a straw mulch soil cover and slowest when ryegrass was grown through the dormant period of the trees.

It is suggested that the mechanism of coalescence is the decrease in *mechanical stability* of aggregates or the ability of an aggregate to resist deformation and fragmentation from intrinsic stresses within the soil. The mechanical stability of the aggregates can change due to irrigation rate. The glasshouse study showed that the lower the irrigation rate the slower the coalescence. This is due, firstly, to reduced incipient failure and aggregate mellowing (Quirk and Panabokke, 1962; Utomo and Dexter, 1981) and, secondly, to reduced wetness (Keller *et al.*, 1970). Furthermore, it is hypothesised that the rate of coalescence is dependant on the initial aggregate size distribution. The glasshouse study showed that the fine aggregated bed (15%< 250 μm) showed a slower vertical strain rate than the coarse aggregated bed (70%> 2000 μm). This effect is contrary to our field observations. However, measuring the degree of welding and deformation between aggregates showed the opposite effect relative to vertical strain which indicates that bulk physical measurements may be an inadequate measure of coalescence.

The process of coalescence differs from hardsetting and crusting. We describe coalescence as the slow decline in soil physical fertility in soils that have a high proportion of water stable aggregates. An ideal aggregated bed coalesces losing essential porosity required for low soil strength and rapid water movement equating to a diminishing range of non-limiting water (Letey, 1985). The rate of coalescence is dependant on irrigation rate and aggregate size distribution. Visual and experimental evidence suggests that a coarse aggregate bed (70% > 2000 μm) irrigated slowly with continual ryegrass growth coalesces at the slowest rate.

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Soil Carbon Fractions as a Land Quality Indicator

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Introduction

Maintenance of the soil resource is widely acknowledged as an essential part of a sustainable land management system. However, the identification and measurement of appropriate indicators of land quality is difficult. Soil organic matter is recognised as being involved in many aspects of the chemical, biological and physical fertility of soils. Soil carbon declines rapidly with many agricultural practices, but measurements and modelling of changes in soil carbon suggest that different fractions of soil carbon change at different rates. As such, to use soil carbon as a land quality indicator (LQI) requires measuring soil carbon, but with particular emphasis on the dynamic fractions of soil carbon.

Methods

Paired samples were collected from adjacent areas with different management at sites in Northeast Thailand and NSW, Australia. Samples were collected down the profile to 40 cm from areas of a Paleaquult (Ubon, Thailand) which had been cropped to rice or was under primary forest, and from areas of a Paleustalf (Warialda, NSW) which had been cropped to wheat for 18 years or had never been cultivated and only lightly grazed. In each case, soil from the uncultivated area was used as a reference.

The labile carbon (C_L) of the paired samples was measured by oxidation with 333mM $KMnO_4$ and, along with the total carbon (C_T) and non-labile carbon ($C_{NL} = C_T - C_L$), used to calculate a Carbon Management Index (CMI) (Blair *et al.*, 1995). $CMI = LI \times CPI \times 100$, where LI (Lability Index) = $L_{Sample} / L_{Reference}$, L (Lability) = C_L / C_{NL} and CPI (Carbon Pool Index) = $C_{T\,Sample} / C_{T\,Reference}$. For the Paleustalf, the mean weight diameter (MWD) of soil aggregates was calculated after wet sieving and hydraulic conductivity (K) was measured by disc permeametry at 10mm tension (Whitbread, unpubl.).

Results and Discussion

Samples collected down to 40cm from the Paleaquult in Thailand indicate the large decline in total carbon, and larger decline in labile carbon, down the profile. The carbon in the top 20cm is massively decreased by an extended period of cropping (Table 1). These changes are reflected in low CMI values. The high CMI in the 20-40cm layer of the cultivated soil results from an increase in C_T and C_L relative to the forest soil, indicating movement of C down the profile. In more extensively cropped soils in this region, the lability of carbon (L) has been shown to stay constant, or even increase, down the profile, indicating even greater movement of labile C. These changes in soil carbon and CMI after periods of cropping are associated with reduced fertility and low rice yields.

Table 1. Soil carbon fractions of an Paleaquult from Ubon, Thailand.

	Depth (cm)	C_T (mg/g)	C_L (mg/g)	L	CMI
Forest	0-10	23.02	4.55	0.25	100
	10-20	6.88	1.45	0.27	100
	20-40	1.46	0.16	0.13	100
Cultivated	0-10	6.76	1.37	0.25	30
	10-20	3.81	0.44	0.13	27
	20-40	1.73	0.22	0.15	136

The sample from the cropped and grazed areas of the Paleustalf from Warialda (Table 2) show that the physical fertility of the soil is reduced by cropping, as indicated by lower mean aggregate size and reduced hydraulic conductivity. These changes are associated with a decline in the CMI as a result of changes in C_T and, more particularly, C_L. Measurement of C_T and C_L in the different aggregate size classes shows the importance of carbon, particularly labile carbon, in the formation of stable aggregates.

Table 2. Soil carbon fractions, aggregate size and hydraulic conductivity of an Paleustalf from Warialda, NSW.

	C_T (mg/g)	C_L (mg/g)	L	CMI	MWD (μm)	K (m x 10^{-5} s^{-1})
Uncultivated	25.22	5.31	0.27	100	621	7.09
Cultivated	6.68	1.14	0.21	21	393	1.82

Soil carbon, and particularly the labile carbon fraction, is important for soil fertility. The CMI is a broad indicator of soil quality, which has been correlated with changes in soil fertility as well as with long term productivity. The CMI has potential as an LQI.

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The Recognition of Soil Quality by Wheatbelt Farmers, and Their Responses to Land Degradation Problems

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Interest in soil quality has been aligned to the weather:
people talk about it, few understand it and hardly anyone does anything about it (Herberen 1992)

There are five principal reasons for examining soil quality and farmers understanding of what is soil quality and how to measure it. Firstly, recent government reports (Hamblin 1992, SCARM 1993) have identified various soil indicators for monitoring soil sustainability at the farm level, but at this stage there has been no rigorous experimentation to test their validity in Australian agroecosystems. Secondly, farmers need indicators of soil quality which they can easily and reliably use to monitor their soil sustainability. Farmers are also unlikely to adopt the soil sustainability indicators derived by scientists, if they require too much technical expertise, are expensive and timely to conduct and the results are difficult to interpret (Baker and Dalby 1994). Thirdly, farmers have been slow to adopt sustainable management practices because they can not see the benefits of the new techniques and perceive a higher risk and uncertainty with them (Vanclay 1992). Fourthly, there is a strong desire by farmers to monitor their farm goals and determine if changes in farm management are leading towards a more sustainable farming system. A simple monitoring tool which illustrates trends in soil quality may act as a persuader to change or affirm management practices. Lastly, awareness of land degradation is an important first step down the road of recovery, but if that recognition comes too late or not all the end result is costly and in some cases irretrievable. Therefore it is important to assess the accuracy of farmers' perceptions on soil quality as well as the impact of landcare and farmer groups, on their perceptions.

The importance of maintaining a healthy soil can be measured by the huge losses accrued in agricultural production. In 1983 conservative estimates put the loss in agricultural production as a result of land degradation at $600 million a year (Woods 1983). Some of the more visible forms of land degradation, such as salinity, are seen as having a great impact on production, but for every dollar lost as a result of salinity, water and wind erosion cost $5, soil acidification $25, soil structure decline $125, and soil nutrient degradation $625 (Institute of Foresters of Australia 1989). Hence the ability of farmers to be aware of the early warning signals of land degradation is paramount. This poster will examine farmers' awareness of soil problems and other issues along an environmental transect from Northam to Merredin in Western Australia. This unpublished survey by Lobry de Bruyn and MacKenzie in the Western Australian wheatbelt found that there was a high level of ignorance concerning the soil resource. For instance it has been long since recognised that organic matter is of considerable importance in maintaining soil structure, nutrient levels, moisture content and soil biota activity, but 33 of the 41 farmers interviewed had no idea of their soils' organic matter content and only 4 of the remaining 8 farmers gave a figure that was close to the actual value. Soil acidification is considered to be a serious soil problem, yet nearly half of the farmers interviewed did not know at what pH level acidity becomes a problem and did not know if their pH was changing (having had their soils only tested once). For successful monitoring of soil quality, and especially to observe trends, farmers will need to be committed to regular check ups and not just take once-off measurements.

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Soil quality and fertility of Victoria's agricultural soils.

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Introduction

Phosphorus and potassium availability directly influence the productivity of Victoria's agricultural soils. An extensive soils chemical data set has been used to investigate the temporal and spatial changes in the K and P status of pasture, horticultural and cropping surface soils. The study reported here is intended to provide land managers with improved soil nutrient information.

Methodology

Between 1973 and 1994 inclusive, the State Chemistry Laboratory analysed approximately 80,000 soil samples submitted by farmers from across Victoria. Chemical characterisation of each sample was assessed using bicarbonate P (Olsen) and 0.1M HCl extractable K soil tests. The results and location nearest to the sampled site were recorded and digitally archived.

To illustrate fertility trends, maps based on means of test results within shires were developed using a PC based Geographic Information System (Arcview 2.1 © ESRI). Changes over time for each shire were identified by splitting the data set into two halves (ie. 1973-1983, 1984-1994) and then using t-tests (GENSTAT v5.3.1) to identify significant differences ($P<0.05$) in means between time periods.

Results and Discussion

Potassium

Mean available K was lower in the south west and in the majority of the eastern half of Victoria (Fig. 1A). The proportion of samples received from across the state with a deficient concentration (< 80 mg kg^{-1}) of available K has steadily decreased from 24% in 1973 to 6% in 1994. Many shires show significant increases in K between decades (Fig. 1B). This result is probably due to the increased use of potash in dairying and horticultural areas, but the change is difficult to explain in Mallee shires. The relatively low sample numbers in the north west may have yielded unreliable means.

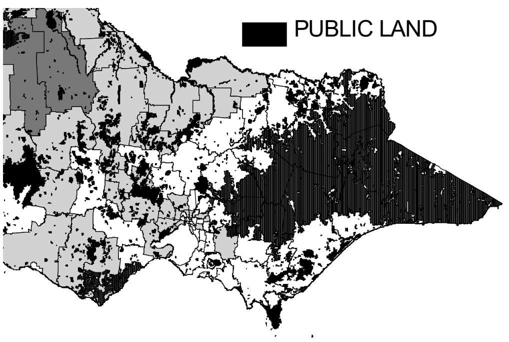

Fig. 1A. Mean Skene K (mg kg^{-1}) of samples found within each Victorian shire (1973-1994)

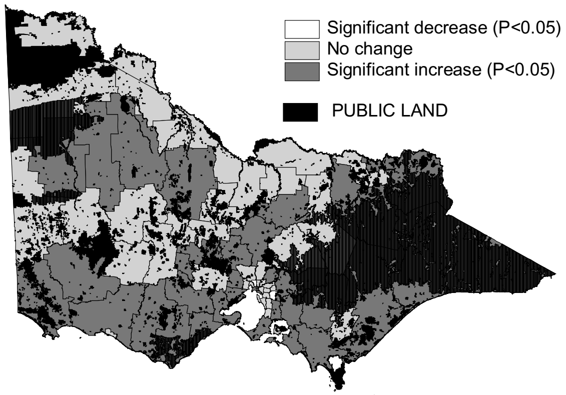

Fig. 1B. Significant change in mean Skene K

Phosphorus

Mean available P was highest in shires supporting dairying and horticulture (Fig. 2A). Some of these shires have also shown significant increases in P (Fig. 2B). The incidence of P deficiency (< 8 mg kg^{-1}) is higher than that of K. The proportion of deficient soils for the state as a whole, gradually increased from 33% to 40% from 1976 to 1986, then decreased to 31% in 1994.

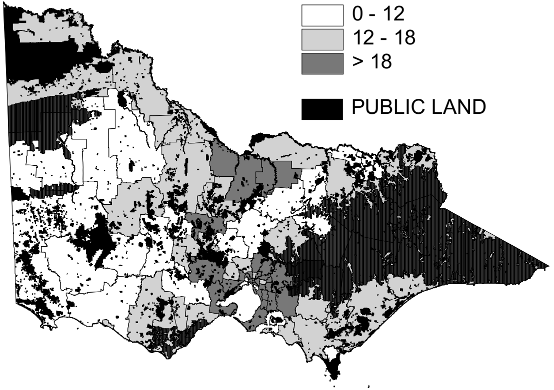

Fig. 2A. Mean Olsen P (mg kg^{-1}) of samples found within each Victorian shire (1973-1994)

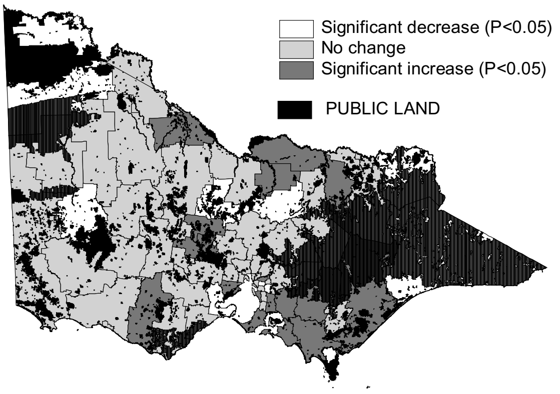

Fig. 2B. Significant change in mean Olsen P

Long-Term High Superphosphate Rates Cause Little Change In Standard Determinants Of Soil Quality

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A soil nutrient audit was conducted on a long-term grazing trial to determine the effects of sustained high application rates of superphosphate. The grazing trial, sited on a duplex basalt-derived soil, was sown to perennial ryegrass, subterranean clover and phalaris in 1977 (Cayley and Hannah, 1995). Experimental treatments commenced in 1978, and consisted of 6 rates of superphosphate ranging between 1 and 33 kg P/ha/year, and 3 stocking rates representing low, medium and high stocking pressures. Soils were sampled to 80 cm in December 1994, and analysed for total P, total S, and pH (in both water and $CaCl_2$). Topsoil samples to 10 cm were analysed for available P (Colwell 1963), available S, bulk density, organic carbon, electrical conductivity and exchangeable K, Al, Ca, Mg, Mn and Na.

Superphosphate application over the 17 years significantly increased total P concentration in the 0-5 cm and 5-10 cm layers, but had no significant effect at lower depths in the profile. Total S was significantly affected only in the 0-5 cm layer. Most of the applied P was still in the soil profile, whereas most of the S had been removed from the profile, presumably by leaching. There was no significant effect of fertiliser application rate on pH at any of the depths sampled.

Available P and S in the topsoil were both strongly responsive to superphosphate application. Values of available P in the top 10 cm ranged from 6.1 mg/kg at the low P application rate to 129.4 mg/kg at the high rate. Corresponding values of available S ranged from 12.6 to 18.6 mg/kg. Other topsoil analyses showed no significant effect of fertiliser rate on bulk density, organic carbon, electrical conductivity, nor extractable K, Mg, Mn, and Na. Exchangeable Ca concentration increased significantly, by 38% in the 0-5 cm layer and by 18% at 5-10 cm. Higher fertiliser rates were associated with a significantly increased exchangeable Al concentration in the 5-10 cm layer, but there was a slight and non-significant decrease in concentration in the 0-5 cm layer. The Ca may have displaced Al to lower in the topsoil.

Earthworms were sampled from the site in September 1992, and no significant relationship was found between earthworm numbers and fertility (Baker *et al.* 1993).

Above-ground measurements of pasture and animal production have shown that herbage production is increased 3-fold by the higher fertility, and the optimum stocking rate increased 4-fold, leading to a more profitable wool-producing enterprise (Cayley and Saul 1993).

On the basis of this evidence it appears that the basalt-derived soils which cover large areas of Western Victoria can tolerate high rates of fertiliser application without detrimental effect. Further work is planned to more accurately quantify the rate at which P and S are removed from the profile, and to test the effect of fertiliser application on the pH buffering power of the soil. Collaborative work testing other aspects of soil quality would be welcomed.

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Stubble Management Practices Modify The Soil Strength Of Cropping Soils In NE Victoria.

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Introduction

Conservation cropping techniques based on retention of crop stubbles, minimum tillage at sowing and herbicide control of weeds have been an option for the grains industry in SE Australia since the late 70's. These principles were developed to overcome the widespread occurrence of crop yellowing, poor growth and yields induced by degraded cropping soils. This degradation was largely a result of past cultivation and burning practices, which caused a higher fraction of fine dust particles, often greater bulk density, propensity towards surface waterlogging, low organic matter content, hard setting characteristics on drying, slaking on wetting and restricted root growth. Consequently, poor crop growth, excessive rainfall runoff, lowered water use efficiency and low yield occurred on these degraded soils.

Previous work by researchers at the Institute for Integrated Agricultural Development (IIAD), Rutherglen, has shown that stubble retention improved many soil attributes compared to conventional stubble management. These benefits included increased biological activity, sorptivity, nitrogen status (after one year) and larger, more stable aggregates. The improvement in physical structure of the soil lead to improved water conservation and increased water use efficiency, which resulted in higher cereal yields.

Changes in soil structure can be examined by measurement of the resistance to a mechanical probe. Soil resistance to a penetrometer is one of the best means currently available for estimating root resistance in soils (Campbell and O'Sullivan, 1991). Root growth is severely restricted by soil resistances of the order of 1 MPa (A Ellington, pers. com.). However, there have been optimal ranges of soil resistance found for some crop species (Glyn Bengough, 1991).We used a penetrometer to measure soil resistance and provide a quantitative means of assessing the long term differences in soil conditions as affected by stubble management in NE Victoria.

Methods

In 1985, four sites were established in NE Victoria on soils associated with changes in the topo-sequence. Included were granitic sands overlying weathered bedrock in the upper sequence, mid slope gradational soils, and low lying duplex soils. Stubble management at the sites consisted of four treatments, stubble; (a) retained standing, (b) shredded, (c) burnt and (d) incorporated into the soil with a cultivator.

Soil resistance was measured using the "Bush" cone penetrometer (12.9 mm diameter cone), which measured up to 15 depths at intervals ranging from 1 cm to 3.5 cm (total depths of 15 cm and 52.5 cm, respectively). For statistical analyses, measurements were taken between wheel tracks for consistency. However, additional transects were taken across wheel tracks to ascertain the influence of agricultural machinery. At some sites, 7.3 cm diameter soil cores were taken and divided into 2 cm increments for (a) matric potential (filter paper method) (b) gravimetric water content and (c) bulk density.

Results and Discussion

Standing stubble significantly reduced soil resistance compared to the burnt treatment (up to 20 %). This was a consistent result in the top 15 cm of the profile at a range of sites and moisture contents (5 to 35 %). Part of the difference could be accounted for by increased moisture content. However, at similar moisture contents, resistance was often less under standing stubble. On the lighter high and upper slope soils, incorporation of stubble reduced resistances to approximately 0.02 MPa depending on the depth of tillage. Generally, retaining stubble on the lighter soils resulted in a reduction in resistance which would favour root growth. However, on the duplex soils, differences were less frequent. Shredded stubble often showed greater resistance than burnt on these soils, largely as a result of lower moisture content. There appears to be an influence of the shredded matter on rainfall runoff and moisture distribution within the profile. Measurements across a range of soil types have clearly demonstrated that retaining stubble can modify the physical structure of the soil in a manner which is measurable and conducive to improved root growth.

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Soil Quality and the Natural Resource Conservation Service.

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The Natural Resource Conservation Service (formerly SoilConservation Service) of the U.S. Department of Agriculture is establishing a Soil Quality Institute to develop and disseminate information and technology on soil quality for ecosystem-based soil resource management. The institute will consist of a small staff that will be located with partnering research agencies and institutes. The functions of the institute are to acquire and apply scientific principles for assessing, monitoring, enhancing, and restoring soil quality; develop, test and disseminate tools for applying soil quality concepts in agency programs; develop training materials and train field staff; build partnerships with research groups and application agencies; and enhance awareness among land users and others on the importance of a quality soil resource.

The Potential For Land Rehabilitation Using Chemical-Adsorbing Magnetic Particles

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The development of chemical-adsorbing magnetic particles capable of being used both in the assessment and in the rehabilitation of contaminated land is described. An emphasis is placed on the development of low-cost recyclable technology using readily available materials. This is a with a view to devising appropriate methods for the treatment of large tracts of contaminated land, especially in developing countries.

The particles thus developed demonstrate a high affinity for organics including aliphatic and aromatic hydrocarbons, and representatives of organochlorins. Initial investigations on the ability of these particles to reduce levels of pesticides such as dieldrin and DDT in soil are promising. The technology may also be useful in probing soil quality with respect to organic contaminants.

Management of Goldmine Tailings Using Revegetation Techniques

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Today's goldmine operators in Western Australia use highly efficient carbon-in-pulp processes to recover gold from 'live' ore and retreated 'tailings' materials. Highly saline water is used in processing. Characteristics of the processed materials that make conditions adverse to plant growth include:

- high concentration of heavy metals and salts
- extremes of pH
- lack of essential plant nutrients
- lack of micro- biological organisms
- textural and structural characteristics which limit aeration and infiltration
- high levels of reflected light (light coloured tailings) causing physiological stress to vegetation
- physical damage by sand blasting

The potential for vegetative rehabilitation of tailings structures is being explored. Over saline tailings surfaces at a Western Australian gold mine (Westonia, [31_18'S, 118_42'E]), revegetation by seeding of chenopods gave an overall density of 31,100 plants per hectare and revegetation cover of 22 percent, 26 months after seed broadcasting (Fig. i). Considering the low seeding rate(s) applied, extremely high salinity and low nutrient composition of the tailings material, and the limited variety of seeded species, the revegetation over the sampled areas must be considered successful. Underlying salinity affected establishment numbers, as did the surface on which seed was sown, *i.e.* slope or upper surface, and (or) seeding rate. Elevated salinities accounted for an absence of vegetation. *Atriplex lentiformis* (quail bush), *A. undulata* (wavy leaf saltbush), and *Maireana brevifolia* (small leaf bluebush) were the dominant species sampled over the tailings in 1995. All three species have shown the ability to establish successfully on saline tailings material, and continue to fruit prolifically. All are original seed mixture species. However, an increase in the number of volunteer species sampled over the tailings facility suggests the tailings material is becoming more accommodating to plant re-colonisation. Surface salinity of **vegetated** areas has progressively decreased from April '94 to September '95, *i.e.* from 63.5 dS m^{-1} to 10.7 dS m^{-1}, (83 percent salinity decrease) (Figure I).

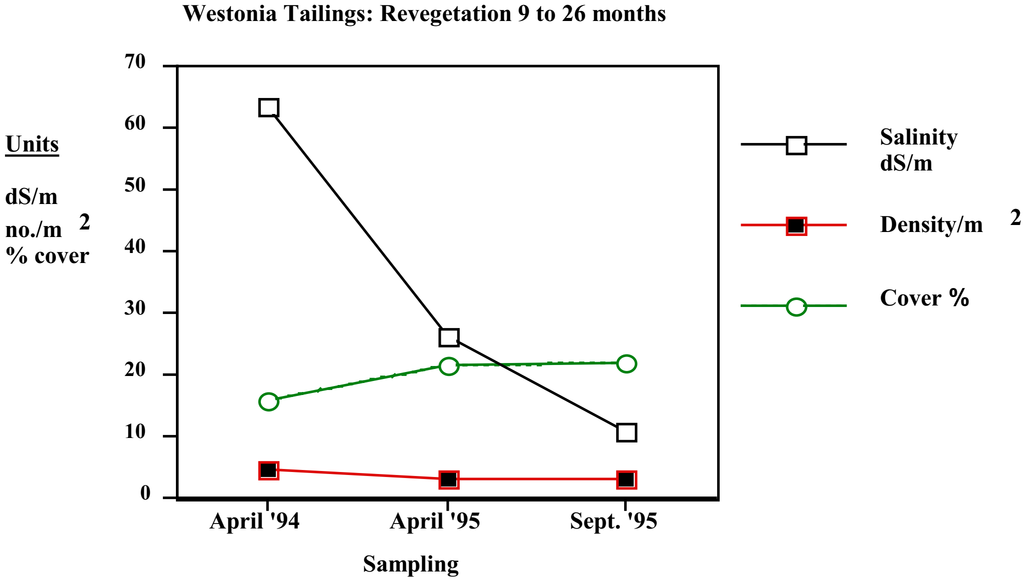

Figure I : Mean salinity values, plant densities and revegetation cover from vegetated assessment transects: over time (26 month old revegetation in September '95.)

Fatty Acid Methyl Ester (FAME) Profiles As Indicators Of Management-Induced Changes In Microbial Community Structure In Cropping Soils In Southern Australia.

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Currently there is considerable effort being made world-wide to assess what soil properties (physical, chemical and biological) have potential as indicators of soil health / quality. The requirement is for simple, robust and easy to interpret measures that can be applied to all soils. A number of soil chemical (eg. pH, cation exchange capacity, organic matter) and soil physical properties (eg. soil texture, bulk density, water holding capacity) appear to be meet this requirement, but indicators that describe the biological health (or "soil biology") of soils are not readily available. Several biological properties have been proposed including microbial biomass, CO_2-C respiration, abundance of functional groups of soil microorganisms and invertebrates and soil enzyme activity (see Pankhurst *et al.* 1995 for a recent evaluation). The major problem with these measurements is that they are (i) time consuming and therefore expensive, (ii) difficult to both interpret and explain to land managers, and (iii) relatively unstable because they are affected by short term fluctuations in environmental conditions.

GC-FAME analysis of organisms and soils

Recent technological developments may provide a solution to this problem. Extraction of lipids from microorganisms, their conversion via alkaline methanolysis to fatty acid methyl esters (FAMEs) and their chromatography, has been developed by Microbial ID, Inc., (MIDI), Newark, DE, USA, as a rapid and highly successful method to identify bacteria. Bacterial isolates are identified by comparing their FAME profiles with those contained in a MIDI data base of more than 8000 bacterial profiles. Limited data bases are also available for fungi and actinomycetes.

More recently the FAME technology has been applied to the analysis of environmental samples, including soils. Here the extracted FAMEs come from the whole community of soil organisms present in the sample and thus provide a "snap-shot" profile of the composition of that community. The soil FAME profiles are very complex but can be analysed using principal component and dendrogram analysis. Individual fatty acids within the profiles can also be identified ("signature fatty acids") which may allow for the detection of specific organisms or functional groups of organisms within the community. Using this methodology, we have shown that soils with different cropping histories and tillage practices can be distinguished by their FAME profiles. We have also demonstrated that this capacity to differentiate soils using GC-FAME is robust, ie. it is not subject to minor variations associated with sudden fluctuations in the populations of organisms in response to changing environmental conditions, and measurements can be made on air-dried soil. We have also demonstrated a positive correlation between total 'peak area' of soil FAME profiles and the soil microbial biomass.

We conclude that GC-FAME has potential as a management tool (and bio-indicator) for assessing and monitoring the effects of farming practices on the soil microbiota.

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Best Practices To Manage Acidifying Soils Under Pastures In Victoria

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Introduction

Soil acidification affects the productivity of approximately 35 million hectares of agricultural land in Australia (Anon. 1995). In Victoria three million hectares are strongly acidic ($pH_{CaCl2} < 4.8$) and a further 5.6 million hectares (pH 4.9-5.5) are threatened by soil acidification. In north-eastern Victoria the average pH of soils used for grazing enterprises is already 4.0-4.2. On such soils marked declines in pH have not been measured (Crawford *et al.* 1994, Ridley *et al.* 1990a) and this is believed to be because soils are strongly buffered due to increasing dissolution of aluminium at low pH (Bache 1988, Helyar *et al.* 1988). In addition soils used for grazing have relatively high contents of organic carbon which will also help to buffer against pH decline. Many landholders and scientists have interpreted the lack of measured pH decline to mean that acid addition has not occurred. However, the reliance of our agricultural system on legume based pastures, inefficient use of water and nitrogen by annual pasture species, produce removal associated with agriculture and accumulation of organic matter in soil indicates otherwise. Recent research indicates that acid addition to soils under annual grass pastures is likely to be in the order of 3 kmol H^+/ha/year. When a deep rooted perennial grass is included in the pasture, acid addition may be reduced by about 1 kmol H^+/ha/year (Ridley 1995).

Discussion

Landholders have traditionally managed declining soil acidity by adopting techniques, such as sowing of acid tolerant pasture species and use of super lime and Mo at sowing, which minimise the investment in lime. As a result of a lack of awareness that acidification has occurred, living with strongly acid soils, and also inconsistent extension messages, amendment of acid soil is often not perceived to be of high priority. Land degradation is insidious, and slow declines in productivity may not be attributed to soil acidification. Increasing problems of phalaris persistence, attributed to aluminium toxicity indicate that soil acidification is affecting production on soils used for grazing (Ridley 1995). At present only light textured soils with low pH buffering capacities are markedly affected. In future, more soils will be affected and increased subsoil acidification will occur. Increasing awareness of the problem is needed so that landholders can make decisions on how to manage soil acidification before subsoil acidification precludes choices of management solutions.

In deciding how to manage soil acidification, landholders need to give careful consideration in balancing short-term profitability with the long term degradation of the soil resource. The best practices to manage soil acidification will involve:

(1) Making a decision as to how far the soil should be allowed to acidify. As the soil acidifies, increasing availability of aluminium reduces the number of plant species which can be grown, and thus reduces the number of potential farming enterprises.
(2) Use of lime to balance alkalinity lost when plant and animal products are removed , and to balance acidity generated through nitrification and subsequent nitrate leaching;
(3) Sowing perennial grass based pastures which can make increased use of soil water and nitrogen compared with annual species, where this is profitable and practical;
(4) Altered grazing management where this is compatible with management and profitability;
(5) Use of acid tolerant species to maintain production and profitability in the short term, while addressing the management of soil acidfication by the other management options available.

The consequences of letting acidification continue are complex. There are both private and public good considerations involved and innovative thinking is required by government policy makers. .Management to reduce acid inputs to soils will only be undertaken by a minority of farmers who are highly motivated, have a long term custodial view of land management, can run a profitable farming enterprise and have a high management ability.

Inhibitory Effects Of Brassica Root Exudates On Rhizobia

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Root exudates from four *Brassica* species, were tested for their inhibitory effects on three strains of rhizobia in the laboratory using plate sensitivity methods. Rhizobia growth was inhibited by the root extracts from three of the *Brassica* species whilst one of the species did not effect rhizobia growth.

Introduction

Increased cereal crop yields following Brassica crops have been attributed to the antimicrobial effects of chemicals released by brassica plants (Kirkegaard *et al* 1994). These chemicals, identified as isothiocyanates, are the result of the breakdown of glucosinolates. They are capable of controlling plant fungal pathogens including Rhizoctonia and *Gaeumannomyces graminis*, the organism that causes take-all, the most serious wheat disease in Australia (Angus *et al* 1994). Because of these properties, brassicas are often used as break crops and possibly have a role as substitutes for synthetic organic pesticides. However, little is known about the effects of these chemicals on other, possibly beneficial soil biota such as rhizobia. Rhizobia form a symbiotic relationship with legumes enabling the conversion of atmospheric nitrogen to an organic form. This is the major source of soil nitrogen in Australia agriculture. It is therefore important to monitor the effects of these chemicals, released by brassica crops, on rhizobia.

Methods and Materials

Juice from approximately 1 kg of root material from mature crops of *Brassica campestris* subsp. *rapifera* cv Barkant, *Brassica campestris* subsp. *oleifera*, cv Pasja, *Brassica napus* .var *napobrassica* cv Highlander (swede) and *Brassica napus* var *napus* cv Rangi was extracted and sterile filtered. Sterile antibiotic disks were saturated with the exudate before being placed onto a lawn culture of three rhizobia strains (commercial inoculant TA1 and two field isolates). Plates were grown at 25°C and zones of inhibition measured after 48 hours.

Results

All three rhizobia strains displayed similar inhibition patterns to the different brassica root exudates (Table 1). Zones of inhibition occurred with the Rangi rape and Pasja, whilst no inhibition occurred with the Barkant turnip. Some inhibition occurred with the swede but, although a definite zone was formed, some very small bacterial colonies grew up to the disk with all three rhizobia strains.

Table 1 Inhibition of rhizobia by root extracts from different *Brassica* species (Results for duplicates shown)

	Zone size (mm) Rep1/Rep2		
Exudate	Rhizobia strain A*	Rhizobia strain B*	TA1
Brassica campestris subsp. *rapifera* cv Barkant	0/0	0/0	0/0
Brassica campestris subsp. *oleifera*, cv Pasja	0/0.5	1/2.5	3/0
Brassica napus.var *napobrassica* cv Highlander	4/4	5/5	4.5/5
Brassica napus L. var *napus* cv Rangi	3/3	4.5/5	4/5
Sterile distilled water	0/0	0/0	0/0
Streptomycin (10 ug)	5/6	**	**
Neomycin (10 ug)	**	12/11	10/14

* Different rhizobia field isolates ** Not tested

Discussion

Clearly the chemicals in the extracts from the roots of some *Brassica* species have an inhibitory effect on rhizobia growth. Swede root extracts were only slightly inhibitory to rhizobia growth , whilst the Barkant turnip extracts appeared to have no suppressive effects. The similar effects from Pasja and Rangi rape were not surprising as Pasja, a turnip/rape hybrid, is closely related to rape.

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Incidence And Possible Influence Of Soil-Borne Fungal Pathogens In Vineyard Nurseries.

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The viticulture industry has often assumed that problems in vine establishment in vineyard nurseries are predominantly due to physical factors and that soil-borne fungi are rarely involved. In order to investigate this hypothesis, we investigated the incidence of potential soil-borne fungal pathogens at 4 vineyard nurseries (8 sites) in South Australia in May / June 1995 and tested the pathogenecity of these isolates in greenhouse tests. Many vineyard nurseries submerge dormant vines in hot water to eradicate nematodes, prior to them being sold to commercial vineyards. Further studies evaluated the ability of this hot water treatment to eradicate *Rhizoctonia* from dormant rootlings and thereby prevent the transfer of *Rhizoctonia* from nurseries to commercial vineyards.

Fusarium (*F.solani, F.oxysporum and F.moniliforme*), *Rhizoctonia, Pythium* spp., *Phoma* spp. and *Cylindrocladium* were isolated from inside vine roots in 100%, 88%, 63%, 38% and 88% of vineyard sites, respectively. *Phytophthora* spp. was not isolated from inside vine roots, but was isolated from rhizosphere soil in two out of four nurseries.

In greenhouse tests, using Chardonnay vines on their own roots, one isolate of *Pythium irregulare* reduced shoot growth by 72%. Two isolates of *Phytophthora*, taken from different nurseries, significantly reduced shoot growth by up to 92%. Two isolates of *Rhizoctonia* [taken from cereal rye-corn (used by nurseries to increase the organic matter status of the soil)] significantly reduced shoot growth by 20% and 32%, respectively and one isolate of *Cylindrocladium* significantly reduced shoot growth by 24%.

Using Chardonnay vines on Ramsey rootstocks, *Pythium irregulare* reduced shoot growth by 66%, while one (out of 2) *Rhizoctonia* isolates taken from cereal rye corn significantly reduced shoot growth by 18%. Two isolates of *Fusarium* significantly reduced shoot growth by 18% and 20%, respectively (but did not significantly influence shoot growth of Chardonnay vines on their own roots). *Cylindrocladium* did not significantly influence shoot growth of Chardonnay vines on Ramsey rootstocks.

Two batches of dormant vines (n=10), naturally infected with *Rhizoctonia*, were placed in water at 52 C for 5 min and immediately immersed in cold water. *Rhizoctonia* could not be detected in treated vines and was isolated from 75% of untreated vines.

These studies suggest that a wide range of soil-borne fungal pathogens are present in vineyard nurseries and that they have the potential to influence vine growth and establishment. The influence of these fungi on Chardonnay shoot growth was dependant, in part, upon whether vines were grown on their own roots or Ramsey rootstocks. Should these fungal pathogens be shown to influence grape yields, this study suggests that the viticulture industry needs to develop best-practice mechanisms for identifying, controlling and preventing the transfer of soil-borne fungal pathogens from nurseries to vineyards.

Ability Of Earthworms To Increase The Foliar Concentration Of Elements, Reduce The Disease Severity Of Soil-Borne Fungal Pathogens And Increase Wheat Grain Yield In The Field.

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In field trials conducted during 1994/95, the earthworm *A.trapezoides*, at an equivalent density of 100 or 300 m^{-2}, significantly increased wheat grain yields in a red-brown earth soil by 56 and 82%, respectively.
Greenhouse and field experiments were conducted in order to try to explain this yield increase.

In greenhouse and field trials, *A.trapezoides* at an equivalent density of 300 m^{-2}, reduced the disease severity of both *Rhizoctonia solani* (causative agent of bare patch) and *Gaeumannomyces graminis* var. *tritici* (causative agent of take-all). Pot trials showed that the ability of *A.trapezoides* to increase wheat shoot weight and reduce take-all disease was dependant upon the soil matric potential.

Further pot trials demonstrated that in soil inoculated with *R.solani,* the earthworm *A.trapezoides* caused a further reduction (rather than an increase) in wheat shoot weight, when a mixture of cereal / pea straw was placed on the soil surface. We suggest that *R.solani* may have colonised the cereal / pea straw (which was incorporated into the soil by *A.trapezoides*). This, in turn, may have increased the *R.solani* inoculum in the soil, increasing disease and resulting in the observed reduction in wheat shoot weight.

In pot trials, the earthworm *A.trapezoides* at an equivalent density of 314 m^{-2}, significantly increased the foliar concentration of Al, Ca, Fe, K , Mn, N and Na in wheat in a sandy loam soil, but did not influence the foliar concentration of B, Cu, Mo, Mg, P, S or Zn. In a red-brown earth soil, *A.trapezoides* at an equivalent density of 314 m^{-2} also increased the amount of plant available NH4-N and phosphorous by 174% and 59%, respectively. In the same soil, *A.trapezoides* at an equivalent density of 314 m^{-2}, did not significantly influence either microbial biomass or microbial respiration after 29 or 63 days incubation.

These results suggest that the earthworm *A.trapezoides* can influence wheat grain yield in the field and that this process may, in part, be mediated by a reduction in *Rhizoctonia* and take-all and by increased nutrient uptake.

Resource Monitoring Kit For Use On-Farm

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As part of a project currently monitoring dairy farm sustainability a set of resource base tests, including soil quality measures have been developed.

The test system is housed in a modified caravan to allow transport to the test site. A number of measures are possible and include; Soil Respiration, Organic Matter, Ec, pH, Available nutrients, calico test strip, earthworm numbers and infiltration rate.

A range of tests for water and plant material are also presented.

Many of the tests are portable and can be used by operators with a minimum of training.

Interpretation data sheets are being prepared to assist land managers in their decision making.

One aim is to use the system to track changes in soil, water and plant nutrients using a control chart approach.

The poster describes the system and discusses the developments to date.

Key words : soil health, sustainability indicators-soil,
on-farm testing, soil analysis, monitoring, participatory research.

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Iron Deposition In The Development Of Waterlogging

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Traditionally, revegetation has been used to manage the problems of waterlogging and salinity. However, in certain areas on the Dundas Tableland, Victoria, this strategy has proven ineffective. It has been proposed that oxidisation of iron in rising groundwater is causing the formation of impermeable layers in the discharge areas (Gardner and Hindhaugh 1994). This causes the discharge areas to continue up the slope causing "iron ochre scalds" to form with subsequent tree death.

The mechanism for the development of impermeable layers is proposed as:

1. Development of a sodic soil by rising saline ground waters and winter rainfall (with fresh water) waterlogging and flushing.
2. Clay dispersion and temporary blockage of soil pores.
3. Development of ferrihydrite gels which transform to more stable minerals (eg. schwertmannite and goethite which cement dispersed clay in the pores) causing permanent clogging of soil pores.

In order to evaluate this mechanism, two sites on the Dundas Tableland will be characterised and monitored in terms of soil chemistry, physics and mineralogy (Fitzpatrick *et al.* 1992), ground water hydrology and botanical composition. The sites have been made available through the cooperation of Don and Jenny Smith ("Merriefields") and Chris and Christina Hindhaugh ("Englefield"). Novel ways of managing the iron ochre scalds such as the use of explosives and other drainage strategies will be investigated.

Acknowledgments

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Microbial Biomass and Activity Indices to Assess Minesite Rehabilitation

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Bauxite mining in Western Australia disturbs approximately 450 ha of native jarrah forest each year, and rehabilitation of the minesites is an important part of the mining operation.

Restoration of physical, chemical and biological properties of the soil, recovery of organic matter and re-establishment of nutrient cycling processes, are essential in successful minesite rehabilitation. Microbial biomass is a labile fraction of organic matter, responsible for decomposition and mineralisation of plant nutrients in the soil but sensitive to disturbance or changes in soil management. The re-establishment of microbial biomass and activity is vital for the re-development of soil processes in a rehabilitated soil.

Chronosequences of rehabilitated bauxite minesites at Jarrahdale, Western Australia, were studied for the recovery of microbial biomass and activity in the soils. The sites studied had received either freshly-stripped (direct-returned) forest topsoil or stockpiled forest topsoil, before being replanted to forest up to 20 years previously. Microbial biomass carbon was estimated by the release of ninhydrin-positive compounds following a 10-day fumigation of the soil. The estimate of microbial C was combined with basal respiration rate to express its activity level as the metabolic quotient (unit of CO_2-C respired per unit of microbial biomass C; qCO_2).

Microbial biomass C in the local undisturbed jarrah forest was in the range of 284 - 629 μg microbial C g^{-1} soil. Microbial C in the rehabilitated sites which had received direct-returned forest topsoil, increased sharply from the third year of rehabilitation to reach levels equivalent to the forest soils after the sixth year of rehabilitation, while soil organic C increased gradually but remained below the forest soil C (35 - 77 mg g^{-1} soil) even after 18 years of rehabilitation . The qCO_2 of the rehabilitated soils was high during the second to fourth years (>3.9 μg CO_2-C h^{-1} mg^{-1} microbial-C), but decreased to a level similar to that of forest soils (2.1 - 3.2) after 6 years.

Microbial C was extremely low in the site which had received stockpiled topsoil after 3 years of rehabilitation (15 μg g^{-1} soil compared to 88 μg g^{-1} soil in direct-returned site of the same age) and required a further 3 years to reach a level comparable with the 3-year-old site with the direct-returned topsoil. After the sixth year, the accumulation of microbial C in the soils with stockpiled topsoil was rapid and reached the level similar to forest microbial C after 9 years of rehabilitation. The metabolic quotient (qCO_2) of the stockpile-returned sites was markedly higher than that of the direct-returned-topsoil sites during the eight years of rehabilitation and finally decreased to the forest level after 9 years of rehabilitation.

Our results suggest that the use of stockpiled topsoil delays the onset of microbial biomass accumulation in the rehabilitated sites but it may not restrict the ultimate level reached. The delay of microbial biomass re-establishment in the sites with stockpiled topsoil might be related to the apparently poor establishment of understorey vegetation. Related studies indicate that the recovery of microbial biomass C is positively correlated with understorey plant cover.

The microbial indices (microbial C and qCO_2) appear to be sensitive indicators of the impact of soil disturbances and stresses on the microbial communities in the soil and provide a useful indication of the recovery of soil processes, as forest ecosystems develop in the rehabilitated minesites.

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