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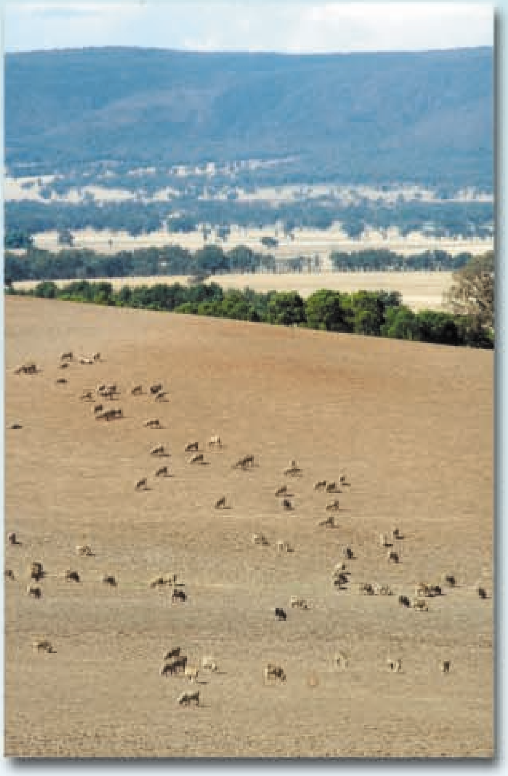
Monitoring Soil Change

Principles and practices for Australian conditions



Neil McKenzie, Brent Henderson and Warwick McDonald

CSIRO Land and Water
Technical Report 18/02, May 2002

CSIRO LAND and WATER

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CSIRO Land & Water

CSIRO Mathematical & Information Sciences

National Land and Water Resources Audit

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Cover: Soil profiles from a paired-site in the Mid North of South Australia. The profile on the left supports eucalypt woodland while the profile on the right has been farmed for over 50 years. Compared to the profile under woodland, the surface horizon is compacted, eroded and has less organic matter. The profile is also more leached due to wetter conditions – as a result structure in the B horizon also differs and it is more sensitive to clay dispersion (Site 1 of Naidu et al. 1996; Monoliths and images: David Jacquier, Neil McKenzie, Bill Van Aken, Bob Schuster).

National Land & Water Resources Audit

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Managed well, soil circulates chemical elements, water and energy for great human benefit. Managed poorly, it is impossible to imagine an optimistic future.

Richter and Markewitz (2001)

Monitoring soil change

Extended summary

Context

The general proposition that our natural environment should be monitored is widely supported by natural resource management agencies, industry groups and community organizations.

- Monitoring data can provide feedback to assess the effectiveness of natural resource policies, determine the success of land management systems and diagnose the general health of landscapes.
- There is also a desire for a set of environmental statistics to match well-established economic and social indicators.
- The emergence of a range of large-scale environmental problems in Australia has added to the general demand for better information on *trends* in resource condition.

Information is required at various levels of sophistication for many land-uses and across landscapes that are vast and diverse. Effective programs of monitoring have to be closely integrated with other activities that generate essential knowledge for natural resource management – these include land resource survey, simulation modelling, environmental histories and field experimentation.

The purpose of this report is to present the principles and practice of soil monitoring in a form that allows interested parties to develop monitoring programs that are scientifically defensible and capable of generating social, environmental and economic benefits. The emphasis is on monitoring that involves repeated measurements at a set of well-selected sites. Recommended directions for monitoring soil change are presented.

Rationale for investment in monitoring

The primary reasons for collecting most forms of natural resource data are to:

Reduce risks in decision-making – Reducing risk in decision-making requires the provision of information to be closely linked to, and preferably driven by, the decision-making process, whether at the scale of the paddock, enterprise, small catchment, region or nation. Decision makers include individuals and groups within government, industry and the broader community.

Improve our understanding of biophysical processes – This is required to:

- Create realistic models for explanation and prediction (e.g. simulation models);
- Develop sustainable systems of land-use and management; and
- Provide the scientific basis for sound policies in natural resource management (e.g. establish baselines and detect significant deviations; establish cause and effect).

A blueprint for monitoring soil change in Australia

The report provides an analysis of the conceptual and technical issues relevant to monitoring soil change. It concludes that useful programs of soil monitoring must have the following features.

- A clear purpose and close linkage to: a decision-making process at the farm, catchment, region, state or national level; or a scientific purpose.
- Monitoring sites are located *after* land resource or ecological surveys have been undertaken to ensure the sites represent well-defined landscape units and systems of land use. This allows results to be extrapolated to other locations with confidence.
- Monitoring and computer modelling activities are carried out in a complementary way. The latter is undertaken to assess whether soil change can be detected in a reasonable time. Modelling should also be used to help determine where to locate monitoring sites and to specify the frequency of measurement. Modelling can also be used to help extrapolate results from monitoring sites.
- Monitoring is directed to areas where early change is likely. This avoids wasting resources on measurement programs and it ensures that monitoring provides an early-warning system.

Soil monitoring requires a balanced investment in the following complementary areas.

Community and landholder programs

A range of programs and guides to soil monitoring have been produced for landholder and community groups. Most have a strong focus on improving land literacy and they have been of great value through their contribution to improved land management.

While there is potential for capturing the information gathered from such programs to construct district or regional overviews, the task of detecting soil change using this approach will be very difficult because of issues relating to accuracy and precision of measurement, quality control, and inevitable bias in the location of monitoring sites.

A large investment would be necessary to upgrade community and landholder programs so that they generated soil data of a similar standard to those gathered in, for example, the Streamwatch program for water quality monitoring. There should be continued support of community programs where motivation is strong and technical capacity is sufficient.

Industry programs of soil monitoring

Agricultural industries have greatly expanded their monitoring activities in recent years. There is a need to create partnership schemes to encourage the sharing or pooling of such data. The pooled data provide industry groups with information on trends in resource condition. For the same reason, they are invaluable to public agencies responsible for natural resource management. However, mechanisms for respecting commercial sensitivities are necessary. Where possible, support should be provided to develop clear protocols for measurement, undertake training, develop and maintain databases, and ensure regular feedback on results.

The full value of data sets generated by industry will only be realised when evaluations are undertaken of the validity of regional-scale conclusions. In particular, statistical assessments of bias, precision and accuracy are required.

Statistically-based soil monitoring for high-priority issues

There is a compelling case for establishing several clearly focussed networks for monitoring soil properties in regions with substantial natural resource problems.

- These networks require good statistical design with careful stratification on land-use and soil type. It is envisaged that each network would involve up to several hundred sites.
- A prime candidate is the establishment of a monitoring network for pH in those parts of Australia identified by the National Land and Water Resources Audit as having a serious or potentially serious acidification problem. Such a network would augment the existing extension programs and provide a reliable long-term assessment of the effectiveness of current strategies for amelioration.
- Proposals for statistically-based networks should be developed by an appropriate panel of experts (see below).

Land resource survey

- Land resource surveys provide a means for stratifying a region and the basis to statistically locate monitoring sites. They also provide essential information for interpreting the results from monitoring.
- With some improvement, new land resource surveys can also provide a more effective basis for identifying priority regions for monitoring. To achieve this, land resource surveys need to provide better statements on resource condition.
- The present incomplete land resource survey coverage severely compromises the utility of soil monitoring and simulation modelling more generally. The land resource survey coverage of Australia should be completed to a level of detail proportional to the intensity of present and possible land use.

Soil monitoring as part of long-term ecological research

There is a need for a restricted number of substantial long-term scientific studies of ecosystem and landscape processes in catchments that represent, in the first instance, the main regions used for agriculture and forestry in Australia.

These long-term studies would include measurement and modelling of water, sediment, nutrients, biological production and related processes. These studies are essential for developing an improved understanding of processes controlling the sustainability of current and planned systems of land-use.

Excellent prototypes for such studies exist internationally and there are some nascent studies in Australia that deserve much greater support. A comprehensive approach is required both in terms of the regions represented and the range of processes measured.

Expert panels and assessments

There is a strong case for maintaining several national panels to undertake expert assessments.

- Decision-makers require advice on likely changes in soil and land resource condition and they cannot wait until there is statistical certainty in trends from long-term monitoring sites. Interim procedures are required so that assessments of change can be based on risk, probability and expert opinion.
- Oversight of monitoring activities requires informed design, planning, management, assessment and review. An expert panel has a function in each role.
- It would appear prudent to have several expert panels responsible for soil-related matters. A suggested set would include panels on acidification, nutrient balance, soil biology, contaminants, soil physical quality, erosion and salinity. A panel is also required to integrate and evaluate the interactions and combinations.

Organization and investment

Australia has a long history of having a complicated and at times very poorly coordinated organizational system for acquiring and managing information on soil and land resources. There have been some notable improvements during the last decade but many more are required.

- A stable organizational and funding structure for acquisition and analysis of land resource data is essential. A steady but modest stream of funds over the long-term is more likely to be beneficial than a large investment over a short period.
- Technical and policy groups responsible for land resource survey, monitoring and simulation modelling must be more closely linked.
- The National Land and Water Resources Audit has identified both the regions where soil change is of major concern along with the relative benefits of halting or reversing current trends. Soil change associated with nutrient depletion, excessive fertilizer use, erosion, salinity and sodicity are all significant. However, soil acidification looms as *the* major soil degradation issue. Monitoring pH is arguably the most straightforward of all soil properties – monitoring networks in regions at risk are essential to confirm the severity of the problem, track changes and provide feedback on the success or otherwise of remediation strategies.

Public investment in land resource survey has been shown to generate benefits far in excess of the costs of survey. Similar analyses are not yet available for soil monitoring, simulation modelling or studies of environmental history and this needs to be rectified to ensure appropriate investment. Lack of investment in natural resource information will cause several problems.

- Resources will be poorly directed for natural resource management (e.g. Landcare activities, revegetation, support for beneficial land management activities).
- The magnitude of natural resource problems will not be appreciated – avoidable environmental degradation or low agricultural productivity being the result.

Mapping, modelling and monitoring as complementary activities

Monitoring provides one component of the biophysical information base necessary for natural resource management (*Figure (i)*).

Monitoring programs must be considered with the mutually beneficial activities of mapping and modelling, and all three should then be set within the context of environmental history – the latter provides an understanding of rates of change on much longer time scales (decades, centuries and millennia).

In isolation, each activity fails to provide appropriate information for land management and planning. In combination, they provide a powerful and synergistic means for transforming the quality of land management in Australia (*Table (i)*).

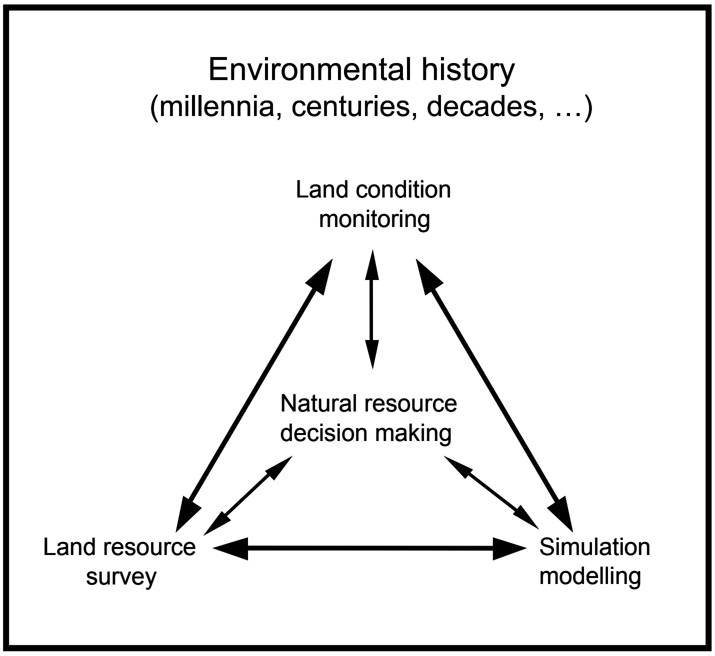


Figure (i): Mapping, monitoring and modelling are complementary activities for natural resource management and they must be set against the context of the environmental history of events and processes for a given landscape.

Table (i): Complementary benefits of mapping, monitoring and modelling

Complementary Relationship	Benefits
Mapping → Monitoring	• Spatial framework for selecting representative sites • System for spatial extrapolation of monitoring results • Broad assessment of resource condition
Monitoring → Mapping	• Quantifies and defines important resource variables for mapping • Provides temporal dimension to land suitability assessment (including risk assessments for recommended land management practices)
Modelling → Monitoring	• Determines whether trends in specific land attributes can be successfully detected with monitoring • Identifies key components of system behaviour that can be measured in a monitoring program
Monitoring → Modelling	• Provides validation of model results • Provides input data for modelling
Modelling → Mapping	• Allows spatial and temporal prediction of landscape processes
Mapping → Modelling	• Provides input data for modelling • Provides spatial association of input variables

Methods for monitoring soil change

Soil monitoring is challenging for several technical, institutional and social reasons.

- The areas to be monitored are very large.
- Most soil attributes change slowly (often over decades) and early detection can be difficult.
- Short-range spatial variation in soil is typically large and it can be easily confused with temporal variation because sampling is usually destructive (see below).
- Measurement is often time consuming, physically arduous and relatively expensive.
- Results from soil monitoring are often strongly site specific.
- Community motivation for soil monitoring is lower than for other aspects of the environment where there is more obvious aesthetic appeal (e.g. birds, waterways, weather).

There are four general approaches to monitoring soil change – a coordinated national system requires elements of each (*Figure (ii)*).

Simple monitoring: This involves the regular recording of a single variable at one or more locations.

Survey monitoring: When a problem becomes apparent at a location but there are no long-term records, a survey of current conditions across an area can be undertaken. By using land-use histories, soil change can be inferred by substituting space for time.

Proxy monitoring: This involves the use of proxy or surrogate measures to infer historical conditions in the absence of actual measurements of the desired variable (e.g. satellite data on land cover being used to infer soil carbon levels).

Integrated monitoring: This involves recording and understanding changes in the total landscape. It involves long-term interdisciplinary programs of scientific study and the aim is to understand cause and effect, usually for a small study area, although the principles and results are broadly applicable.

Understanding soil and landscape processes

The need for a whole-system view

A conceptual model of how landscapes operate is essential for devising a monitoring system whatever its purpose and design. Landscapes have a range of properties that need to be considered in relation to monitoring.

- The behaviour of many landscapes is influenced by positive and negative feedback loops. Monitoring individual components separately (e.g. only soil and not vegetation and hydrology) will be insufficient for an understanding of whole-system behaviour.

- Landscapes are comprised of hierarchies of processes. Some scales of observation are more effective than others for monitoring change. Furthermore, supporting information collected at a broader scale is needed for context. Likewise, information collected at a more detailed level is needed for a clear understanding of mechanisms of change.
- Some landscapes may have multiple steady states and exhibit sudden and unpredictable behaviours – simple, survey or proxy monitoring will often be of limited value in these circumstances because they do not yield information on the underlying causes of change.
- Some processes within landscapes may also exhibit chaotic behaviour and have limited predictability regardless of the level of information and modelling capability.

Patterns of change with time

Landscapes and soil properties naturally change with time. Different patterns and rates of change affect the design of monitoring schemes. Some change is slow and gradual (e.g. acidification) while in other cases it is episodic, rare and not easily reversed (e.g. erosion). Various examples of change are presented in the report. In some cases, monitoring will not be feasible.

Key technical issues for soil monitoring

Sampling

Scales of soil variation

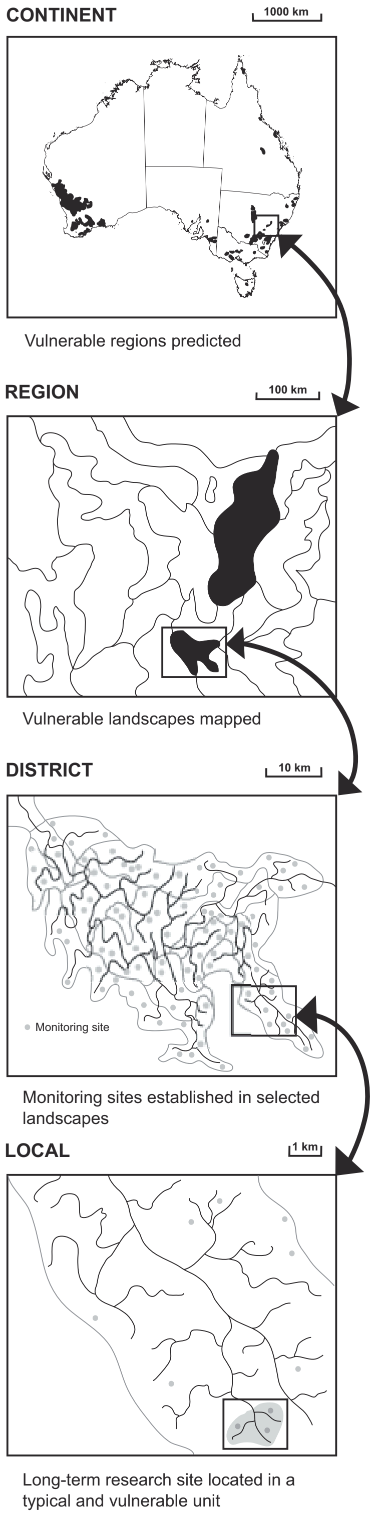
Soils vary in space, both vertically and horizontally, and through time.

- A large proportion of soil variation occurs over surprisingly short distances (up to half the variance within a paddock may already be present within a few square metres).
- Different soil properties have contrasting scales of variation.

The large short-range spatial variability of most soil properties has several major implications for monitoring:

- Most measurements of soil properties involve the collection of a specimen – sampling is destructive and subsequent measurements are undertaken on separate specimens. The short-range spatial variability can be easily confused with change over time unless there is careful sampling and sufficient replication.
- The large magnitude of variability means that an equally large effort in measurement is necessary to detect trends – the signal to noise ratio is typically low.

Figure (ii): Overview of monitoring and natural resource information provision at various scales



Mapping	Modelling	Monitoring
• Synthesis • ~1:2,000,000 scale • Broad landscape types and interpreted soil properties • Predict locations of vulnerable regions	• Gross simplification of landscape processes • Broad material budgets • Exploratory analysis	• Proxy monitoring using satellite-based methods (e.g. land cover) supported by synoptic mapping and modelling.
• Soil-landscape units • 1:100,000 scale • Delineate vulnerable landscapes • Limited laboratory testing	• Generalized hydrological and simplified farming system modelling • Input data from survey and limited direct measurement • Some capacity for validation from field experiments	• Proxy monitoring of land-use and management. • Field verification of proxy measures • Survey monitoring feasible • Programs to improve land literacy
• Soil map units • 1:25,000-1:100,00 scale • Most sensitive lands identified to guide location of monitoring sites	• Farming system modelling at enterprise level and hydrological modelling at intermediate catchment scale • Input data from direct measurement • Validation from field experiments	• Simple monitoring • Network of sites for direct measurement of soil change in selected and vulnerable landscapes • Programs to improve land literacy
• Full inventory restricted to the long-term ecological research site • More detailed than 1:10,000 • Intensive field measurement to support experimental program	• Detailed deterministic modelling • Comprehensive validation of models	• Integrated monitoring • Major long-term ecological research site • One of perhaps 20 or so sites in Australia • Direct monitoring of landscape processes

Site selection

The value of a set of measurements depends on effective sampling. Guidelines are provided on procedures for sampling, site layout, location, soil description and field procedures. Reference is made to relevant national standards and guidelines. The concept of the soil individual is defined along with the volume of soil necessary to obtain representative measurements.

The only sure way of avoiding bias is through statistically based sampling and protocols. However, it may be impossible to apply when measurement is expensive and only limited replication is possible. The advantages and disadvantages of alternatives are considered and methods for maximizing the efficiency of statistical methods are identified

It is inevitable for objectives and questions to change during a long-term monitoring program so flexibility should be built into the design. Simple initial designs are best. This maximizes flexibility for later measurement programs involving new variables.

Measurement

Site and soil characterization

Site and soil characterization of monitoring sites is required to provide:

- A basis for extrapolating results to other similar soil and landscape types;
- A means for grouping or stratifying sites to aid measurement and analysis; and
- Insights into anomalous or unusual results.

A minimum standard for site and soil characterization is presented. Note that this site and soil characterization is a separate activity from the actual monitoring of particular soil properties.

Selection of soil properties for a monitoring program is considered. A provisional list of candidate soil properties for monitoring is presented and it is based on recent New Zealand experience. The soil properties are total carbon, total nitrogen, mineralisable N, pH, Olsen P, bulk density and macroporosity. Confirmation of the validity of this list is required for Australian conditions. For example, extra variables would be needed to capture changes in salinity and sodicity (e.g. clay dispersion). The merits of direct measurement in the field versus laboratory determination are considered along with processing requirements and laboratory standards.

Indirect measurement

The role of remote sensing and indirect measurement methods are briefly reviewed. Maps of soil properties, land types or sustainability indicators are an inefficient means for detecting change because their predictive capability for a given location is low. As a result, comparisons of maps prepared for different times will have a very low accuracy and precision. However, the maps are valuable because they show patterns of resource condition and provide an essential tool for designing and prioritising monitoring efforts. They are also necessary for analysing and generalizing results from a monitoring program.

Data management

Long-term monitoring may proceed for decades and involve the collection of large quantities of data. The challenge of creating a data management system for long-term soil monitoring should therefore not be underestimated.

The key lessons of data management from long-term agricultural experiments and ecological monitoring studies are presented. Ultimately, it is the stability, interest and dedication of responsible individuals, institutions or agencies that ensure the success of long-term monitoring – this is difficult against the backdrop of institutional change and short-term programs of funding that have characterized natural resource management in Australia in recent times.

Soil archiving

Soil specimens collected during a monitoring program should be stored in archives. Most soil properties do not change when soil is stored in a dry condition and in secure containers. International experience has demonstrated that archives have great scientific and economic value. They allow:

- Retrospective studies of nutrient balances and pollutants;
- Calibration of new measurement methods against previous procedures.
- Substantial cost savings when new methods of analysis become available or unforseen soil properties have to be measured (e.g. unusual industrial contaminants) – fieldwork does not have to be repeated.

Recommendations on the design and management of soil archives are presented.

Change over time

Choosing an appropriate frequency of measurement will depend on the objectives of the study, understanding of system behaviour, patterns of variation in the relevant soil properties across the landscape and through time, statistical design (e.g. sampling method, sample size, degree of replication, specimen processing strategies), measurement technology and resources.

A case study is presented for monitoring of soil pH, organic carbon and hydraulic conductivity on a range of soil types. Using published values for spatial variability, the sampling effort required to detect significant changes in these soil properties is calculated for periods of 10 and 20 years. The case study highlights key issues.

- A large sampling effort is often required to detect the relatively small changes over time against the often-large spatial fluctuations that occur at a range of scales.
- Some soil properties can be readily monitored (i.e. those that are less spatially variable, responsive to management and easy to measure) while others are impractical because of the large spatial variability and high cost of measurement. Selecting tractable soil properties is crucial to the success of a monitoring program.
- pH and organic carbon are two important soil properties amenable to monitoring.

- It is practical to monitor soil change at local and regional scales. However, it is essential to repeat measurements over time at the *same* site and to then analyse differences between individual sites over time. The alternative of comparing the mean value of a soil property across all sites at time zero with the mean for all sites at a later time is an inefficient and ineffective method for detecting change.
- Monitoring soil change relies ultimately on very good quality measurement at representative field sites often over extended periods (i.e. decades).
- Information on land management is critical for interpreting the results of monitoring.

The Checklist

The report concludes with a checklist of design considerations and a standard layout for monitoring sites. The checklist addresses purpose, method, sampling, measurement, archiving, data management, analysis, people, institutions and criteria for cessation. The checklist is intended for individuals with responsibilities for commissioning, designing and implementing programs that aim to monitor soil change.

Contents

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Figures

Figure 1: Mapping, monitoring and modelling are complementary activities for natural resource management and they must be set against the context of environmental history for a given landscape.

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Figure 10: Concept of the soil individual.

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Figure 12: Overview of monitoring and natural resource information provision at various scales

Figure 13: A possible layout for a soil-monitoring site.

1 Introduction

The general proposition that our natural environment should be monitored is widely supported by natural resource management agencies, industry groups and community organizations. It is generally accepted that monitoring data can provide feedback to assess the effectiveness of natural resource policies, determine the success of land management systems and diagnose the general health of landscapes. There is also a desire for a set of environmental statistics to match well-established economic and social indicators. The emergence of a range of large-scale environmental problems in Australia has added to the general demand for better information on *trends* in natural resource condition.

Monitoring programs for various components of natural systems have been established in Australia. Well-established networks and procedures exist for weather, air quality, water quantity, water quality, particular aspects of land-use (e.g. commodity production), and some biota (e.g. birds). Large archives of remotely sensed data from airborne and space-based platforms are also providing new ways of detecting change (e.g. Graetz et al. 1998; McVicar 2001). Soil monitoring has been a more difficult task and this is consistent with overseas experience (Bullock et al. 1999; Mol et al. 2001). Indeed, in some countries with much better soil mapping coverages and databases than Australia, it has been debated whether soil monitoring is feasible (Mol et al. 2001). However, there are now good examples of monitoring schemes and strategies for determining changes in soil condition (e.g. Skinner and Todd 1998; Mol et al. 2001; Richter and Markewitz 2001; Huber et al 2001).

Objective 6 of the National Land and Water Resources Audit (NLWRA) was to provide “a framework for monitoring Australia’s land and water resources in a structured and ongoing way.” The NLWRA has commissioned several studies relating to monitoring. This report focuses on soil monitoring but this is set within the broader context of an integrated landscape approach. Most aspects of soil condition are closely related to vegetation, and land management more generally. For the sake of brevity, the term land condition will often be used but the focus is on the interaction between soil, other relevant ecosystem components, and land use.

It will be evident, even after a brief consideration of the issues surrounding land condition monitoring, that no single approach can hope to satisfy all purposes. Information is required at various levels of sophistication for many land-uses and across landscapes that are vast and diverse. It will also be apparent that effective programs of monitoring have to be closely integrated with other activities that generate essential knowledge for natural resource management – these include land resource survey, simulation modelling, field experimentation and environmental histories.

Within this context, the purpose of this report is to present the principles and practice of soil monitoring in a form that allows interested parties to develop monitoring programs that are scientifically defensible and capable of generating social, environmental and economic benefits. The emphasis is on monitoring that involves repeated measurements at a set of well-selected sites.

Rationale for data collection

The primary reasons for collecting most forms of natural resource data are to:

- Reduce risks in decision-making; and
- Improve our understanding of biophysical processes.

Reducing risks in decision making

Reducing risk in decision-making requires the provision of information to be closely linked to, and preferably driven, by the decision-making process, whether at the scale of the paddock, enterprise, small catchment, region or nation. For example, a farmer needs information at the scale of the paddock while a Commonwealth funding agency will usually require information at the regional and continental scale. Decision makers in Australia require timely access to information at relevant scales. Developing an adequate information delivery system to realize this is a substantial task.

Many publicly funded programs for gathering information have general-purpose objectives: for example, the multitude of schemes for measuring indicators of landscape health; or land resource survey programs at medium to reconnaissance scales. Some of these activities are very effective (e.g. ACIL 1998; Fargher 1999). Community-based programs of monitoring have been favoured in recent years (see Australian Conservation Foundation 1996; Buxton and Goodwin 1999) and there have been substantial benefits through improved land literacy and public awareness. However, only a few such programs are developed to the stage where they provide a database with sufficient scientific rigour to allow the detection of trends in soil condition. Substantial improvements are necessary to better target public and industry investment in information acquisition and provision. Better targeting requires a clear view of the reasons for acquiring and delivering natural resource information – these are considered in the following sections.

Government

The provision of reliable natural resource information to support policy decisions by Commonwealth, State, Territory and regional agencies is necessary because of the emergence of large scale environmental problems, including global warming, dryland salinity and soil acidification. Improved natural resource information is required to:

- Assess the effectiveness of, and better target, major natural resource management programs (e.g. schemes for widespread planting of perennials to control recharge);
- Implement trading schemes (e.g. for salt, water and carbon) to achieve better natural resource management outcomes;
- Establish baselines (e.g. for contaminants); and
- Set targets and monitor trends.

Industry

Agricultural industries require better natural resource information to:

- Optimize the matching of land use and management with land suitability (some sectors, most notably viticulture and industrial scale farm forestry, have increased investment in user-specific land resource assessment during recent years);
- Gain market advantage by demonstrating the benign nature of production systems (e.g. green labelling);
- Implement environmental management systems to comply with duty of care regulations and industry codes; and
- Optimize the use of inputs (e.g. soil nutrient testing to guide fertilizer rates) at the level of the paddock or finer (e.g. variable rate application of fertilizer in precision agriculture).

Regional Communities

Regional communities require better natural resource information to:

- Assess and improve the efficacy of natural resource management and target community action (e.g. remedial tree planting, fencing, weed control); and
- Improve awareness of landscape processes.

Improving process understanding

Improving the understanding of landscape processes is the second main reason for monitoring land condition. It is largely the domain of research and development agencies and is a long-term venture. Most scientifically focussed programs of long-term monitoring relevant to natural resource management have involved some form of field experiment at the scale of the plot (e.g. agricultural tillage trials), through to the small catchment (e.g. paired catchment studies in ecohydrology; habitat fragmentation studies in ecology (e.g. Lindenmayer et al. 1999)). Other sources of monitoring data include the existing observation networks for weather (e.g. rainfall, temperature etc.) and hydrology (e.g. stream heights). These networks provide core data sets to the scientific community but the justification for their existence is based primarily on direct economic benefit.

Regional remote sensing provides data that are dense in space and time across Australia. In isolation, remote sensing is of little value, however, coupled with other monitoring networks, it has a great potential to provide spatial and historical context (e.g. McVicar et al. 2000).

In Australia, most scientific investigations relating to natural systems are short-term (often 3 years or less), plot-based and restricted to a limited range of species. Due to current funding arrangements, only a few long-term, comprehensive ecosystem studies have been initiated in recent decades (e.g. Warra Long-term Ecological Research site in Tasmania, www.warra.com/warra/index.htm). This is in contrast to previous decades that witnessed numerous large or long-term studies with a significant monitoring component. For example:

- comprehensive catchment studies to determine the effects of land management on water quality and quantity (e.g. Langford and O’Shaughnessy 1977);

- long-term agricultural experiments testing crop rotations, tillage systems and related agricultural practices (Grace and Oades 1994; special issue of the Australian Journal of Experimental Agriculture, Volume 35, Issue 7);
- plot and hillslope studies to determine rates of erosion (e.g. Freebairn and Wocker 1984a);
- investigations of landscape processes (e.g. Thompson and Moore 1984); and
- nutrient cycling studies (e.g. Khanna and Raison 1986; Attiwill and May 2001).

Many of these studies have provided fundamental insights into Australian landscapes and land management systems. Some forms of long-term experimentation (e.g. replicated agronomic experiments) have declined for reasons apart from resource limitations – there have been some doubts relating to efficiency. In particular, the advent of simulation modelling (see below) supported by field experimentation has created new ways to understand the behaviour of land management systems, particularly the interaction with climate variability (e.g. Carberry et al. 1998).

In the international sphere, there has been widespread recognition that long-term ecological research (including human systems) is essential to support natural resource management (Callaghan 1984; Munn 1988; Heal et al. 1993; Leigh and Johnston 1994; Richter and Markewitz 2001; Likens 2001) – a similar recognition is emerging in Australia and the implications are considered in later sections.

In summary, improved soil information is required across space and time to:

- Better understand natural processes (e.g. to establish baselines and detect significant deviations (Vaughan et al. 2001); establish cause and effect);
- Create improved models for explanation and prediction (e.g. better simulation models to assess the environmental impact of farming systems);
- Develop improved systems of land-use and management (e.g. Stirzaker et al. 2000); and
- Provide a scientific basis for improved policies in natural resource management.

2 Mapping, modelling and monitoring as complementary activities

Monitoring provides one component of the biophysical information base necessary for natural resource management (Figure 1). Monitoring programs must be considered with the mutually beneficial activities of mapping and modelling, and all three should then be set within the context of environmental history. In isolation, each activity fails to provide appropriate information for land management and planning. In combination, they provide a powerful and synergistic means for transforming the quality of land management in Australia. A major challenge facing public agencies and industry bodies is to achieve maximum benefit from information gathering and interpretation through integration of these activities.

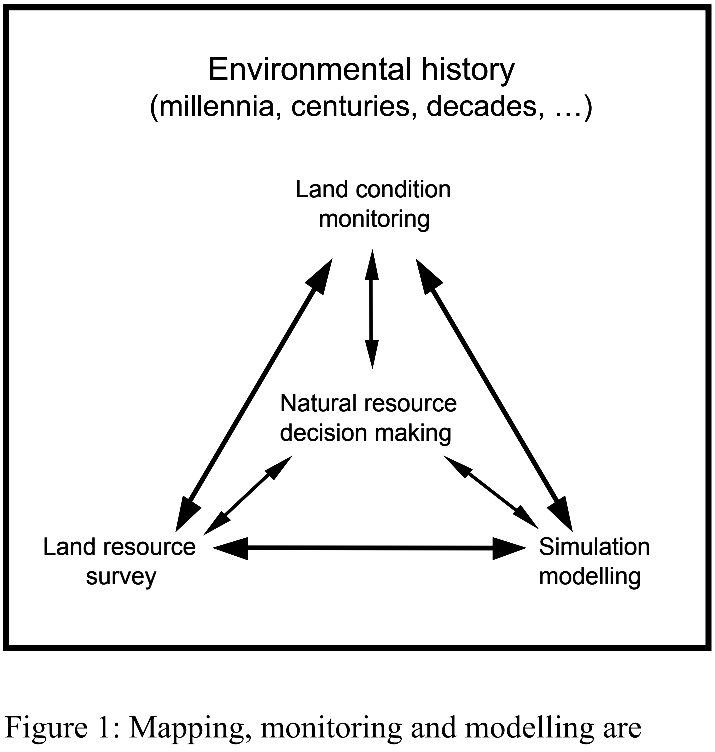


Figure 1: Mapping, monitoring and modelling are complementary activities for natural resource management and they must be set against the context of the environmental history of events and processes for a given landscape.

Table 1: Complementary benefits of mapping, monitoring and modelling

Complementary Relationship	Benefits
Mapping → Monitoring	• Spatial framework for selecting representative sites • System for spatial extrapolation of monitoring results • Broad assessment of resource condition
Monitoring → Mapping	• Quantifies and defines important resource variables for mapping • Provides temporal dimension to land suitability assessment (including risk assessments for recommended land management practices)
Modelling → Monitoring	• Determines whether trends in specific land attributes can be successfully detected with monitoring • Identifies key components of system behaviour that can be measured in a monitoring program
Monitoring → Modelling	• Provides validation of model results • Provides input data for modelling
Modelling → Mapping	• Allows spatial and temporal prediction of landscape processes
Mapping → Modelling	• Provides input data for modelling • Provides spatial association of input variables

The essential context: environmental history

Conceptual models and narratives of environmental history have been developed at the global, continental, regional and, in some instances, local scales. The temporal dimension for these models ranges from millions of years to decades. The chronologies of geologic, geomorphic, atmospheric, oceanic and ecologic events are critical for the analysis of current and future landscape processes (Williams et al. 1998). For example, they provide insights into potential impacts of global warming, extreme events (e.g. floods, droughts), natural baselines (e.g. erosion rates and sediment movement), groundwater behaviour, salt movement and population dynamics. The Tertiary (65-1.8 million years before present) and Quaternary (1.8 million years ago to present) geological periods are of particular importance because many landscape and pedologic processes and events during this period shaped the contemporary landscape.

More recent histories dealing with Aboriginal and European land-use are essential for inferring baselines and interpreting the significance of contemporary rates of change (e.g. Scott 2001). For example, many parts of southern Australia experienced dramatic environmental change in the late 1800s (clearing and erosion) and again in the 1930s and 1940s (extended drought, rabbit plagues and subsequent erosion). Current day rates of erosion, organic matter decline and nutrient loss are often modest when compared to the period when European land-use and pests were introduced.

Agricultural scientists and natural resource managers require a good appreciation of the relevant aspects of environmental history because it sets the context for contemporary land management. In relation to soil monitoring, Richter and

Markewitz (2001) provide an excellent example of an environmental history for the strongly weathered soils of the southeast United States and many of the observations have implications for how the now forested landscapes (they were once farmed) can be harvested and managed. Similar regional histories are required for Australian soils.

Mapping

Land resource mapping provides the basic description of landscape attributes. Mapping is essential for sound planning and management at all scales. It can provide a baseline for determining resource condition but this requires particular care during the design of the field program. It also provides input data to computer models for predicting likely changes in condition under various land uses. There are significant deficiencies in the current land resource mapping coverage of Australia.

- The land resource map coverage of agricultural areas is incomplete and in most areas the scale is too broad to be useful for decisions at the farm level.
- Incompatible land resource survey methods have been used by different agencies and this has made compilation of national and regional overviews of land resource condition difficult.
- Many of the key soil and land attributes controlling land degradation or productivity are not measured in a rigorous manner and this seriously limits our capacity to make an assessment of the magnitude of land resource management issues.
- Statistically-based methods have not been used so unbiased estimates of baseline or current conditions are not possible.
- Because of their broad scale, mapping units often contain a wide range of soils and as a consequence, they may not form an effective basis for stratifying the landscape as a precursor to the establishment of monitoring sites. They do not provide a good basis for extrapolation either.

A detailed analysis of land resource survey is not possible here but in the mid-term (10-15 years), there are very good reasons for Australia to aim at achieving a land resource survey coverage at nominal scales of 1:50 000 for intensively used lands, 1:100 000 for agricultural areas (cropping and pasture) and 1:250 000 for the extensive pastoral regions (see McKenzie 1991 and McKenzie et al. 2000a). Obtaining this coverage will require a modest but long-term investment in survey activities (i.e. similar to investment levels during the last decade). Permanent resource assessment teams are required in State, Territory and Commonwealth agencies to ensure continuity of staff and continual improvement of natural resource databases. There is also a clear need to develop better methodological links with modelling and monitoring groups. The incomplete land resource survey coverage severely compromises the utility of soil monitoring.

Modelling

Computer simulation modelling of farming systems, forest growth and landscape processes (e.g. erosion, soil acidification, hydrology) provides a means for understanding recent and likely changes in resource condition under a wide range of management systems (Hook 1997). Fully realizing the potential benefit of simulation models requires:

- Ensuring that survey and monitoring programs provide appropriate data for running and validating models (with statements on accuracy and precision); and
- An active research program (including field experimentation) to develop better and more integrated simulation models useful for guiding land management decisions.

Simulation models are invaluable for exploring potential changes in soil condition. They can be used to assess whether monitoring is even feasible. The annual and decadal variations due to climate may mask subtle but important changes in soil condition–it may well be that detection of a statistically significant change is only possible over an impractically long period (e.g. > 50 years). While research will be needed to confirm the model results at a restricted number of sites, investment in a large monitoring network would not be sensible in such circumstances. In other cases, monitoring will be both tractable and informative.

Monitoring

As noted earlier, monitoring is undertaken to support natural resource decision-making, improve process understanding, or both. Either way, it usually involves:

- Establishing baselines for various ecosystem components; and
- Detecting change over time, particularly deviations from natural variation.

Monitoring should be designed to test clearly defined ideas. However, reliable translation of monitoring results into management actions nearly always requires an understanding of *why* change is occurring. This translation usually requires more than monitoring data alone – the issues involved in gaining this understanding are considered in the next section.

3 Monitoring: approach and purpose

Some challenges

Before considering various approaches to soil monitoring, some consideration is required of why soil monitoring has lagged compared to other forms of natural resource monitoring. There are technical, institutional and social reasons. These can be appreciated by making comparisons with water quality monitoring. In Australia, public agencies, private industry and community groups spend millions of dollars each year on water quality monitoring. Monitoring water quality has been tractable for the following reasons.

- Waterways are geographically constrained entities and the task of selecting measurement sites is relatively straightforward.
- Large changes in water quality occur over time scales that can be readily measured using either manual or automatic methods.
- Most attributes have well-established methods of measurement and a wide-range of relatively inexpensive technologies can be employed.
- Water quality measurements can often be translated into information that is directly relevant to human health, environmental management and economic wellbeing.
- Water quality measurements often integrate the effects of broad land management or relate directly to point sources of contaminants – as a consequence, formulation of remedial land and water management strategies is often possible.
- Waterways are a common property resource – their management has been the responsibility of communities and government.
- Waterways have a deep aesthetic attraction and this provides a powerful motivation for community-based monitoring.

Apart from farm-based soil testing by fertilizer companies, soil monitoring has not received substantial investment in Australia, and it contrasts with water quality monitoring in the following ways.

- The areas to be monitored are very large – site selection to ensure both representativeness and the extrapolation of results is a difficult task.
- Most soil attributes change slowly (often over decades) and the early detection of this change is technically challenging.
- Short-range spatial variation is often large and this can be easily confounded with temporal variation because sampling is usually destructive (see below).
- Measurement is often time consuming, physically arduous and relatively expensive.

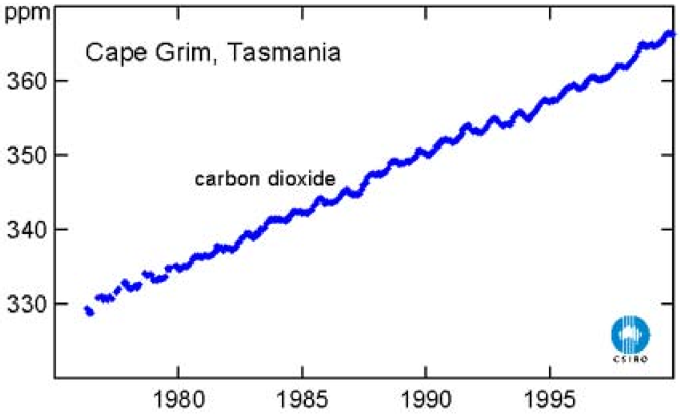
- Results from soil monitoring are often strongly site specific because they arise from interactions between climate, soil type and land-use.
- While soils have undoubted aesthetic appeal and symbolic significance ("… we've golden soil and wealth for toil"), their appreciation often requires labour and this discourages many from exploring the subterranean pleasures of the continent.

Approaches to monitoring

Four general categories of land condition monitoring can be recognised (Vaughan et al 2001).

Simple monitoring
This involves the recording of a single variable at one or more locations over time. A very good example from air quality monitoring is the measurement of carbon dioxide and other Greenhouse gases at Cape Grim in north-western Tasmania (Figure 2).

Figure 2: Changing concentrations of carbon dioxide key at the Cape Grim Baseline Air Pollution Station in north-western Tasmania (CSIRO Atmospheric Research).



The information from Cape Grim attains its value and significance because it can be related to causal processes (e.g. burning of fossil fuels) and it has a predictive capacity because the role of carbon dioxide in controlling the energy balance of the earth is reasonably well understood. Simple modelling without this underlying knowledge will normally limit the utility of results.

A soil-related example is presented in Figure 3 and it shows trends in soil pH. The data come from the Representative Soil Sampling Scheme of England and Wales (Church and Skinner 1986; Skinner and Todd 1998). These results come from one of the very few long-term regional networks for monitoring soil change. A statistically significant change is only evident with pH under permanent grassland. Even though this is an example of simple monitoring (i.e. one variable), keeping track of land management is vital for reliable interpretation.

Simple monitoring can be undertaken across geographic domains of varying extent ranging from the individual site, to the paddock, region or continent.

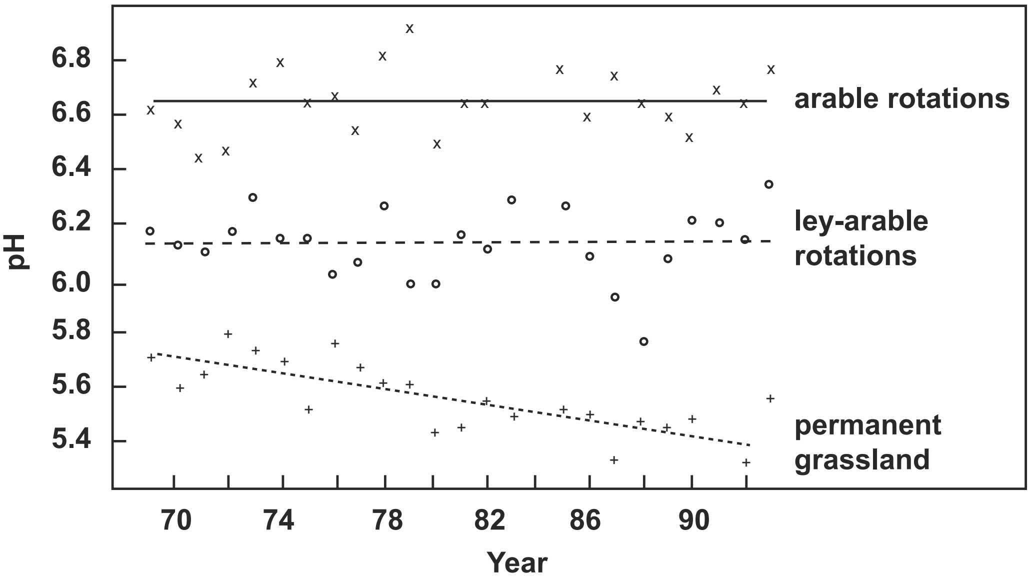


Figure 3: Trends in mean pH ($CaCl_2$) from the Representative Soil Sampling Scheme of England and Wales. The only statistically significant trend occurs in permanent pasture (maximum standard error of year mean = 0.059; consult Skinner and Todd (1998) for further statistical details).

Survey monitoring

Some environmental problems appear at particular locations (e.g. salinity outbreaks) but there is no monitoring record at the location or for other areas where the problem may manifest. Monitoring surveys aim to provide a substitute for the historic records by undertaking a survey of current conditions across an area. Survey monitoring when applied to soil has the following features.

- It is assumed that soils at different locations were once the same in every respect.
- Some form of land-use history is available for each location.
- Sampling of sites with different management histories allows inferences to be made about the impact of land management practices over time – space is substituted for time.

One of the best examples of survey monitoring in Australia is provided by the series of studies on the effects of agricultural management on Tenosols (Cotching et al. 2002a), Dermosols (Cotching et al. 2002b), Ferrosols (Sparrow et al. 1999) and Sodosols (Cotching et al. 2001), in northern Tasmania (brief descriptions and maps of Tenosols, Dermosols, Ferrosols and Sodosols are provided by NLWRA (2001). Each study was restricted to a well-defined soil type and involved the selection of paddocks under a range of clearly documented land management systems. Observations were replicated. In most cases the soil type was defined by detailed soil mapping. The studies revealed a variety of soil responses to different systems of land management, with the most notable degradation being associated with intensive farming of Sodosols. Figure 4 presents results from Sparrow et al. (1999) showing the negative relationship between organic carbon and the period of cultivation for Ferrosols while Figure 5 shows contrasting soil strength profiles under different management systems in the Tenosols studied (Cotching et al. 2002a). Note that soil strength is considered to be a limiting factor in cereal crop root development when it exceeds a penetrometer resistance of 3500 kPa (Hignett 2002).

Paired site studies are another example of survey monitoring. In most cases, sampling is undertaken at the same time from an undisturbed (typically forest or woodland) and adjacent disturbed site (typically under some form of agricultural use). While sampling within each site may be statistically based, the paired site is usually selected without any form of randomisation. Much of our knowledge on the effects of agriculture on soil properties has been derived from studies of paired sites (see Conteh 1999). Bridge and Bell (1994) provide a very good example of a paired site study with their investigation of the impact of 50 years of continuous cropping on Ferrosols in southern Queensland.

The main limitation of survey monitoring is the assumption that space can be substituted for time. It is usually very difficult to confirm that sites with different management histories were once the same, and that the assumed starting point provides an appropriate baseline. For example, the sites may have been severely degraded prior to the start of the different management histories – failing to detect an impact of management may be inconclusive as a consequence. Another difficulty is the general absence of reliable information on management history – this limits inferences relating to the observed differences.

Proxy monitoring

Another way of overcoming the lack of long-term monitoring records involves the use of proxy or surrogate measures to infer historical conditions in the absence of actual measurements of the desired variable. Proxy monitoring has been used successfully in the biophysical sciences in specific circumstances. A classic example is the use of oxygen isotope ratios of air trapped in ice cores from the Arctic and Antarctic. The ratio is a function of air temperature at the time of deposition so it can be used to construct a long-term record of temperature (see Figure 8).

The results of proxy monitoring in relation to soil monitoring are equivocal. Many schemes for inferring soil condition using surrogates have been proposed (e.g. Hamblin 1998) but few have been rigorously tested. Increasingly, existing land resource data, commodity statistics and remotely sensed data are being used to compute balances of nutrients or parameterize simulation models (SCARM 1998; NLWRA 2001). These approaches require careful testing. For example, sequences of remotely sensed images can be used to measure land cover. With appropriate field observation, correlations can be developed between the land cover classes and soil carbon levels – if reliable, these relationships could be used in conjunction with the remote sensing to monitor soil carbon. In most cases, such proxy monitoring will be less sensitive for monitoring than direct measurement but it may provide other advantages such as information on spatial patterns. Surrogate measures will often be needed as an interim measure until the results from more direct monitoring methods become available.

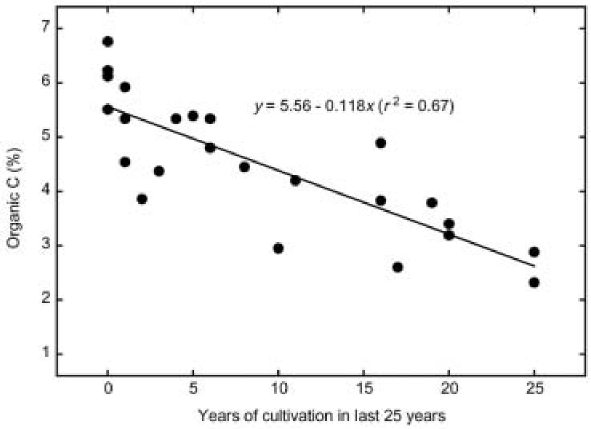


Figure 4: Relationship between organic carbon and cultivation history for the Ferrosols of northern Tasmania studied by Sparrow et al. (1999).

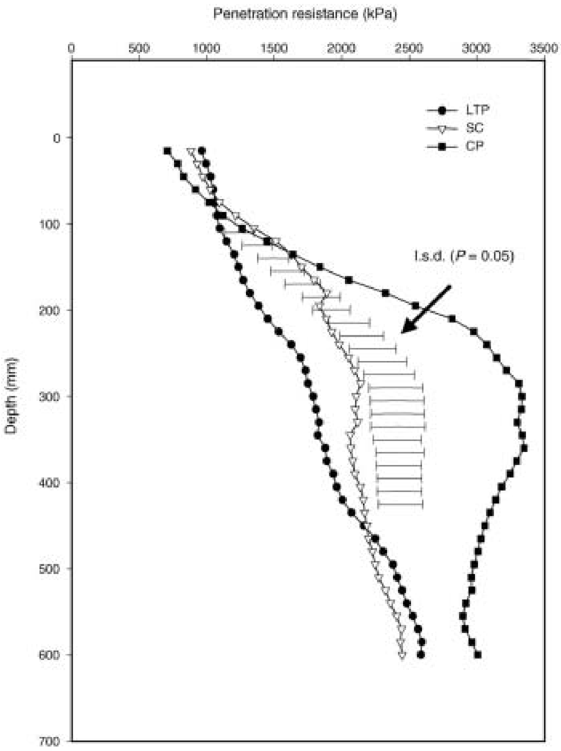


Figure 5: Contrasting soil strength profiles measured by Cotching et al. (2002) in several management systems for the Tenosols of northern Tasmania studied. The management systems were long-term pasture (LTP); cropping with shallow tillage (SC), and cropping with more rigorous and deeper tillage (CP).

Integrated monitoring

Simple, survey or proxy approaches are useful but they are generally unable, by themselves, to answer why changes are occurring. This requires a different strategy for gathering information. Integrated monitoring (Munn 1988; Vaughan et al. 2001) has an overall objective of recording and understanding changes in the total landscape. It aims to:

- Establish cause and effect;
- Derive scientifically defensible resource management or pollution control programs;
- Measure the environmental response to the management actions; and
- Provide early warning of emerging resource issues.

Integrated monitoring involves long-term interdisciplinary programs of study. It is often centred on a calibrated catchment where measurements aim to develop a detailed balance of the inputs and outputs (water, sediment, nutrients and contaminants) along with intensive biological monitoring of the terrestrial and aquatic components of the landscape. The monitoring is usually carried out in conjunction with research projects and some form of manipulation of sub-catchments is often undertaken (e.g. clearing, burning, different grazing regimes etc.). The success of various long-term integrated monitoring studies (e.g. Hubbard Brook, New Hampshire, United States (Bormann and Likens 1967; Likens and Borman 1995)) has led to the establishment of several networks of long-term ecological research sites in several countries (e.g. www.lternet.edu; Sykes and Lane1996; Vaughan et al. 2001). The utility of this approach and its feasibility in Australia will be considered in later sections.

Defining the purpose of monitoring

Virtually every text on monitoring emphasizes the need for developing clear objectives to guide measurement and data analysis. However, most evaluations of long-term monitoring programs and field experiments reveal that the majority of benefits were unforseen at the outset (e.g. Leigh and Johnston 1994). Defining the purpose of monitoring can be difficult because there is the need to incorporate flexibility so that the unexpected can be detected. Keeping this in mind, the following discussion on the purpose of monitoring will maintain the earlier distinction between programs that aim to provide information to reduce risk in decision-making, versus those that aim to improve process knowledge.

Reducing risk in decision-making

In Australia, soil-monitoring schemes have been proposed either formally or informally for a range of variables to determine:

- Trends in carbon sequestration under a range of land uses;
- Levels of soil acidification in key agricultural zones where impacts are anticipated on production and environmental quality;
- Water use efficiency under a range of farming systems;

- Nutrient leaching under different forms of land management;
- Watertables and salinity;
- Soil structure; and
- Soil erosion under a range of land management systems.

Monitoring systems are valuable when they provide either an early warning of change, or have a specific role in an environmental management system (e.g. indicating when a regulatory limit for pollution has been exceeded). Pannell and Glenn (2000) provide an excellent framework for evaluating whether a monitoring program will be of benefit for agricultural land management. The following draws heavily from their analysis and generalizes readily to natural resource management in its broadest sense.

Pannell and Glenn (2000) emphasize that *the value of a monitoring program depends entirely on whether it can change a decision maker's management choices*– the change in management, if it does occur, is the result of a reduction in uncertainty about the impacts of different management strategies. A range of related insights and principles follow from these observations.

- The range of land management options and perceptions of risk varies between farms and regions – the utility of monitoring will likewise vary considerably.
- The value of monitoring may reduce with time as uncertainty is reduced. In some instances, particularly when only a qualitative appreciation of a biophysical component of the system is required, a few measurements may suffice and further measurements will have limited value. For example, a land resource survey (i.e. measurement at one time only) may indicate that particular land management units are moderately acid – there may be sufficient knowledge to recommend an appropriate long-term liming strategy and further frequent monitoring (e.g. on an annual basis) may be deemed unnecessary. Such minimalist approaches are inevitably the result of sufficient knowledge and understanding, based on past long-term monitoring and research.
- The gross value of monitoring a particular variable will be zero if there is no realistic probability of a resulting change in management.
- The value of monitoring will be high if environmental or production outcomes are sensitive to management choices. This is often not the case for many agricultural systems and so the benefits of monitoring are relatively low. Conversely, if environmental or production outcomes are very sensitive to management choices, then the optimal choice may be so obvious that monitoring is redundant.
- The greater the current level of uncertainty about a variable, the greater is the value of monitoring, provided it leads to a reduction in uncertainty. For example, there are usually significant levels of uncertainty about the levels of soil contaminants in most regions (e.g. cadmium) but knowledge relating to other variables may be much better (e.g. average levels of organic matter under cropping systems relating to particular combinations of soil type and climate).

- Monitoring will be beneficial when there is a close relationship between the monitored variable and the payoff from different management options. For example, in many agricultural systems, there is a good relationship between nutrient levels, crop yield and, as a consequence, economic return. It is therefore worthwhile to monitor soil nutrient levels. The relationship between other soil properties and crop yield is more complex (e.g. bulk density, organic carbon) and monitoring of these may be less worthwhile.
- The greater the degree of uncertainty about the consequences of different management strategies, the lower will be the value of a related variable used for monitoring. For example, electrical conductivity of streams is often used to monitor the impact of dryland salinity. Widespread tree planting is commonly promoted as a management solution. However, there are several uncertainties about the consequences of tree planting on water quality (there may be a temporary increase in electrical conductivity), farm incomes and rural economies more generally. The uncertainties relating to the management strategies diminish the value of the monitoring program - we know there is a problem but are unsure how to respond. Complementary research is required to understand the influence of management.
- Unless management decisions are dichotomous, there is no sense in which a monitored variable has threshold level. There may be different optimal management strategies for the different levels of the monitored variable. Furthermore, the decision to switch between strategies will involve economic considerations so defining a threshold level for a variable based only biophysical criteria is pointless. The exception is where regulatory requirements dictate change at a particular level.

Pannell and Glenn (2000) used the principles outlined above to propose the following criteria for selecting variables for monitoring.

Selecting the region for monitoring

The region to be monitored must have:

- a resource management problem (see below) (essential);
- a high degree of threat to the resource within the region (desirable); and
- the problem occurring across large areas (desirable).

Selecting the site for monitoring

The sites or farms used for monitoring should:

- be representative of the region (see section on sampling below) and managed by a respected operator (desirable for extension purposes);
- have a resource management problem (see below) (essential);
- have a problem that threatens the resource to a high degree (desirable); and
- have contextual data available (essential).

Priority problems

- In at least some situations, it is worth changing management or policy to deal with the problem (essential).
- The payoff has some sensitivity to the management option so that land managers benefit from its adoption (essential).
- The payoff is not so sensitive to the management option that it is obvious whether the option should be adopted (essential).
- There is a high degree of threat to the resource (desirable) and it is extensive (desirable).

Selecting variables

- There is a high uncertainty about the magnitude and dynamics of the variable to be monitored (desirable).
- There is low uncertainty about links between the monitoring variable, management practices and system output (e.g. crop yield, water quality etc) (highly desirable).
- The variable can be measured reliably and accurately (desirable).
- The cost of measuring the variable at the requisite monitoring sites is low (desirable).

Improving process understanding

The previous section focussed on the direct provision of information for decision-making and the rationale was completely utilitarian. An equally important aspect of monitoring is the role it plays in improving our understanding of biophysical processes – if necessary, this endeavour can also be justified successfully on utilitarian grounds because it provides essential knowledge for natural resource management. However, links between the acquisition of knowledge (e.g. through fundamental science in a range of seemingly disparate disciplines) and its application may be complex and unpredictable. Most monitoring systems in Australia that aim to improve process understanding are operated by research and development organizations or natural resource management agencies.

As noted earlier, various approaches to monitoring (simple, survey, proxy and integrated), when combined with experimental science, have yielded many of our fundamental insights into the behaviour of natural systems. Defining the purpose for new monitoring activities that aim to improve process understanding requires an appreciation of weaknesses in our current understanding of Australian ecosystems. Richter and Markewitz (2001) put forward the following reasons why our current understanding of soil and ecosystem change is inadequate.

- Nearly all long-term soil-ecosystem studies are confined to agricultural systems.
- Nearly all long-term soil-ecosystem studies are conducted on relatively fertile soils.
- Many long-term monitoring sites lack appropriate experimental design.

- Long-term agricultural studies focus on mainly on yield response or soil change rather than on the processes that affect the soil and plant response.
- Most long-term ecological studies are focussed on a relatively narrow set of natural science issues that involve current land management regimes and ecological processes.

Long-term integrated monitoring studies, particularly those that adopt a catchment-ecosystem approach can address the issues raised by Richter and Markewitz (2001) and at the same time address many contemporary natural resource management challenges. Likens (2001) observes these studies have value because they:

- Address scientific and environmental questions at scales that are realistic and applicable to management;
- Quantify connections between landscapes and the larger biogeochemical cycles for a region or the Earth or both (they connect inputs and outputs, for example, the pathway of industrial emissions can be traced quantitatively including deposition on the land, potential transformation, and eventual transport via groundwater and streams);
- Quantify the coupling of streamflow measurements with determinations of streamwater chemistry and sediment loads to evaluate changes in water quality;
- Evaluate net change (accumulation or loss) of nutrients or other materials (including the estimation of weathering rates and gaseous flux) and allow integration over large areas.
- Provide baselines for evaluating environmental change (e.g. global warming, El Niño and ecosystems services);
- Test ecological and environmental questions experimentally including nutrient limitations, ecosystem function (e.g. nitrogen dynamics, organic matter), and response to disturbance (e.g. various agricultural practices, fire, erosion, acidification, pesticides and other toxic substances).

These benefits are based on experience in the Hubbard Brook Ecosystem Study (Likens and Bormann 1995) started in 1963. It is part of the Long-Term Ecological Research (LTER) Network in the United States (www.lternet.edu) that has various aims including:

- Understanding ecological phenomena over long temporal and large spatial scales;
- Creating a legacy of well-designed and documented long-term experiments and observations for future generations;
- Conducting major synthetic and theoretical efforts; and
- Providing information for the identification and solution of ecological problems.

The LTER Network is committed to long-term ecological research on the following core areas:

- Pattern and control of primary production;

- Spatial and temporal distribution of populations selected to represent trophic structures;
- Pattern and control of organic matter accumulation and decomposition in surface layers and sediments;
- Patterns of inorganic inputs and movements of nutrients through soils, groundwater and surface waters; and
- Patterns and frequency of disturbances.

Current status of soil monitoring in Australia

Apart from soil monitoring to directly support agriculture (see Chapter 5 in NLWRA 2001), activities in recent decades have been ad hoc and limited in scope. While there have been some very useful examples of survey monitoring (see above), there are few, if any, instances of coordinated programs where monitoring is closely linked to natural resource management.

Summary

Defining the purpose of monitoring is critical. A major challenge is establishing genuine links between the provision of data and decision-making. This is difficult to achieve even when the agency commissioning the monitoring program is also the decision maker. Effective natural resource management also requires a sound understanding of biophysical processes. Long-term integrated monitoring is an essential component of any strategy for obtaining this information base. Limited attention has been given to the establishment, coordination and maintenance of such activities in Australia – although there has been some notable progress in relation to forest management (e.g. House and Simpson 1998). The Long Term Ecological Research Network provides an appropriate model that can be adapted to Australian conditions and institutional capacities, particularly given the needs of major natural resource management programs (e.g. Greenhouse policy, Natural Heritage Trust, National Action Plan for Salinity and Water Quality, State of the Environment reporting). General strategies for monitoring are provided in later sections.

4 System understanding

Conceptual framework

A conceptual model of how biophysical systems operate is essential for devising a monitoring system whatever its purpose and design. The purpose may be to support decision-making or to increase system understanding, and the design may range from simple monitoring of a local landscape with community participation, through to integrated monitoring involving inter-disciplinary research teams.

Landscapes have a range of properties that need to be considered in relation to monitoring (Boyle et al. 2001).

- The behaviour of many landscapes is influenced by positive and negative feedback loops. Explanations of behaviour in terms of simple linear causal mechanisms in such systems will often fail. Their non-linear nature means that monitoring individual components separately (e.g. only soil and not vegetation and hydrology) will be insufficient for an understanding of whole system behaviour.
- Landscapes are comprised of hierarchies of processes. The level or entity selected for study (e.g. monitoring site) usually relates to a scale of observation where the entity appears most cohesive, explicable and predictable, although entities often tend to match human scales of unaided perception (e.g. we describe soil profiles in pits rather than much larger volumes of soil that may be more relevant to land management). Allen and Hoekstra (1992) recognize that at some scales of perception, phenomena become simpler than at others. They also recognize that developing a capacity for prediction requires consideration of the scale in question, the more detailed scale below to provide insights into mechanisms (e.g. measurements in the field), and the more general scale above to provide context and signficance (e.g. catchment studies). As a consequence, monitoring should be undertaken with an awareness of these levels and every attempt should be made to measure at scales where the signal to noise ratio allows the ready detection of trends.
- Some landscapes may have multiple steady states and exhibit sudden and unpredictable behaviours. These include:
  - birfurcations (where system development may proceed in either of two divergent directions);
  - flips (involving sudden discontinuities and rapid change); or
  - ongoing processes of birth, growth, death and renewal.

  Simple, survey or proxy monitoring will often be of limited value in these circumstances because they do not yield information on the underlying bio-physical processes or triggers of change.

- Some processes within landscapes may also exhibit chaotic behaviour and have limited predictability regardless of the level of information and modelling capability.

Illustrations of ecosystem behaviour and soil change

The following examples illustrate various aspects of ecosystem behaviour and soil change over a wide range of time scales (Figure 6). Each pattern of change requires an appropriate strategy for monitoring if some capacity for forecasting is required. In some cases, soil monitoring may not be feasible or even necessary.

Example 1: Soil acidification – unexpected slow process

Rates of soil acidification are generally faster under agriculture systems of land use compared to natural systems. Substantial improvements in productivity over large areas were caused by the widespread adoption of legume-based pastures, at first in southern, and then further north. However, limited awareness of the need to apply lime to counteract the acidifying effect of the new pastures and other processes (e.g. acidification caused by ammonium fertilisers, addition of organic acids, removal of alkalinity in crop and livestock products) has caused very large areas to become acid. The process has been slow (i.e. decades) and the initial symptoms are subtle. There is now a very large lime deficit in Australia's farm systems and the affects on productivity are substantial and predicted to worsen (NLWRA 2001).

Rates of soil acidification depend on many factors including the buffering capacity of the soil. Reversal of the acidification process, at least in the early phases is straightforward (through the addition of lime). With time, subsoils become acidified and remediation is difficult. There are also several potential off-site impacts from soil acidification (e.g. erosion, increased recharge and dryland salinity; acidification of waterways) – there is no guarantee that these off-site processes will be gradual and as easily remedied as the early phases of on-site acidification.

Monitoring soil acidification is more tractable than other soil processes. It can be measured cheaply but rates of change tend to be slow.

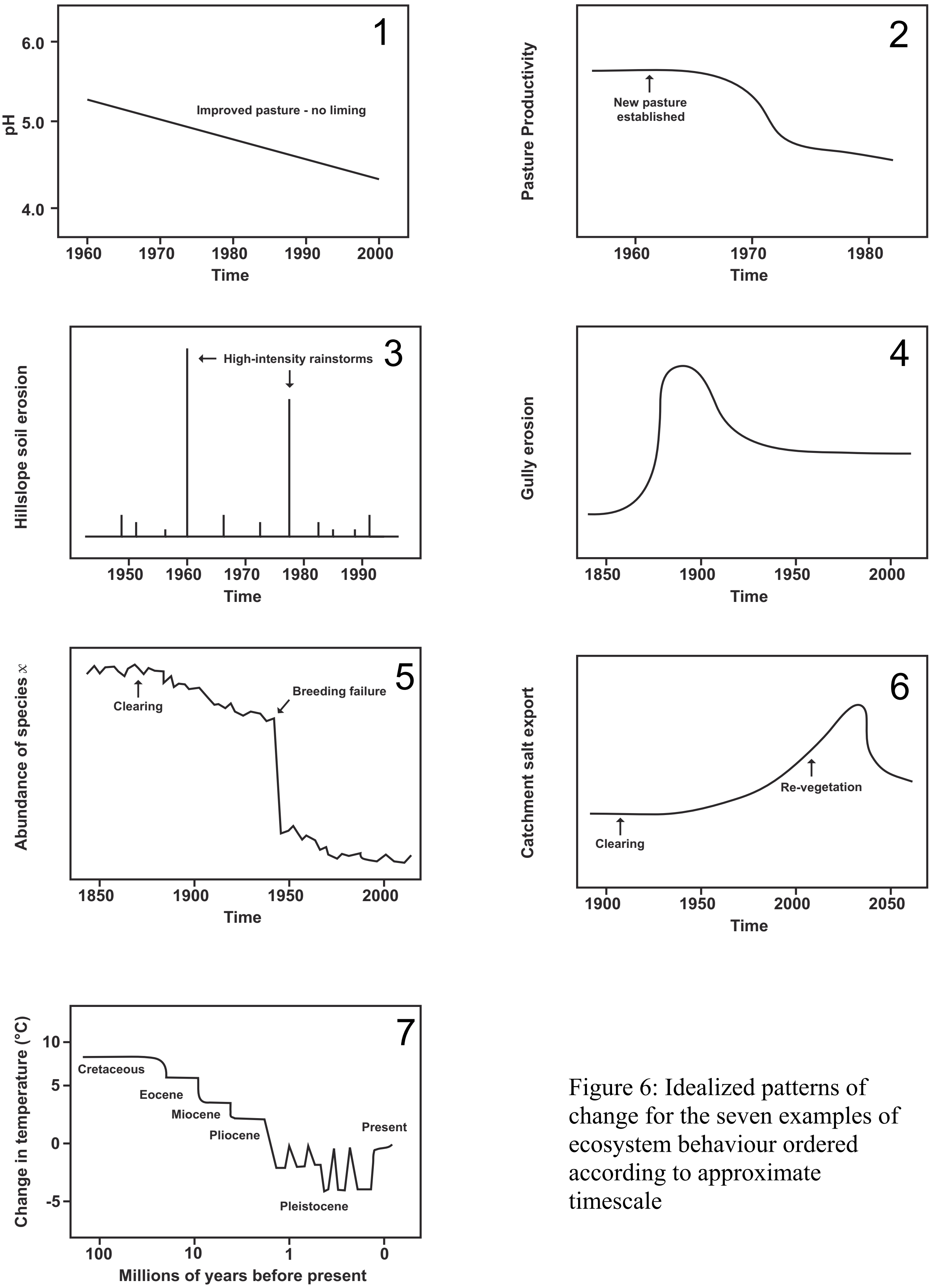


Figure 6: Idealized patterns of change for the seven examples of ecosystem behaviour ordered according to approximate timescale

Example 2: Pasture composition and production – climate sequences and time delays

There are many interactions over time between pasture growth, climate and soil. Jones et al. (1995) provide an excellent review of long-term grazing trials in subtropical and tropical Queensland. Important changes in botanical composition occurred after many years and these sometimes affected animal production. The reasons for delays in botanical change included the following.

- A gradual change in soil nutrient status associated with species change (e.g. increased nitrogen associated with the introduction of legumes) or grazing (declining nutrient reserves due to export from the system) (see Figure 7).
- Underlying plant demographic factors were related to the pattern of rainfall events. Patterns necessary for the recruitment of some species may recur once every few decades (e.g. successive years with above average rainfall followed by periods without significant water-stress).
- Rare events can cause widespread mortality (e.g. water-logging). The response to grazing may be slow and the grazing system may take years to equilibrate.
- Long-term monitoring is essential in grazing systems because of the feedbacks between soil processes and pasture growth. Responses to change, either in soil properties or botanical composition, make take decades to manifest.

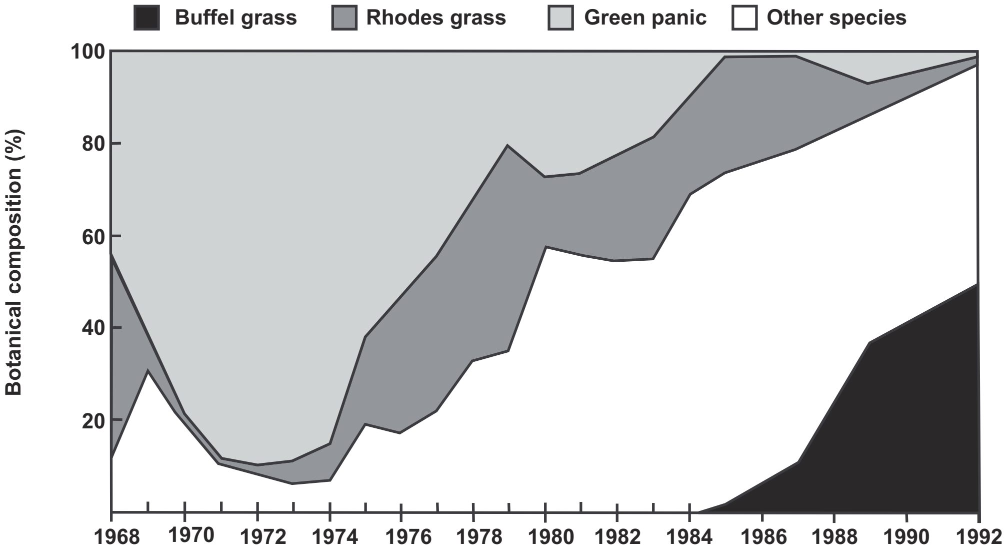


Figure 7: Changes in botanical composition (1969-92) of a pasture sown to green panic and Rhodes grass into a fertile clay soil in 1968 in near-coastal subtropical Queensland (after Jones et al. 1995).

Example 3: Erosion – extreme events

Soil erosion is a serious land management problem in many parts of Australia. Monitoring soil erosion and sediment transport is an expensive and technically demanding activity. A characteristic of soil erosion is its episodic nature. For example, over 50% of the erosion observed at two experimental sites on the Darling Downs over a period of 6-8 years was due to only two storms (Freebairn and Wockner 1986b). Likewise, large quantities of soil loss were associated with a single rare event at Cowra in southern New South Wales – a temperate area that is less well known for high intensity rainfall and destructive erosion events (Hairsine et al. 1993). Rare and extreme events are not often well recorded but their impact may completely dominate the historic record.

Establishing monitoring sites may not be the most efficient method for determining the impact of extreme events. Instead, developing a capacity to accurately model erosion and deposition may be far more useful. Field monitoring will still be needed but the focus is on model testing and obtaining reliable estimates of key parameters over a range of conditions. This approach was used to develop the well-known Universal Soil Loss Equation. A similar effort is needed to support a new generation of improved erosion models.

Example 4: Gully erosion – system flips

In southeastern Australia, a major episode of gully erosion started during the period of rapid agricultural expansion during the late 1800s (Prosser et al. 1994; Prosser and Winchester 1996; Scott 2001). Rapid gully extension occurred into the early 1900s and by the 1940s, many of the gully networks had reached their present extent (although sediment yields from the gully networks remain a problem to this day and new gully systems still form). Many of these gullies are large (often 10 m deep) and enormous quantities of sediment have been mobilized. Large slugs of sediment from the initial period of instability associated with clearing are still working their way down major river systems.

Historical evidence and the preservation of a few relatively intact landscapes reveals that the landscape prior to gully erosion was characterized by alluvial flats with a dense cover of tussock grass and sedge. These swampy meadows (chain of ponds) were dominated by Hydrosols and at the time of European arrival, basins up to at least 40 km^2 existed without incised channels. Many of these areas now have deep gullies - local hydrology and soils have been dramatically altered. However, the patterns of buried soils and sediments in these areas indicate that such processes have occurred before.

At various times during the last 10,000 years, individual episodes of gully erosion occurred. Evidence suggests that the primary trigger was disturbance of vegetation (e.g. by fire) – this led to the threshold for incision being exceeded with subsequent massive and episodic gully erosion.

The disturbance caused by European agricultural led to a widespread and broadly synchronized phase of gully erosion – the system flipped into a new equilibrium. However, dating of sediments has shown that pre-European phases of gully erosion were not strongly synchronized - instability appears to be triggered as much by internal factors (e.g. accumulation of an excessive quantity of sediment in valley floors) and thresholds to stability being exceeded at different times locally rather than regionally.

The environmental history of gully erosion suggests that the major phase of change caused by European land use has already occurred. Monitoring efforts need to be adjusted accordingly (e.g. focussing on the continuing impact of sediment down river systems rather than on soil erosion per se).

Example 5: Populations – stress and collapse

Clearing and the resulting fragmentation of habitat over large parts of Australia devastated the populations of many organisms. The impact of habitat fragmentation has been documented for a restricted number of readily observed species (e.g. Saunders et al. 1991). After initial disturbance, it is not unusual for populations to survive under stress for a period and then eventually collapse in numbers. Patterns of change in less readily observed soil organisms are poorly documented, let alone understood, although the change associated with the conversion to agriculture has been undoubtedly profound for many tens of thousands of species. Soil organisms provide a wealth of ecosystem services (e.g. nutrient cycling, disease suppression, water filtration). As a minimum, carefully designed programs of survey monitoring are required to better document the magnitude and nature of change in populations of soil organisms.

Example 6: Hydrologic response to revegetation - hysteresis

Two of the most serious problems associated with the widespread clearing of deep-rooted perennials in Australia are rising groundwater and dryland salinity. This large perturbation to the hydrologic regime is causing a cascade of effects including changes in soil-water and salt balances. A widely favoured remedial measure is replanting with deep-rooted perennials to confer conservation and production benefits. However, there is a suggestion that revegetation will in the short-term cause stream salinity to increase because of the reduction in fresh water entering the stream system. In the longer term, groundwater levels will decline and their contribution to stream salinity will reduce, so concentrations will re-equilibrate at lower levels (Dawes et al. 2001). This type of possible behaviour is an example of hysteresis – the effect of the perturbation, in this case clearing and subsequent revegetation, does not lead to a simple reversal of response by the natural system. While monitoring of soil change (e.g. soil-water regime, salt storage within the profile) may be useful, a good understanding of system processes at a range of space and time scales is necessary to provide good advice for natural resource management.

Example 7: Global climate – positive and negative feedbacks

Soil properties respond to changes in climate and weather over a wide range of time scales—hours, days, seasons, decades, centuries and millennia— and a large proportion of Australia's soils bear the imprint of past climates that differ to those of today. Some soil processes also provide feedbacks to the climate system (e.g. carbon and water fluxes). The factors controlling climate variation provide an excellent demonstration of the complex behaviour generated by positive and negative feedbacks.

A reconstruction of global surface temperatures during the last 100 million years is presented in Figure 6(7) (after Crowley 1990). For most of the time leading up to 2 million years ago, the temperature exceeded that of today. During this period, and particularly from 150 to 50 million years ago, there is little evidence for continental scale ice sheets. Various lines of evidence also indicate that the atmosphere at this time had a much higher level of carbon dioxide. Several mechanisms triggered a series of cooling events during the Tertiary period. Significant amongst these are the major changes to ocean currents associated with plate tectonics (e.g. the drift northwards of Australia led to the establishment of the Antarctic circumpolar current and this reduced the movement of warmer waters towards Antarctica and triggered cooling).

The cooling through the Tertiary gave way to the dramatic oscillations of global climate throughout the Quaternary period (Figure 8). This resulted in some new sets of soil processes (e.g. widespread additions of dust) and changes in rates for others. The broad mechanisms of change are reasonably well understood (see Williams et al. 1998). The regularity of the oscillations is associated with variations in the earth's orbit. The global climate system during the late Cretaceous and Tertiary appears to have been buffered against these orbital variations but cooling events of the Tertiary apparently led to a less buffered and more unstable system. However, the orbital variations alone are an insufficient explanation for the increasing oscillations of climate that reached their greatest magnitude during the Pleistocene.

There appears to be a complex set of positive feedbacks so that relatively small changes in solar radiation caused by orbital variations triggered much larger effects (e.g. disruptions to ocean currents, changes in albedo). Some of these events appear to have caused major changes in global climate over remarkably short periods (i.e. decades). The sensitivity of the global temperature system to feedback is one reason why predicting the impact of increased atmospheric CO_2 is such a difficult task. There are many other examples of positive and negative feedbacks in ecosystems but their effects pale against those of global climate change.

Two things emerge from a consideration of soil change over thousands of years or longer.

- Soil change is intimately bound with regional and global processes affecting geology and climate – the interactions are complex and profoundly significant for landscape evolution. Knowledge relating to these processes is essential for models that underlie land resource survey, salinity management and mineral exploration to mention a few.
- Monitoring of some contemporary processes (e.g. soil turnover by organisms) may provide some insight into factors that have formed soils, but in general, many processes have either ceased to operate at the rates they once did, or they occur at such slow rates that monitoring is not feasible.

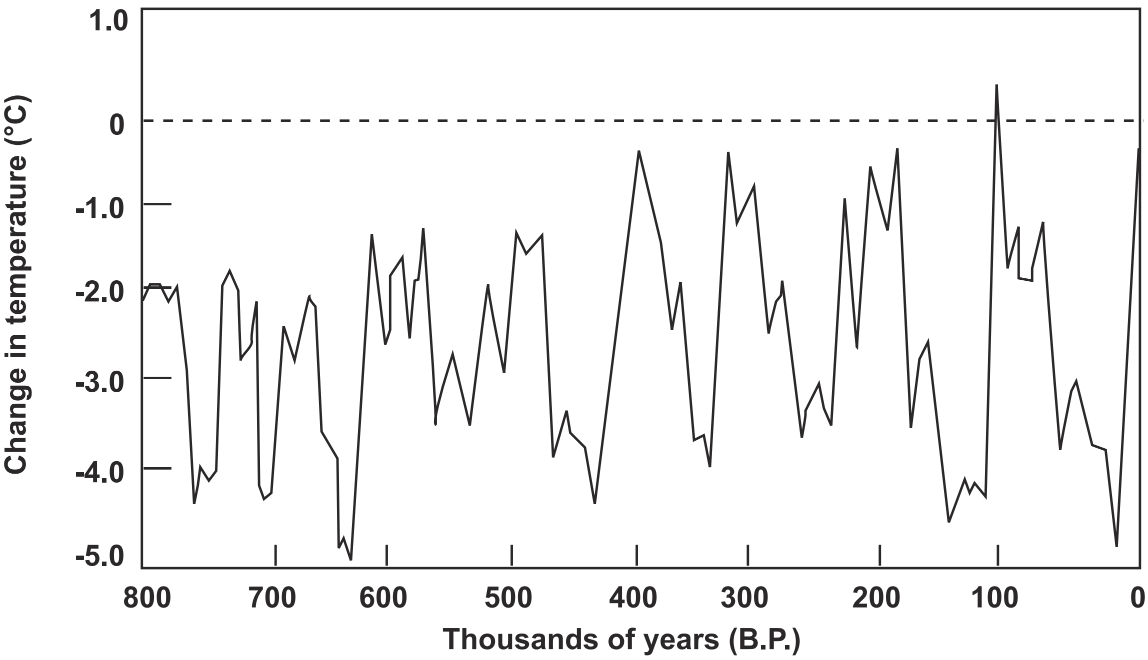


Figure 8: Estimate of surface temperature compared to the present for the last 800,000 years, inferred from oxygen isotope ratios in fossil plankton that settled to the sea floor (after Imbrie et al. 1984).

Implications for monitoring

The different forms of system behaviour listed above present many challenges to natural resource scientists seeking to provide useful information to decision makers. In some cases, cause and effect are straightforward, and the variables to monitor are self-evident. For example, the early stages of soil acidification in a district can be monitored using a set of statistically located sites for pH measurement along with information on land management at each site. The resulting information may provide direct practical benefit to land holders because they can then apply appropriate quantities of lime to ameliorate the problem. The monitoring results from the England and Wales Representative Soil Sampling Scheme presented in Figure 3 are an illustration of such monitoring.

In other instances, a much broader ecosystem-view may be required. For illustration, we can continue with a hypothetical scenario involving acidification. Soil acidification may become more severe in a district, with a subsequent cascade of effects. For example, pasture production and evapotranspiration may decline with subsequent rises in groundwater leading to water logging and possibly dryland salinity. Farm income then declines, private resources for amelioration are not available, and the problem worsens. The availability of nutrients in soil changes, and variations in stream water chemistry may be deleterious for particular groups of organisms. Changes in ecosystem structure and function within the pasture, riparian vegetation and freshwater systems may be sudden and unpredictable as thresholds are passed. In this case, a monitoring system restricted to soil pH measurement in farmer’s paddocks supported by land use history will be completely inadequate–other components of the system must be monitored and the effort devoted to each will depend on the broader system understanding. It is conceivable that different components of the ecosystem could exhibit all of the behaviours shown in Figure 6.

It has been traditional for scientists trained in the reductionist mode to restrict their activities to investigations of relatively simple systems where cause and effect can be isolated and understood. Most systems for monitoring, with the exception of some examples of integrated monitoring, are of this kind.

The examples of system behaviour presented above are not of restricted theoretical interest, they relate to major natural resource management problems facing Australia, and most exhibit elements of behaviour typical of complex systems (i.e. system flips, bifurcations, hysteresis, episodic perturbation, unpredictability). Monitoring schemes must therefore be framed with system understanding forming the basis for design.

5 Sampling

The following sections focus on soil monitoring but this in no way implies that other components of the landscape are less important. It will be assumed that there is sufficient system understanding—both social and biophysical—to justify soil monitoring. This is a major assumption that requires careful consideration.

Soil properties vary at different scales in both space and time. Unfortunately, only a few soil properties can be measured directly using remote sensing (e.g. mineralogy of near surface layers can be inferred from gamma ray spectrometry and spectral signatures). Likewise, only a few soil properties can be routinely monitored *in situ* (e.g. soil water content and some aspects of solution chemistry), although this is changing with the development of new sensors. Most measurement involves collection from the field of specimens that are modified or destroyed during laboratory measurement. Our knowledge relating to the dynamics of most soil variables is derived from observations at discrete field locations. Any conclusions relating to spatial or temporal patterns of change are therefore based on a sample and there is incomplete knowledge of the system (we cannot measure everywhere and at all times). Inferences must be set against ever-present natural variation. The detection of patterns of change, as distinct from natural variation, is a practical concern and an issue that must be addressed during the design phase of a monitoring program. Appropriate statistical theory and good practice will amongst other things:

- Contribute to ensuring that the information gathered is scientifically defensible and collected in a cost-effective way;
- Provide an assessment of uncertainty for the estimates coming from monitoring programs. This is an essential element in determining the usefulness of information for policy (Olsen et al. 1999).

Programs of monitoring that do not have a sound statistical foundation will be at best flawed, and at worst, erroneous and a complete waste of resources. Good science and statistical analysis form the basis for policies that can be expected to have stronger support across sectors.

Scales of variation

Soils vary vertically and horizontally as well as temporally. A large emphasis has been placed on the variation of soil properties in vertical sections (soil profiles) - substantial databases and classification systems capture the great range of soil conditions found across Australia (e.g. Isbell 1996). There has also been a major effort to characterize the horizontal variation of soil properties in the various soil and land resource mapping programs. Virtually all the characterization of this horizontal or spatial variability has been qualitative and focussed on the morphological properties of soil with less attention being given to chemical and physical properties, and virtually no characterization of soil biology.

Most survey programs have assumed that readily observed soil morphological properties used for field mapping are well correlated with more difficult to measure chemical and physical properties. While there is a degree of correlation between soil properties, the substantial literature on spatial variability (e.g. Beckett and Webster, 1971; Wilding and Drees, 1983; Burrough, 1993) demonstrates that soil properties have varying levels of covariance. Furthermore, the proportion of variance in a particular attribute accounted for by a land resource map can be very low (e.g. <50% and often <30%).

Of great importance to monitoring is the inescapable reality that a large proportion of soil variation occurs over surprisingly short distances. Beckett and Webster (1971), in their landmark review, concluded: "up to half the variance within a field may already be present within any m^2 in it." Table 2 gives an indication of the magnitude for several soil properties. The diagrams in Figure 9 show the scale and magnitude of variation for soil properties from a number of studies. The diagrams show the amount of variation encountered with increasing distance for four soil properties (pH, organic carbon, nitrate and phosphorus). The curves for each soil property come from different locations. Curves that intersect the y-axis near zero do not vary substantially at very short distances. If the curve reaches a low plateau with increasing distance, then variability is less than those with a high plateau. The curves in Figure 9 have only been plotted to distances (lags) of 500 m. However, if more data were available for longer lags (e.g. kilometres to several hundred kilometres), then there would be a series of steps or possibly a continual increase in variation with distance. The key features of Figure 9 are:

- The same soil property can have contrasting degrees and scales of variation in different locations.
- The pattern and magnitude of variation differs between soil properties.
- The proportion of soil variation occurring over short distances can be a large component of the total variation encountered.

This large short-range spatial variability of most soil properties has several major implications for monitoring:

- Most measurements of soil properties involve the collection of a specimen – sampling is destructive and subsequent measurements are undertaken on separate specimens. Short-range spatial variability in soil properties is problematic because spatial and temporal patterns can be easily confounded unless there is careful sampling and sufficient replication.
- The large magnitude of variability in most soil properties implies that a proportionally large effort in replication is necessary to detect trends – the signal to noise ratio is typically low.

Table 2: Variability of soil properties that occur in landscape units of a few hectares or less (Wilding and Drees 1981).

Variability of property	Number of profiles needed*	Property
Least (Coefficient of Variation <15%)	>10	Soil colour (hue & value) Soil pH Thickness of A horizon Total silt content Plasticity limit
Moderate (Coefficient of Variation 15-35%)	>10-25	Total sand content Total clay content Cation exchange capacity Base saturation Soil structure (grade & class) Liquid limit Depth to minimum pH Calcium carbonate equivalent
Most (Coefficient of Variation >35%)	>25	B2 horizon and solum thickness Soil colour (chroma) Depth to mottling Depth of leaching (carbonates) Exchangeable hydrogen, calcium, magnesium, & potassium Fine-clay content Organic matter content Plasticity index Soluble salt content Hydraulic conductivity

* Employing 95% confidence interval and a limit of accuracy ±10% of mean.

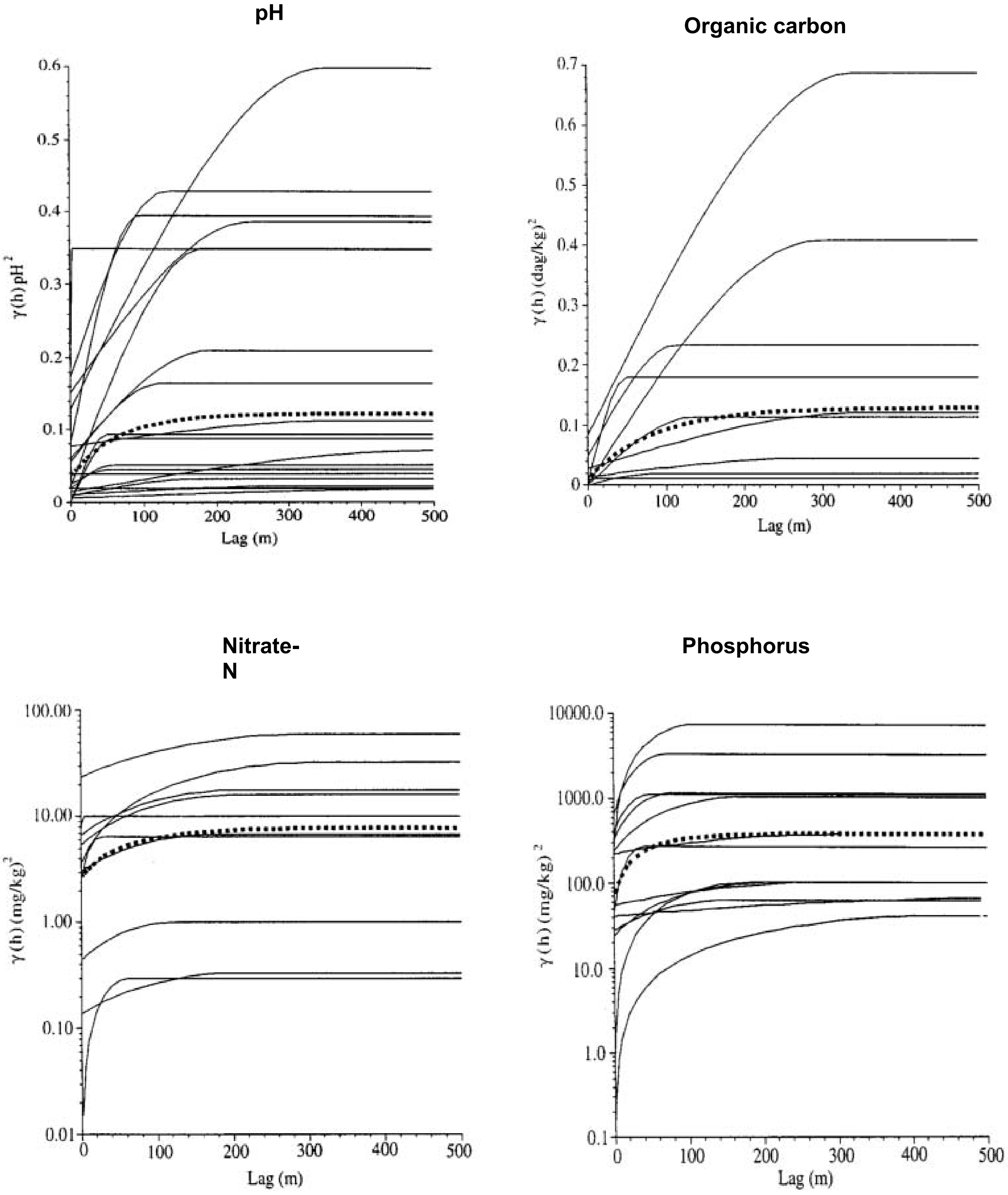


Figure 9: Variograms of pH, carbon content (dag/kg), nitrate nitrogen (mg/kg) and phosphorus for surface horizons from a large number of studies compiled by McBratney and Pringle (1999) – the average is the dotted line. Consult McBratney and Pringle for data sources and averaging method.

Defining the target population and individual

Devising a statistical framework for monitoring involves many considerations and statisticians should be involved in studies from the outset. The following discussion is restricted to general issues of statistical design and it is relevant to soil monitoring regardless of the geographic extent (e.g. paddock, experimental catchment, regional network of sites or continental scale). After clarifying the objectives of monitoring (see above), definitions of the target population and soil individual are required.

Target and sampled population

The *scope of inference* of a monitoring program refers to the domain over which the results are to apply. It may be defined in purely geographical terms (e.g. local region, state or continent) or use other criteria (e.g. rainforest, cropping lands, public lands etc.). The *target population* refers to the aggregate of units that make up the scope inference. For example, if the scope of inference is Australia's cropping land then the target population may be defined as all fields used for cropping in a specified year. In contrast, the *sampled population* is the aggregate of units from which a *sample* or subset of units is selected for inclusion in the study (Cochran 1977, Olsen et al. 1999).

Ideally the target and sampled populations coincide so that statistical methods can be used to make inferences about the target population on the basis of the sample. This is not as simple as it seems. For example, the criteria used for defining cropping lands at the start of a monitoring program may become inappropriate if cropping practices change significantly during the study. By way of illustration, new cultivars may allow crops to be grown on more acid soils than before. If sampling is undertaken on land cropped in each successive year, trends in acidity may reflect this transition rather than an actual change in soil condition for the target population.

The study will not meet its objectives when the sampled population is quite different from the desired target population. This creates problems for land resource survey as well as for monitoring. For example, unbiased estimation of regional baselines for soil carbon and pH across agricultural areas using land resource survey data has not been easy because some survey agencies in Australia preferentially sample roadside reserves to maximize the number of sites observed because field time is limited – the target population is the land used for agriculture (predominantly paddocks used for cropping and grazing). Unfortunately, roadside reserves, rather than paddocks alone, constitute a significant proportion of the sampled population. Biased estimates are a result because sites in reserves usually have more organic matter and contrasting pH compared to the paddocks used for cropping and grazing.

The soil to be sampled

The value of a set of measurements depends on effective sampling. Every sample should represent a defined body or class of soil. The body or class is most commonly a morphologically defined soil horizon or stratigraphic layer with clearly defined dimensions. In soil nutrient testing for agriculture, the management unit (usually a paddock but sometimes a subdivision based loosely on soil type) is often used with an arbitrary depth (usually 0.10 m, but deeper sampling for nitrogen is becoming more common).

Soil measurements will have long-term value if they have an associated site and profile description that conforms to standards defined in the Australian Soil and Land Survey Field Handbook (McDonald et al. 1990). Standards allow for consistent data and enhance the capacity of large databases to provide useful information at landscape, regional and continental scales. The profile information provides a basis for extrapolation and assists in interpretation (see Measurement below).

The soil individual and geo-referencing

The soil unit or individual to be characterised requires specification beyond that provided by standard site and profile descriptions (e.g. McDonald et al. 1990). In particular, the lateral dimensions of the soil individual of interest should be clearly defined, and for statistical purposes should be kept constant in any quantitative investigation.

Dimensions

Most soil measurements involve the extraction of a specimen from a larger body of soil. The dimensions of the larger body, or soil individual, are determined primarily by the purpose of the investigation and logistic constraints. In Australia, the concept of a soil individual has been implicit in the site concept defined by Speight and McDonald (1990) as follows:

> “A site is a small area of land considered to be representative of the landform, vegetation, land surface and other land features associated with the soil observation.”

The extent of a site is arbitrary, but Speight and McDonald (1990) recommend dimensions for observing attributes, and these are summarised in Table 3. The existing definition of the site is flexible and has proven useful in conventional land resource survey – similar sized units are also used for monitoring programs (e.g. Sykes and Lane 1996). However, geo-referencing and the dimensions of the soil individual have to be more systematically specified than in Table 3 if they are to be useful for spatial modelling and monitoring. This is addressed in the next section.

Table 3. The site concept in McDonald et al. (1990) varies according to the attribute measured.

Attribute	Site Dimensions	Site Area
Landform Element	Circle 20 m radius	1256 m^2
Vegetation	Square or rectangle	≥ 400 m^2
Erosion	Circle 20 m radius	1256 m^2
Other landsurface attributes eg. micro-relief, disturbance, coarse fragments, rock outcrop	Circle 10 m radius	314 m^2

A sampling frame (i.e. the basic unit of study) must be defined so that the probability of any location being selected can be specified prior to fieldwork – this is known as the *inclusion probability*. For example, in simple random sampling, every location has an equal inclusion probability while in stratified random sampling there may be preferential sampling of some strata depending on the study purpose. The inclusion probabilities will therefore differ between strata but remain known. These principles apply to sampling within the soil individual and likewise at the regional level. Accurate location is essential in soil monitoring so that subsequent sampling is not undertaken on areas used previously. Accurate location also assists analyses where spatial registration with other data is required (e.g. digital elevation models, remotely sensed imagery). Real-time digital differential global positioning (RTDGPS) allows field location with sub-metre accuracy.

Area of the soil individual

Unless there are strong reasons to the contrary (e.g. paddock scale nutrient testing), we recommend the soil individual as having an area 25 m × 25 m square that conforms to the Australian Map Grid. In landscapes with sharp boundaries, the 25 m × 25 m individual may be subdivided into 5 × 5 m cells to improve resolution, or even 1 m × 1 m. Such subdivision, or stratification, will also be required when there are local patterns of soil variation. The concept of the soil individual is illustrated in Figure 10. It is better to err towards large areas to leave plenty of space for later measurements.

It is recommended that sampling points and any relevant site boundaries be located to within 0.1 m, of their true position. This can be achieved using Differential Global Positioning System (DGPS). In some circumstances (e.g. remote areas), a local benchmark may have to be used for the DGPS base station and locations will only have the required relative accuracy. The required absolute accuracy will only be achieved when the local benchmark is tied to the standard topographic survey (geodetic) framework. The local benchmark must therefore be clearly identified so that it can be located at a later date. If DGPS is not an option, the site should be permanently marked. The procedures used to mark and locate the Rothamsted long-term experiments are worth emulating (see Leigh et al. 1994). They involve a system of posts along fences (used for triangulation) and sunken pegs (below the plough layer) at accurately determined distances from the fences. The records relating to the site should be stored in at least two locations (Likens 2001).

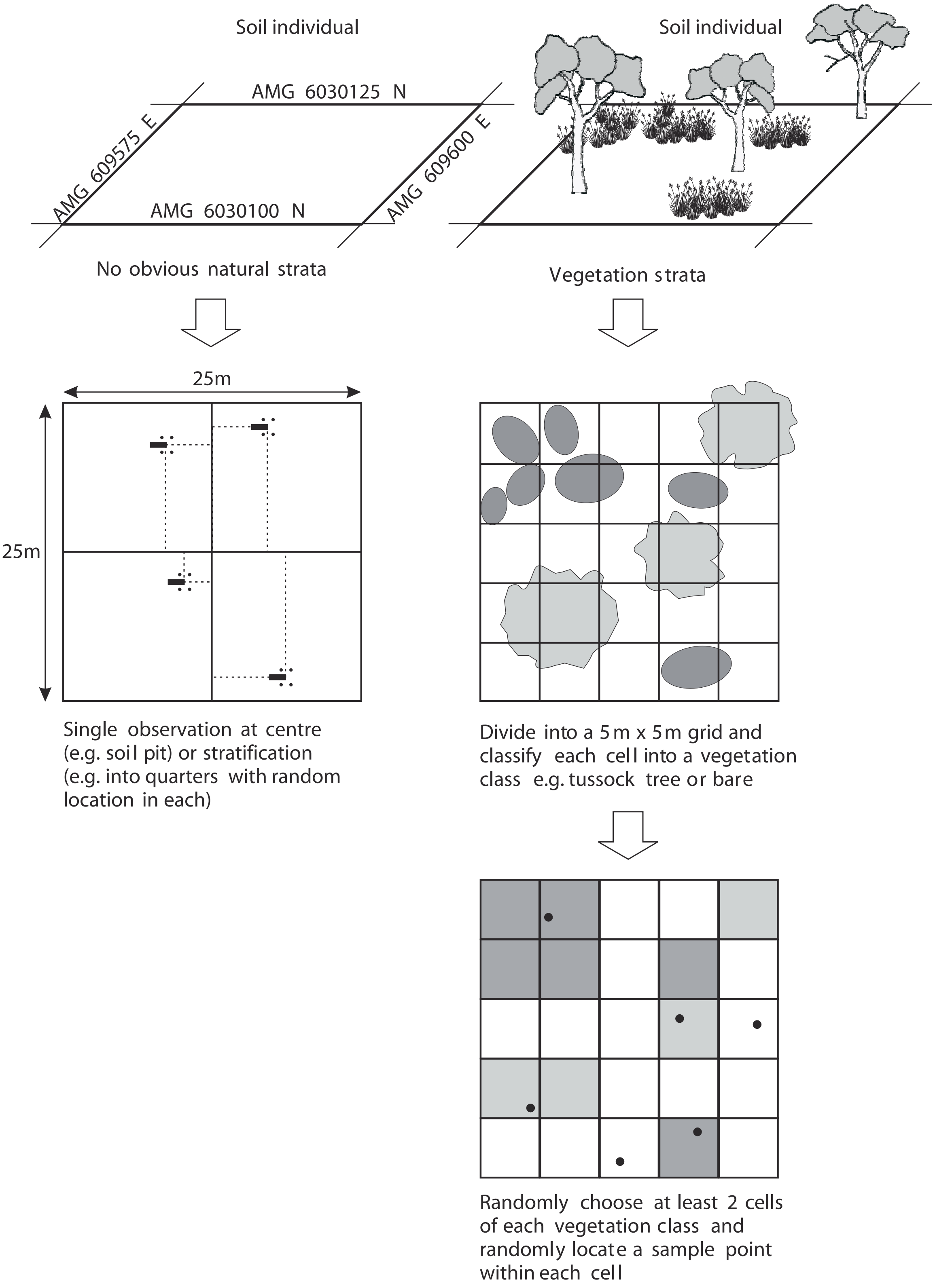


Figure 10: Concept of the soil individual and stratified random sampling using different criteria for stratification (criteria may also include microtopography or rock outcrop).

The selection of 25 m × 25 m is arbitrary and for the following reasons:

- it is equivalent to plot sizes used for soil monitoring networks internationally (e.g. Sykes and Lane 1996);
- it corresponds to a soil volume near the upper limit exploited by mature trees;
- it encompasses commonly repetitive scales of variation in soil (though some large gilgai may have longer length scales);
- current global positioning technology can be used to locate the boundaries of the soil individual with sufficient accuracy;
- it is broadly consistent with the resolution of current technology used for spatial extrapolation (e.g. digital elevation models with this resolution can be generated for many parts of the country); and
- it demands consideration of larger volumes of soil than has been the case in most soil investigations where short-range variability is usually an issue.

Conformity to the Australian Map Grid ensures that soil individuals are contiguous and do not overlap. While some other shapes have some small advantages (eg. circles, triangles and hexagons), squares are easy to lay out in the field.

The volume of the soil individual is large as specified above, and few measurement technologies can integrate at this scale. Replicated sampling within the soil individual and estimation of relevant statistics are therefore required (see section below on *Replication and bulking within the soil individual*).

In soil nutrient testing for agriculture, the use of the management unit (usually a paddock) as the soil individual is well established, although the growth of precision agriculture implies that within paddock variability can be large and management should be adjusted accordingly (see McBratney and Pringle 1999). It is beyond the scope of this report to consider optimal strategies for nutrient management in any detail. However, the recommendations relating to industry-based monitoring in the final section of this report are relevant.

Depth of the soil individual

Placing a lower boundary on the soil individual is more problematic than specifying the area. Many parts of Australia have a deep and often strongly weathered regolith. In the past, most descriptions collected as a part of soil surveys, field experiments or monitoring have been restricted to surface layers or an arbitrary solum (ie. A and B horizons often extending to approximately 1 m). This solum is not necessarily associated with the depth of root growth, and in many landscapes, plants exploit deeper layers (C and D horizons).

The depth of characterisation may be limited by the method of observation (eg. soil augers or backhoe pits are often restricted to 1-2 m) or purpose of the investigation (e.g. agriculturally focused work may only be concerned with the first metre).

Attempts should be made to characterise the soil to a depth where a root-impeding layer is encountered (e.g. lithic substrate, hardpan, water-table) or to where excavation is precluded by available equipment. Reasons for a restricted depth of sampling should be recorded (e.g. standard procedure, lack of time, limit of equipment, coarse fragments etc.).

Lateral processes

Many processes controlling soil formation and landscape function involve significant lateral fluxes of sediment, solutes and water. There is a risk that monitoring sites comprised of soil individuals–even a well-organized set along a toposequence–will fail to appropriately capture changes in soil condition. Some forms of monitoring will require instrumentation and measurement of larger scale entities (e.g. hillslopes) possibly with nested sets of soil individuals. The appropriate design will depend on the study objectives, understanding of landscape processes and resources available.

Sampling across a region

Purposive sampling

The method for locating a monitoring site in the field will depend on the purpose of the investigation. Sample sites are often selected as 'typical' of either a district, land mapping unit (e.g. soil type), or land management unit (e.g. farm paddocks or forest coups). This is *purposive sampling* and it can provide reasonable estimates when a landscape is very variable and resources allow the soil at only one or two sites to be examined. However, it relies heavily on personal judgement and there is no way of knowing just how good this is. There is a strong risk of bias with preference being given to some part of the landscape at the expense of the rest. Bias is almost always present in human judgement, and it cannot be avoided either by training or by conscious effort (Webster and Oliver, 1990).

Most soil monitoring data in Australia have been derived from purposively located sites and this constrains their general use. In most districts, the selection of monitoring and experimental sites for assessing the impact of land-use change is also highly constrained by the availability of areas with minimal disturbance or appropriate land management. Areas with limited disturbance (notional baselines) are often in such a condition because of their original differences with the surrounding landscape (e.g. lower fertility).

As noted earlier, most nutrient testing is undertaken at the level of the paddock – protocols for sampling within paddocks are well established. However, interpretation of regional trends in nutrient status using such data requires a very good appreciation of the factors influencing the purposive selection of paddocks. For example, they may be areas with nutrient deficiencies or alternatively, the better class lands of a district receiving more intensive management– either way, bias may be substantial.

If purposive sampling has to be used to select the location of sites, then time should be spent developing a set of explicit criteria relevant to the particular study. They should be recorded and their effectiveness audited for each site. An example procedure (after McKenzie et al. 2000b) would explicitly state:

- the resources available for sampling;
- criteria used for stratification of the study area (whether it be an experimental plot, catchment or region);
- criteria for allocating samples to strata;

- rules used for locating observations in the field (e.g. Petersen and Calvin, 1986)
- areas excluded from sampling.

With this agreed procedure, the field operators can then:

- select several replicate sites in a specific area;
- use different field operators to select sites in an area
- classify each site according to the criteria; and
- select the best sites based on these criteria.

Probabilistic sampling

The only sure way of avoiding bias inherent in the above approach is by *probabilistic sampling*. The theory is well established. See for example Cochran (1977), Yates (1981), and Webster and Oliver (1990) for designs and computation of statistics. These designs lead to estimates of population parameters without bias (means, variances, etc.) and to the replication needed to achieve sufficient precision. A *design-based* sampling strategy is appropriate in most instances. In some cases, the spatial structure of soil variation within the soil individual or region will be of interest, and in these circumstances a *model-based* or geostatistical approach will be more appropriate (see Brus and de Gruijter, 1997 and de Gruijter, 1999).

While probabilistic sampling avoids bias, it may be impossible to apply when monitoring is expensive and only limited replication is possible. For example, very few agencies have been able to replicate paired catchment studies across regions (although most such studies have replication within the experimental area). Similarly large long-term ecological research sites are rarely replicated although efforts to develop coordinated networks (e.g. www.lternet.edu; Sykes and Lane 1996; Vaughan et al. 2001) are an attempt to overcome the problem.

If probabilistic sampling can be undertaken across a region, then the principles of stratification used within the soil individual (see below) can be used in a similar manner, except the stratifying variables at the regional level will relate most commonly to soil type, landform, geology, vegetation and land management. In this instance, each randomly located observation is a soil individual as defined above. There are many options for designing an appropriate sampling scheme - de Gruijter (1999) provides a good introduction and Webster and Papritz (1995a,b) provide a thorough analysis of sampling within monitoring sites.

Nested sampling is particularly useful where little or nothing is known about the scales of variation across a region. The approach provides information on scales of variation and this can be used to improve the efficiency of later sampling. In brief, a nested sampling design involves division of a population at stage one into classes that are then divided at stage two into sub-classes. Further stages can be made into finer and finer divisions. At each level in the nested design, replicated observations are made at a specified distance from each other. The distance between replicated observations decreases further down the hierarchy. This form of sampling allows separation of the components of variance associated with different sampling intervals. It can also provide data to allow an initial estimate of the semi-variogram.

The United States Natural Resources Inventory (NRI) (Nusser and Goebel 1997) has one of the more statistically sophisticated sampling designs for an operational monitoring system. The NRI was first conducted in 1958 and has been repeated in 1967, 1975, 1977, 1982, 1987, 1992 and 1997. It is designed to assess conditions and trends in the soil, water and related resources of the United States. The NRI uses a two-stage stratified area sample of the entire country. The 1997 NRI collected data from 300,000 first-stage sampling units and 800,000 second-stage sampling points (NRI 2000). Aspects of the NRI relating to measurement and interpretation are considered in later sections. The scale of the NRI is well beyond any soil monitoring programs attempted to date in Australia.

It is inevitable for objectives and questions to change during a long-term monitoring program so flexibility should be built into the design. Overton and Stehman (1996) argue strongly for simplicity in the initial design with limited stratification and equal inclusion probabilities. Minimising sample structure maximizes flexibility for later measurement programs involving new variables.

Fixed location versus flexible network

It is generally assumed that monitoring networks should have fixed sampling locations. However, for a variety of reasons, management may be changed inadvertently or deliberately once the location of a site is known. Fixed locations may also lead to a gradual loss of sites from a network if land use changes (i.e. sites no longer conform to the a priori classification used during the network design) (Mol et al. 1998).

These problems can be overcome with a network of shifting locations. For example, the Representative Soil Sampling Scheme for England and Wales involves re-sampling of farms surveyed both 10 years and 5 years earlier (on each farm four fields are initially selected at random for sampling). In addition, 60 farms are re-surveyed which were first sampled 5 years ago and 60 new farms are selected each year. Once farms have been surveyed on three occasions, they are discarded from the study. This reduces the risk of feedback to farms remaining in the survey for long periods affecting the results; it also introduces new farms to make up for those lost due to urbanization and road development (Skinner and Todd 1998).

The main disadvantage with a flexible network is that trends are more difficult to detect.

Frequency

Some soil properties exhibit natural cycles on a daily and seasonal basis and failure to account for these makes the early detection of trends more difficult. For example, solute concentrations, pH and the availability of various nutrients vary seasonally. Consistency in the timing of measurement is therefore necessary.

Theory and practice

Putting statistical theory into practice can be problematic. Bias can enter because certain parts of the landscape are inadvertently ignored (e.g. areas of rock outcrop or locations under large trees or urban land use might not be registered as potential sample sites). This will lead to biased estimates of some properties.

Probabilistic sampling as outlined above can address some of these problems through randomisation and well-defined rules. The latter include clear definition of the soil individual and criteria for accepting or rejecting sites when in the field – this is necessary so that every site has a known inclusion probability. However, the logistic problems associated with some circumstances cannot be readily overcome. Good documentation of these problems is necessary.

Representative elementary volume

The size of a specimen (i.e. a soil core, clod or loose soil) can have a major influence on measurement. A substantial portion of short-range variation can be caused by measurement methods being applied at inappropriate scales. This variation can prevent the detection of trends in soil properties over time. Every attempt should be made to minimize such unnecessary measurement error.

The size of a specimen should be varied as a function of the soil features of relevance. Where soil structure is important (e.g. for bulk density measurement), the volume should be large enough to contain a representative number of elementary units of structure (i.e. peds and pores) or repetitive units. This volume is the *representative elementary volume* (REV) (Bear, 1972). Bouma (1985) suggested that some 20 elementary units of structure (i.e. peds) should be contained in a REV and evidence to support this was provided by Burke *et al.* (1986) and Lauren *et al.* (1988).

The REV of some soils is large and samples with 20 elementary units cannot be obtained easily (e.g. large coarse fragments or columns and prisms). Substantial short-scale differences will also occur when there is vegetation induced patterning; for example, around large trees (Ryan and McGarity, 1983) or in some rangeland ecosystems (e.g. tussock grasslands, Mulga – see Tongway, 1994). Similar differences are likely between the mounds and depressions of gilgai micro-topography. An extreme case occurs in areas with outcropping rock. In some landscapes, such short-range variation can have an overriding effect on soil properties. In these cases, the soil individual is stratified and measurements are made on separate strata that are then integrated (see above). There are practical limits to the size of specimen and these are considered below in relation to disturbed and undisturbed materials.

The REV is a useful guide for estimating the volume required for reducing variability between measurements, however, the concept has several limitations and it should be applied accordingly. The definition of the elementary unit of structure is qualitative and can be difficult to apply in some soils (e.g. elementary units may not be apparent in weakly structured or massive soils). Furthermore, soil variation is inherently multi-scaled, and there is no conceptual reason for expecting variations in measurement to be less at a specified scale.

Replication and bulking within the soil individual

Design-based sampling will enable determination of the means and variances of variables for a specified layer in a soil individual or larger region. Randomisation avoids bias regardless of the structure of spatial variation, despite the common misconception to the contrary (Brus and de Gruijter, 1997, de Gruijter 1999).

Investigators often need to know the number of replicates required to achieve a given accuracy in estimating the mean. This requires knowledge of the population variance σ^2 either from previous experience or an initial sample. The sample size n needed to estimate the mean μ of a soil body within the limits $\mu - x$ and $\mu + x$ is estimated by

$$n = \frac{t_\alpha^2 s^2}{(\bar{x} - \mu)^2}$$

where t_α^2 is Student's t at the level of probability α, and s^2 is the variance determined on a sample. Unfortunately, the sample sizes are often larger than the investigator can afford. Little is to be gained proceeding with a program if sample sizes are known to be too small to allow the detection of trends over time (see section on *Temporal considerations* below).

Estimating the mean value for a soil individual is often complicated by logistic factors. Obtaining random replicates from the surface and near-surface layers is straightforward when a 25 m × 25 m area is used to define the soil individual (with the lower boundary coinciding with the weathering front). However, collecting a random sample of undisturbed soil cores from deeper layers is more expensive. Every effort should be made to enforce statistical control and achieve efficiency through stratification and bulking. Bulking involves the physical mixing of soil specimens to create a less variable specimen.

If disturbed specimens can be used and the soil properties are additive, then bulking retains the precision of replicated measurement but at a reduced cost (Webster and Burgess, 1984). All specimens that form a bulked specimen must be drawn from the same sampling unit (e.g. the same horizon from the soil individual) and each specimen must contribute the same amount to the composite for ease of calculation. The bulked sample can provide an estimate only of the mean; and not the variance (Petersen and Calvin, 1986). The bulked specimen must be mixed thoroughly prior to measurement.

It is permissible to bulk specimens from within a soil individual for some applications, for example, when estimating a regional mean for soil carbon. However, statistical comparisons will not be possible because the variance of each individual cannot be calculated. Statistical comparison is still possible if soil individuals have been replicated. Decisions on bulking and replication of soil individuals depend on scales of variation, resource constraints and purpose.

Stratification within the soil individual

While simple random sampling within a soil individual is feasible, efficiency is nearly always improved by using stratified random sampling. Figure 10 provides an example of a stratified random design for a soil individual.

The simplest form of stratification is into a simple grid. Soil observations are randomly allocated within strata. Stratification using other variables is also possible: for example, micro-topography (e.g. gilgai shelves and depressions), vegetation (e.g. tussock grasses and bare ground), or rock outcrop. Stratifying variables prone to operator bias or of an ephemeral nature (e.g. vegetation) should be avoided because they may create confusion during later phases of sampling.

Stratified random sampling of soil individuals is the preferred approach (see Papritz and Webster (1995a,b) and the protocol presented in Appendix 2 should satisfy most applications.

Excavation and drilling

Freshly dug pits have many advantages, especially in soils with gravel and where hydraulically operated drill rigs are ineffective. Vertical and lateral variations are easily observed and large intact specimens can be obtained. They allow accurate sampling with little contamination from one specimen to another. Pits are best dug with a backhoe or mini-excavator. However, soil pits involve considerable site disturbance and this greatly limits their use for soil monitoring.

Pro-line drills or thin-walled samplers are acceptable for many purposes. They should have a diameter of 50-150 mm or larger. Pro-line drills can sample most soils to substrate. The cores can be transported to the laboratory prior to sub-sampling and description. Contamination of specimens is minimised and small, undisturbed specimens can be collected. Cores can be also obtained from areas with shallow water tables.

There are several disadvantages with pro-line drills and thin-walled samplers. Lateral variability is not observed and the soil fabric might be disrupted particularly when the soil is too wet or too dry. Undistorted specimens are difficult to obtain in soil with abundant coarse fragments and in some circumstances layers may be impenetrable. McKenzie and Cresswell (2002) provide further discussion on methods for excavation and drilling.

It is essential to have clear protocols and controls for machinery operating on or near monitoring sites. Clearly marked access tracks are necessary and the actual monitoring area should not trafficked unless it is part of the land management system of interest.

6 Measurement

Two aspects of measurement are considered in this section. First is specification of the minimum data set required for characterizing a monitoring site at the start of a study. Second is selection of the actual soil properties to be monitored. General issues are considered because the choice of variables and selection of measurement methods depends on the objectives of each monitoring study, although a preliminary set of soil properties is presented.

Accurate and precise measurement is essential in monitoring and this requires clear protocols for all activities. Protocols for measurement create some of the more difficult problems. Standard laboratory measurement methods should be used wherever possible (e.g. Klute 1986; Rayment and Higginson 1992; McKenzie et al. 2002) but in most cases they do not specify procedures in sufficient detail for some aspects of monitoring. McKenzie et al. (2000b) provide an example of rules and guidelines for soil carbon monitoring beyond those found in Rayment and Higginson (1992).

Measurement methods should be calibrated with other groups undertaking similar studies (see below). Calibration should also be undertaken against standard specimens. Analytical methods (and sampling procedures) should not be changed without thorough testing of the effect of the new procedure against the long-term record. Similarly, methods or procedures developed for one location or study should not be adopted for another area or purpose without careful testing and justification (Likens 2001). Pilot studies are essential for testing measurement methods.

Site and soil characterisation

The site and soil characterization provides:

- A basis for extrapolating results to other similar soils (including sufficient information to assess the relationship with soil or landscape units);
- A means for grouping or stratifying sites to aid measurement and analysis; and
- Insights into anomalous or unusual results.

The site and profile characterization will be performed usually only once – when the monitoring site is established. The soil properties to be monitored on a regular basis will be restricted to a much smaller set. A standard monitoring site layout is presented in Appendix 2. It includes locations for soil pits and these are used to obtain the site and soil profile characterization.

Table 4 specifies the minimum data set for site and soil description. It should not restrict more detailed characterisation if resources permit. The definitions in McDonald *et al.* (1990) are used wherever possible. McDonald *et al.* (1990) do not provide appropriate procedures for some aspects of site description. McKenzie et al. (2000b) recommend extra site descriptors for the characterization of surface organic layers, woody debris, rock outcrop and plant roots, while Tongway (1994) provides a scheme suited to surface condition in the rangelands.

Table 4: Minimum data set for site and soil profile characterization.

Variable	Comments
Site	
Lithology	Table 27 in McDonald et al. (1990)
Substrate	Table 29 in McDonald et al. (1990)
Landform element	As per McDonald et al. (1990)
Landform pattern	As per McDonald et al. (1990)
Slope	As per McDonald et al. (1990)
Vegetation structural formation	As per McDonald et al. (1990)
Floristics	As per McDonald et al. (1990)
Land use	As per BRS (2002)
Morphology	
Soil horizons	Specify designation and upper and lower boundary depths
Soil texture	For each horizon
Colour	Munsell colour of matrix for each horizon, and mottles if present.
Structure	Type, grade, size for each horizon
Coarse fragment volume	For each horizon if present
Segregations of pedogenic origin	For each horizon if present (type and proportion)
Chemical Properties*	Sufficient for allocation to the Great Group level of the Australian Soil Classification
pH in $CaCl_2$ and water (1:5)	As per Rayment and Higginson (1992)
Organic carbon	As per Rayment and Higginson (1992)
Exchangeable cations and cation exchange capacity	As per Rayment and Higginson (1992)
Electrical conductivity	As per Rayment and Higginson (1992)
Physical Properties*	Sufficient for interpretation of the soil-water regime and root growth (see Table 1.2 of McKenzie et al. 2002 for more detail)
Particle size distribution	As per McKenzie et al. (2002)
Bulk density	As per McKenzie et al. (2002)
Water retention	As per McKenzie et al. (2002)
Hydraulic conductivity	As per McKenzie et al. (2002)
Aggregate stability	As per McKenzie et al. (2002)
Taxonomic Class	
Great Group level of the Australian Soil Classification (Isbell 1996)	

* It is difficult to be overly prescriptive because the objectives of studies differ. However, the intention of soil chemical and physical measurement should be to provide an indication of at least soil nutrient availability, limitations to root growth, the soil water regime and the taxonomic class of the soil.

Collection and preparation of specimens for profile characterization

Field investigations will most commonly use mechanical soil corers or backhoes (ACLEP, 1997). Inaccessible sites will require manual digging of pits.

It is common and preferred practice to collect a series of specimens that encompass the whole profile - that is, sampling is continuous down the profile. This contrasts with the practice of collecting specimens only from the centres of selected sampling intervals. Within the general guidelines below, the subdivision of the profile for collecting specimens should be based on both horizons and depths.

As noted earlier, if soil is less than 1 m deep then characterise the full profile. If it is deeper than 1 m, then characterise at least to this depth. However, attempt to characterise as deep as possible and record whether data are censored and if so for what reason.

Some soil properties are more variable in the upper part of the profile (although this does not hold as a general rule) and so greater replication in this zone is often justified. Bulking of specimens is therefore recommended in the upper 0.30 m of the profile for each observation within a soil individual (see below).

A maximum sample interval of 0.30 m is used between 0.30 m and 2.00 m. Below 2 m the sampling interval should be sufficient to characterise whatever is found. The guidelines are intentionally approximate to allow flexibility in profiles that have clear horizon boundaries.

Take cores and clods for bulk density determination from the centres of the selected depth intervals unless there is a reason for characterising the upper or lower boundary of the layer (eg. when a crust or pan is present). All disturbed specimens used for chemical analysis should be obtained from the complete depth range of the layer.

Specimen handling and volume

The procedures for specimen handling described by McKenzie et al. (2002) should be followed where appropriate. Each bulk specimen should contain 1.5 to 2.0 kg of material – such quantities may not be possible when using thin-walled samplers. Approximately 500 g is processed for routine analysis. The remainder is archived. The proportion of coarse fragments (> 2 mm) is determined by sieving the soil after grinding. A larger specimen is required in very gravelly soils to ensure good representation (see McKenzie et al. 2002).

Monitored soil properties

Selection of soil properties

Most of the recommendations on sampling and measurement that apply to site and profile characterization apply equally to soil properties that are monitored on a regular basis. Note that most regular monitoring will involve mechanical coring to minimize site disturbance.

Soil properties to be monitored on a regular basis should satisfy the criteria outlined in Section 3. In particular, measurement needs to be accurate, precise, relatively inexpensive and relevant to the soil and landscape processes of interest.

Soil properties with large short-range variability are more difficult to monitor (see Section 9). Sparling et al. (2002) have evaluated a wide range of soil quality indicators for New Zealand conditions and they have identified a set of seven essential soil properties for inclusion in monitoring programs (Table 5). While this set has been developed in New Zealand, it has considerable relevance to Australian conditions, particularly the temperate areas of southern Australia. However, the proposed set needs to be evaluated for land-uses and soils that are widespread in Australia but uncommon in New Zealand. For example, it would be logical to add soil properties sensitive to changes in sodicity and electrolyte concentration (e.g. dispersive potential of clay (Rengasamy, 2002)) while more appropriate measures of nutrient availability may be needed for the strongly weathered soils that cover large parts of the continent.

Table 5: Soil properties recommended for soil quality monitoring in New Zealand (Sparling et al. 2002).

Soil property	Soil quality information	Applicable to
Total C	Organic carbon content	All soils
Total N	Organic matter nitrogen status	All soils
Mineralisable N	Readily decomposable organic nitrogen	All soils
Soil pH	Soil acidity	All soils
Olsen P	Phosphate available to plants	All soils
Bulk density	Soil compaction	All soils
Macroporosity	Soil aeration and compaction	All soils
QuickTest Cations	Calcium, magnesium and potassium available to plants	Only necessary where the nutrient balance is important
Aggregate stability	Stability of peds	Soils used for cropping and horticulture

Measurement *in situ*

As noted earlier, most measurements of soil properties involve the collection of a specimen – sampling is destructive and subsequent measurements are undertaken on separate specimens. Monitoring would be greatly simplified if reliable measurements could be undertaken *in situ*.

Measurement of some soil properties *in situ* has been undertaken in field experimental programs for many years. The most established techniques include measurement of soil water content using neutron moisture meters, capacitance probes and time domain reflectometry. Similarly, dataloggers are now routinely used for monitoring groundwater levels. Instruments for measuring soil solution chemistry are becoming more widely used for properties such as pH and redox potential. Likewise, resin capsules provide an alternative means for characterizing soil solution chemistry (Skogley et al. 1996). The advantages of *in situ* measurement include:

- Avoidance of artefacts and variability associated with specimen extraction and preparation;
- Non-destructive sampling and limited disturbance of the monitoring site;
- Capacity to generate high-frequency measurements; and
- Compatibility with digital technologies and the capacity for automatic downloading of data via mobile phone networks.

The main disadvantages of *in situ* measurement are:

- Most technologies require regular maintenance and field inspection;
- Costs can be significant;
- Disturbance associated with either the process of installation, or the actual sensor (e.g. impedance of drainage), can cause artefacts;
- Measurement may be restricted to a relatively small soil volume (i.e. less than the representative elementary volume);
- Environmental conditions within the soil are not controlled in the same way as for laboratory measurement and this may cause difficulties in data analysis (e.g. seasonal variations in electrolyte concentration); and

Reliable technologies exist only for a limited range of soil properties.

Laboratory processing and analysis

McKenzie et al. (2002) provide guidelines on drying, grinding and sieving of soil specimens that suit physical and chemical analysis. Particular attention should be paid to homogenisation of specimens prior to laboratory analyses. This is best achieved by passing the soil through a closed-bin riffle-splitter a total of five times (Schumacher *et al.,* 1990). Even with this precaution, variation in sub-samples used for analysis remains (Mullins and Hutchison, 1982; Mol et al. 1998). Specimens for soil biological analysis have separate processing requirements (see Robertson et al. 1999).

Storage of specimens

Undisturbed moist soil specimens (i.e. clods and cores) should be stored at 2-4°C. Specimens should not be allowed to freeze and laboratory measurement should be undertaken as soon as possible. Extended periods of storage should be avoided because microbial activity may change some properties. Bulk specimens should be dried as soon as possible after collection in the field. They should be stored in airtight plastic containers away from direct sunlight and in areas with limited variations in temperature and humidity.

Standards and inter-laboratory comparisons

The Australian Soil and Plant Analysis Council (ASPAC) conducts regular national quality assurance programs to enhance standards of analysis and assist standardisation of soil and plant analytical methods across laboratories. It is beyond the scope of this report to specify procedures for inter-laboratory comparisons and the collection and maintenance of standards. However, they are essential elements in quality control. Any laboratories undertaking measurements for long-term monitoring should contact ASPAC to participate in its activities.

Monitoring soil condition with limited field measurement

The discussion so far has assumed that monitoring of soil condition involves some form of direct measurement in the field. Many proposed, and some existing schemes for the proxy monitoring of soil have limited or no field measurement: for example, the environmental indicators proposed for the National State of the Environment Reporting (Hamblin 1998) and the National Resources Inventory (NRI) of the United States (NRI 2000). The 1987 and 1992 NRI each had nearly one million sample points and almost 30% of sample sites did not require a field visit because information could be obtain from aerial photographs and other sources. No similar program of monitoring (as opposed to single surveys) has been undertaken in Australia.

This report has concentrated on methods that involve direct measurement of soil properties for the following reasons.

- Variables can be selected that relate closely to the biophysical processes of interest.
- Sampling and measurement error is minimized and as a result, change over time can be detected more readily.

However, direct measurement is relatively slow and the generalization of results from a site to large regions can be problematic. Remote sensing generates data with a complementary set of advantages and disadvantages to direct measurement. The disadvantages include the following.

- It can be difficult relating remotely sensed variables (e.g. reflectance measures) to soil variables controlling biophysical processes, although this is changing through the use of hyperspectral methods and temporal analysis (e.g. McVicar and Jupp 2002).
- Most remote sensing variables relate to the land surface or near-surface layers.

However, remote sensing has some great advantages for monitoring.

- Measurements are made across complete regions, often at high spatial resolution.
- The frequency of measurement is high compared to direct field measurement.
- Changes in spatial pattern can be readily detected.

Soil monitoring via remote sensing requires a careful process of calibration with field measurements to enable reliable interpretation – a full discussion is beyond the scope of this report. However, remote sensing has a central role to play in the integration of mapping, modelling and monitoring.

7 Data management

Long-term monitoring may proceed for decades and involve the collection of large quantities of data. Most natural resource management agencies in Australia have a poor record in data management and this problem has been made worse by the substantial institutional change in recent years. An exception is the Bureau of Meteorology. Data from many long-term (>25 years) field experiments are not readily accessible and there has been a lack of adequate reporting of even basic research findings (Grace and Oades 1994).

However, there have been positive gains in the management of soil data from land resource surveys due to the establishment of data exchange standards (ACLEP 1995) and wide acceptance of standard procedures for soil description and measurement (McDonald et al 1990; Rayment and Higginson 1992). Unfortunately, the lack of metadata and inconsistent quality control made it difficult to compile a national soil database for the National Land and Water Resources Audit. The challenge of creating a data management system for long-term soil monitoring should therefore not be underestimated.

The lessons of data management from long-term agricultural experiments and ecological monitoring studies are clear.

- There will be many changes in managerial, scientific and technical staff over several decades. The importance of recording all aspects of the monitoring program is therefore critical (Jones et al. 1996).
- Maintaining records goes well beyond a database of soil properties, plant yields or other outputs. It should also include ancillary data that capture details of land management practices, anomalies of particular years, observations of pests and diseases and any other factors considered relevant to future interpretation (Leigh et al. 1994).
- Continuous data sets must be constantly updated, scrutinized for errors and rigorously reviewed. Data quality should be known and recorded (Shampine 1993)
- Data type and quality (e.g. with respect to sampling procedures, measurement methods) should be consistent and comparable (Shampine 1993)
- Copies of records should be stored in several locations (Likens 2001).
- Clear lines of management responsibility are necessary to ensure individuals with appropriate training undertake measurement and data management.
- Results should be reported at regular intervals (preferably in a form available to the public).
- Data management and analysis procedures should be explicitly addressed during the design phase of a monitoring program.

- Stability, interest and dedication of responsible individuals, institutions or agencies are critical to the success of long-term monitoring (Likens 2001).

8 Archiving

Soil specimens collected during a monitoring program should be stored in secure archives. This can add immense value to a monitoring program as demonstrated by the experience at Rothamsted in England where the archive of crop and soil specimens is now as valuable as the experiments from which they are derived (Leigh et al. 1994). The Rothamsted archive has been used for many purposes including:

- Undertaking retrospective studies of nutrient balances;
- Determining changes in soil organic matter; and
- Tracking the accumulation of industrial inorganic and organic pollutants.

Soil archives in Australia have been associated with research organizations or agencies undertaking land resource assessment. For example, the CSIRO Land & Water soil archive has been used to:

- Analyse specimens from across southern Australia to allow rapid assessment of the distribution of soil with toxic levels of boron at a fraction of the cost necessary for new field work;
- Analyse carbon profiles for a range of Australian soils; and
- Calibrate new methods of analysis.

The archive also includes many specimens collected prior to agricultural development in areas that now have heavy application rates of pesticides and herbicides.

Soil archive management in Australia has been less successful than data management. The following recommendations are based on experience with the CSIRO soil archive, the Rothamsted archive (Leigh et al. 1994), the Sample Archive Building at the Hubbard Brook Long-term Ecological Research Site (Boone et al. 1999) and guidelines for the UK Environmental Change Network (Hornung et al. 1996).

- Specimens must be stored in long-lasting containers with permanent, unambiguous labels that record site number, location, depth, date of sampling, fineness of the specimen (e.g. < 2 mm) and other relevant identifiers. Labels should be on both the container and lid – a copy of the label on plastic or similar material should be placed inside the container with the specimen.
- The soil archive inventory and database from the monitoring program should be integrated. Specimens must be matched to database records (e.g. using bar coding) – individuals responsible for the archive should also be responsible for data management.
- Efficient methods for storage and retrieval are necessary
- Adequate space must be available for long-term storage.

- The archive should be kept air-dry at room temperature in a secure location with a low probability of water damage (e.g. broken pipes, flooding), chemical contamination, fire or other problems. Temperature fluctuations should be minimised to prevent condensation inside containers.
- Long-term storage of field-moist specimens in refrigerators or freezers is generally not recommended because of inevitable power failures.
- Before any form of analysis or storage, the fine earth fraction (< 2 mm) should be homogenised so that the analysed and stored specimens are identical.
- The archive should have a written policy on use and access along with a log of activities and users. The original investigators should have free and easy access to the specimens.
- Sub-sampling archived soil is wasteful because individuals often take more than they need. It is better for users to take the complete specimen, use the amount required, and then return it. To protect against loss of material, archives can maintain a sub-sample for use only in the event that the working specimen is lost.
- Changes in soil properties will occur during storage and these should be monitored by periodic analysis of reference materials or in-house standards.

9 Change over time

Choosing an appropriate frequency of measurement will depend on the objectives of the study, understanding of system behaviour, patterns of variation in the relevant soil properties across the landscape and through time, statistical design (e.g. sampling method, sample size, degree of replication, bulking strategies), measurement technology and resources.

The best frequency for sampling can often only be determined after an analysis of preliminary results. Determining an appropriate frequency of measurement is as important as the length of measurement because short-term dynamics may be of overriding importance. The duration of measurement must be at least as long as the phenomenon being evaluated, or scaled to the frequency of the event being studied (Likens 2001). The examples of system behaviour presented earlier indicate that long-term measurements (i.e. decades) are normally necessary to detect soil change (see also Richter and Markewitz 2001).

The separation of temporal and spatial variation has already been highlighted as a major methodological challenge for soil monitoring. The capacity to obtain an accurate and precise estimate at any point in time is a critical factor in determining whether soil change can be measured in a cost-effective manner – it will take longer to detect a trend when measurements have low accuracy and precision. This section considers statistical aspects of monitoring, paying particular attention to the feasibility of detecting soil change at several spatial scales (from the site to the region). Several scenarios are presented for detecting changes in soil properties that influence both biological productivity and landscape processes (pH, organic carbon and permeability to water). Before these are considered, it is necessary to clarify the role of soil maps in monitoring.

Separating soil change in space and time – the role of soil maps

There is a widespread and appealing misconception that soil and land resource maps provide a practical baseline for monitoring. A corollary is that maps can be generated at intervals by follow-up surveys to provide an indication of changes in soil condition. This view is misguided for the following reasons.

- The predictions derived from a soil map for a given soil property at a specified location will have very wide confidence intervals. This is caused largely by the substantial short-range field variability present in most soil properties (see Table 2). As a result, maps at best provide imprecise snapshots of soil properties at some point in time – more sensitive methods are necessary to detect soil change.
- Virtually all soil and land resource maps produced in Australia rely on purposive sampling so there is no way of estimating their accuracy and precision without supplementary sampling.

- The field measurement program for a survey focuses on sites that provide the maximum amount of information on factors controlling the *spatial* pattern of soil variation. As a consequence, some soil or landscape units that occupy large areas may not be sampled often because they are easy to map, while other less widespread units may receive a disproportionate sampling effort.
- The target population for monitoring rarely coincides with the sampled population for land resource survey. This is usually unavoidable given the resources available for soil and land resource survey. Furthermore, land resource surveyors have to sample at many locations across the complete landscape whereas only a portion of the landscape will usually be of interest for monitoring (e.g. intensively used or vulnerable areas).
- In a survey, observations at a location are rarely replicated so formal estimates of accuracy and precision cannot be calculated – as a result, these sites cannot be readily used for monitoring (i.e. revisiting the original field sites at later times is not sensible). The establishment of reference sites, with replicated measurements, to represent the most common soils encountered during a survey, would overcome this limitation.

Despite these issues, soil and land resource maps have a critical role in soil monitoring for the following reasons.

- Rates of soil change under different systems of land management are highly dependent on the soil type. Some processes (e.g. leaching, organic matter oxidation, acidification etc.) occur at faster rates on given soil types. Soil maps provide a means for stratifying a region and for locating monitoring sites. They also provide essential information for interpreting the results from monitoring.
- Soil and land resource maps provide a basis for identifying priority regions for monitoring. For example, the Australian Soil Resource Information System (NLWRA 2001) provides a series of maps of soil attributes and some of these (e.g. pH) can be used to identify where regional monitoring may be required. More significantly, when these data are combined with other sources (e.g. climate, land cover, terrain) and used as inputs to simulation models, regions can be then identified where significant natural resource management hazards exist (e.g. with respect to landscape balances of water, carbon, nitrogen, and phosphorus; soil erosion; acidification). These maps, rather than forming a baseline for monitoring (something they cannot do with any efficiency), instead provide a means for focussing and ensuring the efficiency of soil monitoring programs.

Scenarios for soil monitoring

Assumptions

Scenarios for monitoring soil change are explored in this section to illustrate the importance of short-range spatial variation. The following assumptions are made.

- Three soil properties (pH, organic carbon and hydraulic conductivity) are examined because they usually have contrasting degrees of short-range variation – typical values for the coefficient of variation are presented in Table 6.

- Four common soil types (Chromosol, Sodosol, Ferrosol and Vertosol) are considered and they are assumed to have the same coefficient of variation for each soil variable but a different mean (and hence different variance). Estimates of the mean and variance at the start of a 20-year monitoring period are shown in Table 7.
- The assumed change in each variable for the four soil types and four systems of land use is also presented in Table 7. The systems of land use are continuous cropping (CC), crop/pasture rotation (CP), permanent pasture (PP) and farm forestry (FF). The change in mean value for each soil property is due to land management over a period of 20 years.
- The magnitude of change has been set at a level where the consequences to either production or environmental values would be of significance for at least one combination of soil and land management system – the change is judged to be at a level that should trigger a response by managers. For example, the pH decline over 20 years from 5.0 to 4.2 for the Chromosol under conventional cultivation would have a detrimental affect on agricultural production. Similarly, the decline of 30 mm/hr in hydraulic conductivity would make the soil prone to runoff and erosion in most environments in Australia. The organic carbon levels and degree of change are realistic and would translate into differences in soil performance.
- The change is assumed to be a uniform linear trend.
- Measurements are made every 5 years on soil individuals (i.e. 25 × 25 m with stratified random sampling within the soil individual) – the variance within a soil individual or map unit remains the same during the 20-year period.

Table 6: Notional coefficients of variation for pH, organic carbon and saturated hydraulic conductivity at the scales of the soil individual, detailed soil mapping unit, and intermediate-scale soil-landscape unit.

Spatial Unit	Coefficient of Variation (%)[1]		
	pH	Organic Carbon	Saturated Hydraulic Conductivit
Soil individual	10	15	150
Detailed soil map unit (1:25,000 scale mapping)	20	50	200
Soil-landscape map unit (1:100,000 scale mapping)	50	75	300

[1] Based on data compiled by Beckett and Webster (1971), Wilding and Drees (1983), Warrick and Neilsen (1980), and McBratney and Pringle (1999)

Table 7: Estimates of soil attributes used in the three scenarios

Soil Variable	Soil Type	Mean Year 1	Variance Soil individual	Variance Soil map unit	Variance Soil-landscape map unit	Change in mean due to land management after 20 years*			
						CC	CP	PP	FF
pH									
	Sodosol	7.0	0.49	4.41	12.25	-0.5	-0.5	-0.4	0.2
	Chromosol	5.0	0.25	2.25	6.25	-0.8	-0.8	-0.6	0.2
	Ferrosol	4.5	0.20	1.82	5.06	-0.3	-0.2	-0.2	1.0
	Vertosol	7.5	0.56	5.06	14.06	-0.2	-0.2	-0.1	0.2
Organic Carbon (%)									
	Sodosol	1.0	0.022	0.250	0.562	-0.2	0	0.6	1.0
	Chromosol	1.5	0.051	0.562	1.266	-0.3	0	0.6	1.2
	Ferrosol	2.0	0.090	1.000	2.250	-0.4	0	0.7	1.5
	Vertosol	1.5	0.051	0.562	1.266	-0.3	0	0.4	0.6
Hydraulic Conductivity (mm/hr)									
	Sodosol	20	900	1600	3600	-10	10	30	50
	Chromosol	50	5625	10000	22500	-30	0	20	70
	Ferrosol	150	50625	90000	202500	-70	-20	30	150
	Vertosol	10	225	400	900	-2	0	20	30

* CC: Continuous cropping, CP: Crop/pasture rotation, PP: Permanent pasture, FF: Farm forestry

Three sets of questions will be considered.

Question 1: What sample size is required to detect a statistically significant change in pH, organic carbon and hydraulic conductivity for a *single soil individual* within 10 years and within 20 years?

Question 2: For the same soil properties and periods, what sample size is required to detect a statistically significant change across a *detailed soil map unit* (e.g. from a 1:25 000 scale map)? And how much effort should be devoted to the within soil individual sampling and how much to the soil map unit?

Question 3: For the same soil properties and periods, what sample size is required to detect change across a *less-detailed landscape map unit* (e.g. from a 1:100 000 map)? And how much effort should be devoted to the within soil individual sampling and how much to the soil map unit?

Sample size calculations

Sample sizes were calculated using the following assumptions.

- The linear trend has an associated rate of change that is given by the slope. This is determined by the size of the effect averaged over the 20-year monitoring period.
- For the 10-year scenario, the same rate of change is assumed but the sample size per year is adjusted so as to detect that rate of change within 10 years.
- The statistical model selected for monitoring change in a soil property allows for a linear rate of change over time and two sources of variation, namely the:
  - within site variation, which can be attributed to both measurement error caused by the technique and the local spatial variation (remember that sampling at each time is destructive); and the
  - between site variation, which allows differences amongst the sites.
- Algebraically this model is of the form $Y_{ijt} = \mu + S_i + \beta x_t + \varepsilon_{ijt}$, for sites $i=1, ..., k$, measurements $j=1, ..., m$, and times $t=1, ..., T$. Note that:
  - μ is the mean value of the soil property in the region at the start of monitoring.
  - x_t is the elapsed time in years from the start of monitoring. Time x_1 therefore equals 0, while x_T represents the time x_T years after the commencement of monitoring.
  - β is the rate of change in the soil property for a one-year change in time (x_t).
  - The ε_{ijt} capture the within site variation and are assumed to be independent and Normally distributed with mean 0 and variance σ^2. A larger σ^2 corresponds to greater measurement error and local variability. The S_i represent random effects for the sites. These enable the underlying site means to deviate from μ. These deviations (or effects) are assumed to be Normally distributed with mean 0 and variance τ^2. The larger τ^2, the greater the variation between sites.
- In the single soil individual case, measurements are made at *one* site and the only source of variation is from within the site (i.e. from the ε_{ijt} as the S_i is then absorbed into the μ).
- The sample sizes are determined to detect the desired rate of change with probability 0.8 over the period of interest. This probability is known as the *power* – it indicates the probability of rejecting the null hypothesis of no change, when the alternative hypothesis that change occurs is indeed true. The value of 0.8 is a commonly adopted level.

The data for the individual site may be analysed as a regression analysis or as an analysis of variance (ANOVA), with monitoring time included as an ordered factor.

For the soil map unit and soil-landscape map unit, where there is strong site-to-site variation, it is very important to maintain knowledge of which site each measurement pertains to, and use the site as a factor in the regression or ANOVA. In doing so we take account of the site-to-site variation and have greatest chance of detecting any change.

The regression approach is more powerful than the ANOVA for detecting a linear change. However, the ANOVA will detect other departures. Decomposing the ANOVA into 1 degree of freedom polynomial contrasts gives a linear contrast with similar power to the regression approach.

A simple adjustment to the data prior to a regression analysis is to subtract the site mean across all years and add the global mean for all observations. Assuming minimum sample size, the regression of these adjusted responses on time will have power of approximately 0.8. It can be shown that the soil and soil-landscape map units scenarios will demand similar sample sizes to the individual scenario provided we make an allowance for the site-to-site variation. If we make no allowance for the contribution to the variance from the different sites in our analysis, the power to detect the change is markedly less and the required sample sizes to achieve a probability of detection of 0.80 necessarily larger.

Table 8 presents the estimated minimum sample size ($n=k \times m$ where k is the number of sites and m the number of measurements per site) for each 5-year monitoring phase necessary to detect the stated change with a probability of 0.80.

Table 8: Sample sizes required every five years to detect trends in three soil properties, across four soil types, and under four systems of land management over periods of 10 and 20 years. Cells in the table containing a dash do not have estimates of sample size because no change occurred for the given combination of soil property, soil type and land management system.

Property	Soil Type	20 years				10 years			
		CC	CP	PP	FF	CC	CP	PP	FF
pH	Sodosol	26	26	40	159	126	126	196	782
	Chromosol	5	5	9	80	25	25	45	403
	Ferrosol	28	64	64	3	142	317	317	13
	Vertosol	180	180	723	180	894	894	3572	894
Organic Carbon	Sodosol	8	–	1	1	36	–	4	2
	Chromosol	8	–	2	1	37	–	10	3
	Ferrosol	8	–	3	1	36	–	12	3
	Vertosol	8	–	5	2	36	–	21	10
Hydraulic Conductivity	Sodosol	116	116	13	5	575	575	64	23
	Chromosol	80	–	180	15	399	–	898	74
	Ferrosol	132	1615	718	29	660	8075	3590	144
	Vertosol	718	–	8	4	3590	–	36	16

The results in Table 8 provide a wealth of guidance on strategies for monitoring soil change. Some initial observations are as follows.

- There is enormous variation in the sample size required at each 5-year monitoring stage between the soil properties. These sample sizes are markedly large if we want to detect the change within 10 years. Moreover, these samples clearly vary with soil type and land management.

- Some changes are easy to detect (e.g. organic carbon under farm forestry) while others require an impossibly large number of samples (e.g. hydraulic conductivity in Ferosols). These large numbers of samples must be viewed against the magnitude soil change for the particular combination of soil type and management system.
- Even if 200 measurements of hydraulic conductivity were made every 5 years (an expensive undertaking), only a few statistically significant changes could be obtained after 10 years (i.e. under permanent pasture for the Sodosol and Vertosol, and farm forestry for all soil types). However, many more changes could be detected after 20 years.
- Table 7 has assumed that changes in soil properties under a given land management practice differ between soil types – only one or two of the changes are significant for land management (e.g. the pH change under conventional cultivation is significant for the Chromosol and Ferrosol but not for the other soil types). This is a pattern of change that would be expected in a specified region that contained the four soil types. Another approach would be to specify the level of change in a given soil type that would trigger a management response – the sampling effort required to detect the change for each soil could then be calculated.
- It may seem counter-intuitive, but the sample sizes in Table 8 actually apply to all three scenarios: the individual site, the soil map unit and the soil-landscape map unit. However, this is only true if the data have been analysed correctly, otherwise many more samples would be needed for the two types of map unit with their greater levels of spatial variation. The essential requirement is to analyse the *differences* between individual sites over time. The alternative of comparing the mean value of a soil property across all sites at time zero with the mean for all sites at a later time is an inefficient and ineffective method for detecting change. This is depicted in Figure 11. The efficiency gained from examining differences between individual sites over time (Figure 11b) can only be achieved if measurements are repeated at the same site over time.

How many sites and how many samples from within a site?

Table 8 gives the sample sizes required to detect the desired effect with probability 0.80. It remains to allocate this total to sites and within sites for the map unit and intermediate map unit data.

The variance of the estimated mean for each time period is given by:

$$\operatorname{var}(\bar{y}_t) = \frac{\tau^2}{k} + \frac{\sigma^2}{km}$$

As the number of sites k increases the variance will reduce and the mean will be estimated with greater precision.

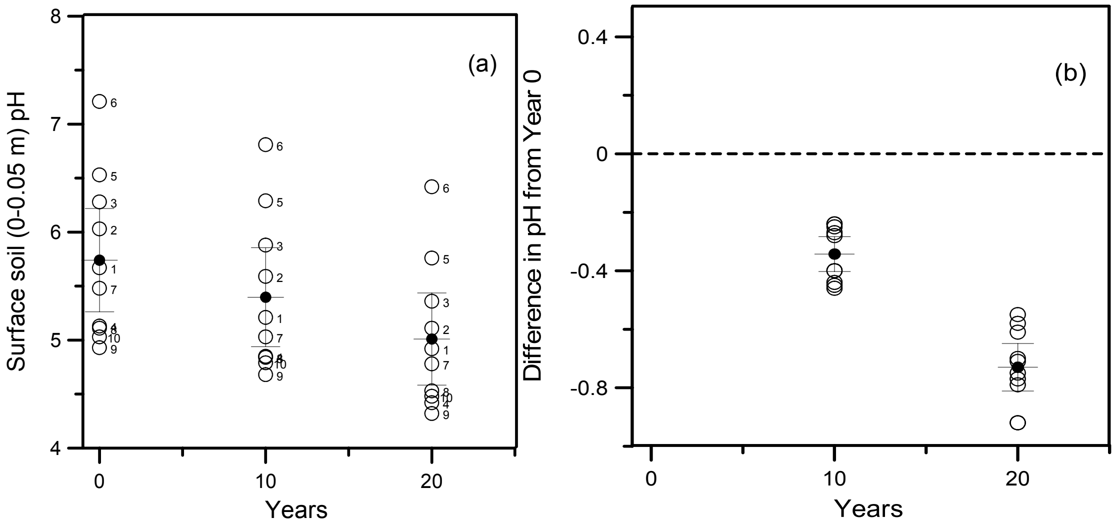


Figure 11: Hypothetical example of pH change over 20 years for 10 sites (site numbers are shown in (a)). In (a) the average pH for each time interval is calculated and presented as a mean (●) with 95% confidence intervals – the intervals overlap for the three times so no statistical significant change is detected. In (b) the information for each site is retained in the analysis and the *difference* in pH for each site from Year 0 is plotted. The resulting confidence intervals are much smaller and a strongly significant statistical difference is detected. The analysis in (b) is not possible if different sites are used in each period of sampling.

We must have at least two measurements per site if we want to determine the individual variance. The number of measurements *m* should however be small as the site-to-site variation contributes a much greater proportion to the total variation – the ratio of the variance of the soil map unit to the within site variance in Table 7 for the Sodosol is 9:1, 11.4:1 and 1.8:1 for pH, organic carbon and hydraulic conductivity respectively. The equivalent ratios for the landscape map unit to the within-site variance for the Sodosol are 25:1, 25.5:1 and 4:1 respectively. The choice of $m=3$ would be appear a natural balance – it ensures that the variance of the estimated mean is minimised and offers some protection against the masking effects of aberrant observations. The only real difference in moving from the soil map unit to landscape map unit is the increased importance that must be accorded to the site-to-site variation – this can only be addressed by making *k* as large as possible.

Other strategies

If we had fixed resources and were solely interested in detecting a change in the 20-year period, it would be desirable to place half at the beginning and the other half at the 20-year mark. This will give us the greatest probability of detecting a change. The risk in such an approach is that we have no idea what happens in between the 0 and 20 years marks (e.g. is the change linear or abrupt?). While the spacing every 5 years is less powerful, it does give us some insight into the nature of change. Additionally it provides some cover against abnormal events, which may confound the results at either end.

While Table 8 includes combinations that require only one sample and others that require many, it would be more logical to specify a minimum and maximum sample size. The maximum sample size would be something that is feasible (perhaps 250). The minimum size would avoid those sample sizes that are too small to offer any safeguards against anomalous results (e.g. 10).

Example: pH change in the Sodosol used for continuous cropping

From Table 7 we see that the mean pH at the beginning of Year 1 is 7.0. Under continuous cropping we wish to detect a change of –0.5 units after 20 years. This corresponds to a rate of change of -0.025 units per year if the change is linear. The assumed individual variance is $\sigma^2 = 0.49$ and the between site variance is

$$\tau^2 = 4.41 - 0.49 = 3.92.$$

Power = prob(detecting a change | monitoring times, $n=k \times m$ (sites × measurements) and $\beta = -0.025$)

= prob($Z < -2 - \beta/\text{se}(\beta)$) + prob($Z > 2 + \beta/\text{se}(\beta)$)

where

$$\text{se}(\beta) = \sqrt{\sigma^2 / Sxx} \text{ and } Sxx = \sum_{t=1}^{T}\sum_{i=1}^{k}\sum_{j=1}^{m}(x_t - \bar{x})^2.$$

Given the monitoring times are fixed, we only have choice over $n=k \times m$. The power of detecting the trend of –0.025 units per year (or the –0.5 drop in 20 years) for a range of sample sizes is given in Table 9.

Table 9: Power of detecting the trend for pH change in a Sodosol used for continuous cropping

$n = k \times m$	5	10	15	20	25	30
Power	0.23	0.42	0.51	0.70	0.79	0.86

From Table 8 we see that a sample size of 26 is required to achieve the power of 0.80.

Note that between-site variance (τ^2) does not influence the estimation of the standard error of the trend β. It does however have a large impact on the estimation of the year means as shown by the combinations for $n = k \times m = 24$ in Table 10.

Table 10: Impact on the estimated variance of the mean of apportioning resources to either sampling more sites (*k*) or undertaking greater replication within sites (*m*).

K	2	3	4	6	8	12
M	12	8	6	4	3	2
var($\bar{y}_t$)	1.98	1.32	1.00	0.67	0.51	0.35

Modelling and monitoring as complementary activities

The previous sections have shown that considerable insight can be gained into the optimal design of a monitoring program through some preliminary statistical analysis. This can be undertaken in a more sophisticated way through the use of simulation models that represent the soil processes and land management systems of interest. For example, farming systems models such as APSIM (Keating et al. 2002) or PERFECT (Littleboy et al. 1989) can be used in conjunction with long-term climate records to generate a range of scenarios. The trends in soil properties generated by these models can provide more realistic representations of the patterns of change (e.g. non-linear or episodic). Statistical analysis of the simulation outputs can be then used to design appropriate sampling schemes.

Data analysis

The analysis of monitoring data is concerned with the detection of trends, cycles, outliers and noise. A summary of data analysis methods is beyond the scope of this report. A good treatment of statistical methods is provided by Manly (2000) while a summary of methods for water quality assessment, that is also relevant to soil monitoring, is provided by ARMCANZ/ANZECC (2000). As with most aspects of monitoring, advice should be sought from a qualified statistician. However, an overly rigid statistical approach (e.g. complete reliance on tests of statistical significance) has some limitations.

Statistical significance and lines of evidence

There are very few long-term programs of soil monitoring in Australia and it will be years before conclusive results will be generated by monitoring programs of the type recommended in this report (see below). It can be envisaged that even with a reasonably comprehensive monitoring program, there will still be situations where soil change is suspected but conclusive data are lacking. Decision-makers require advice on likely changes in soil and land resource condition and they cannot wait until there is statistical certainty in trends from long-term monitoring sites. Interim procedures are required so that assessments of change can based on risk, probability and expert opinion (Vaughan et al. 2001). There are several options:

- Simulation modelling can be undertaken to determine whether suspected trends in soil condition are likely to become clear.
- Panels of experts can be assembled to undertake critical reviews and judge whether a perceived problem is significant – these panels would draw on all lines of evidence (e.g. process understanding, published literature, anecdotal evidence, initial monitoring results, simulation modelling).
- Panels of experts can also engage in creative scenario writing to thoroughly consider a range of future states. These scenarios can be used to devise programs of investigation that lead to early detection (Munn 1988).

Implications

This section has considered some general issues of detecting soil change over time. There are several implications.

- A large sampling effort is often required to detect the relatively small changes over time against the often-large spatial fluctuations that occur at a range of scales.
- Some soil properties can be readily monitored (i.e. those that are less spatially variable, responsive to management and easy to measure) while others are impractical because of the large spatial variability and high cost of measurement.
- pH and organic carbon are two important soil properties amenable to monitoring.
- It is practical to monitor soil change at local and regional scales. However, it is essential to repeat measurements over time at the *same* site and to then analyse differences between individual sites over time. The alternative of comparing the mean value of a soil property across all sites at time zero with the mean for all sites at a later time is an inefficient and ineffective method for detecting change (Figure 11).
- Monitoring soil change relies ultimately on good quality measurement at representative field sites often over extended periods (i.e. decades).
- Information on land management is critical for interpreting the results of monitoring.
- Maps of soil properties, land types or so-called sustainability indicators are an inefficient means for detecting change because their predictive capability for a given location is low so comparisons of maps prepared for different times will have a very low accuracy and precision. However, the maps are valuable because they show patterns of resource condition and provide an essential tool for designing and prioritising monitoring efforts. They are also necessary for analysing and generalizing results from a monitoring program.
- Mapping, modelling and monitoring must be viewed as complementary activities.

10 A blueprint for monitoring soil change in Australia

An understanding of actual or potential soil change caused by land management is an essential input to natural resource management. This report has considered many of the technical challenges involved in obtaining this understanding. The cost of soil monitoring is substantial, and investment has to be balanced with other demands (e.g. funding for survey or modelling). Developing a comprehensive case for investment in soil monitoring is beyond the scope of this report. However, clear directions are apparent for improving the monitoring of soil change. These directions are outlined – they are intended to provide a blueprint for the development of a coordinated strategy involving government, industry and community groups. Commentaries on relative levels of investment are presented in the final section.

To be useful, programs of soil monitoring must have the following.

- Monitoring programs require a clear purpose and should be closely linked to a decision making process at the farm, catchment, region, state or national level, or a scientific purpose.
- Monitoring sites should be located *after* land resource or ecological surveys have been undertaken to ensure the sites represent well-defined landscape units and systems of land use. This allows results to be extrapolated to other locations with confidence.
- Monitoring and computer modelling activities must be carried out in a complementary way. The latter are undertaken to assess whether soil change can be detected in a reasonable time. Modelling should also be used to help determine where to locate monitoring sites and to specify the frequency of measurement. Modelling can also be used to help extrapolate results from monitoring sites.
- Monitoring should be directed to areas where early change is likely (Vos et al. 2000, Tegler et al. 2001). This avoids wasting resources on measurement programs and it ensures that monitoring provides an early-warning system.

Figure 12 provides a general view of how complementary sources of natural resource information are gathered over a range of scales. To ensure a balanced approach, investment is required in the following areas.

Community and landholder programs

A range of programs and guides to soil monitoring have been produced for landholder and community groups (e.g. Hunt and Gilkes 1992). Most have a strong focus on improving land literacy and they have been of great value through their contribution to improved land management. While there is potential for capturing the information gathered from such programs to construct district or regional overviews, the task of detecting soil change using this approach will be very difficult because of issues relating to accuracy and precision of measurement, quality control, and inevitable bias in the location of monitoring sites. Note also that most community programs encourage a loose form of survey monitoring rather than activities with strict schedules for repeated observations at specified locations. A large investment would be necessary to upgrade community and landholder programs so that they generated soil data of a similar standard to those gathered in, for example, the Streamwatch program for water quality monitoring.

It has been beyond the scope of this report to assess the efficacy of community and landholder programs for soil monitoring but it is logical to continue investment to support community programs where motivation is strong and technical capacity is sufficient.

Industry programs of soil monitoring

Agricultural industries have greatly expanded their monitoring activities in recent years. Programs such as TOPCROP (http://topcrop.grdc.com.au/) and Farmscape (Dalgliesh and Foale 1998; http://www.farmscape.tag.csiro.au/) have encouraged a more technically sophisticated approach to farming. Very large quantities of valuable analytic data are collected each year with most relating to plant nutrition. A significant achievement of the National Land and Water Resources Audit involved the synthesis and analysis of a portion of these data.

There is a need to create partnership schemes to encourage the sharing or pooling of such data. The pooled data provide industry groups with information on trends in resource condition. For the same reason, they are invaluable to public agencies responsible for natural resource management. However, mechanisms for respecting commercial sensitivities are necessary. Where possible, support should be provided to develop clear protocols for measurement, undertake training, develop and maintain databases, and ensure regular feedback on results.

The full value of data sets generated by industry will only be realised when evaluations are undertaken of the validity of regional scale conclusions. In particular, statistical assessments of bias, precision and accuracy are required. It may be difficult to ensure a key feature for efficient soil monitoring – repeat measurements at the same sites over time.

Statistically-based soil monitoring for high-priority issues

There is a compelling case for establishing several clearly focussed networks for monitoring soil properties in regions with substantial natural resource problems. These networks require good statistical design with careful stratification on land-use and soil type. It is envisaged that each network would involve up to several hundred sites. A prime candidate is the establishment of a monitoring network for pH in those parts of southern Australia and high rainfall zones in Queensland identified by the NLWRA (2002) as having a severe or potential acidification problem. Such a network would augment the existing extension programs and provide a reliable long-term assessment of the effectiveness of current strategies for amelioration. Proposals for statistically-based networks should be developed by the appropriate panel of experts (see below).

Land resource survey

The land resource survey coverage of Australia should be completed to a level of detail proportional to the intensity of land use. The present incomplete land resource survey coverage severely compromises the utility of soil monitoring and simulation modelling more generally. This is because rates of soil change under different systems of land management are highly dependent on the soil type. Land resource surveys provide a means for stratifying a region and for locating monitoring sites. They also provide essential information for interpreting the results from monitoring.

With some improvement, new land resource surveys can also provide a more effective basis for identifying priority regions for monitoring. To achieve this, land resource surveys need to provide better statements on resource condition. The establishment of a distributed set of reference sites during survey would provide many benefits for monitoring and modelling (McKenzie et al. 1994). These sites would be comprehensively characterized and allow the establishment of an approximate baseline for various soil properties (e.g. carbon, nutrients, aeration, microbial biomass etc). Some of these sites could also be used for monitoring.

Soil monitoring as part of long-term ecological research

There is a need for a restricted number of substantial long-term scientific studies of ecosystem and landscape processes in catchments that represent, in the first instance, the main regions used for agriculture and forestry in Australia. These long-term studies would include measurement and modelling of water, sediment, nutrients, biological production and related processes. These studies are essential for developing an improved understanding of processes controlling the sustainability of current and planned systems of land-use. In particular, there is a need to understand the impacts of changing land use (e.g. revegetation, increasing use of fertilizers) on nutrient movement, catchment water balance and the ecology of waterways.

Excellent prototypes for such studies exist in the United States, with the 24 Long Term Ecological Research sites (http://lternet.edu/), and in Canada, with the Ecological Monitoring and Assessment Network (Vaughan et al. 2001; http://www.eman-rese.ca/eman/). Some long-term studies have been established in Australia, particularly in relation to forest management (e.g. the Warra site in Tasmania (http://www.warra.com/) and others documented by House and Simpson, 1998). The CSIRO Heartlands Initiative (http://www.clw.csiro.au/heartlands/) also provides a good model with its holistic focus and emphasis on participative research. However, a far more comprehensive approach is required both in terms of the regions represented and the range of processes measured.

Expert panels and assessments

The National Land and Water Resources Audit brought together many groups of experts to deliberate on a wide range of matters. There is a strong case for maintaining several panels to undertake expert assessments. More specifically:

- Decision-makers require advice on likely changes in soil and land resource condition and they cannot wait until there is statistical certainty in trends from long-term monitoring sites. Interim procedures are required so that assessments of change can be based on risk, probability and expert opinion (Vaughan et al. 2001). There is also a place for creative scenario writing to thoroughly consider a range of future states (Munn 1988).
- Oversight of monitoring activities requires informed design, planning, management, assessment and review. An expert panel has a function in each role.
- It would appear prudent to have several expert panels responsible for soil-related matters. A suggested set would include panels on acidification, nutrient balance, soil biology, contaminants, soil physical quality, erosion and salinity. A panel is also required to integrate and evaluate the interactions and combinations.

Organization and investment

Australia has a long history of having a complicated and at times very poorly coordinated organizational system for acquiring and managing information on soil and land resources (see Taylor 1973; Gibbons 1983; Christian 1978; McKenzie 1991). There have been some notable improvements during the last decade but many more are required. A stable organizational and funding structure for acquisition and analysis of land resource data is essential. A steady but modest stream of funds over the long-term is also more likely to be beneficial than a large investment over a short period – as noted earlier, investment levels for land resource survey equivalent to those of the last decade would be adequate. This allows accumulation of expertise and consistency of approach over long periods. A high priority is ensuring the groups responsible for land resource survey are closely linked to groups undertaking monitoring and simulation modelling (e.g. of farming systems, catchment hydrology and groundwater).

The National Land and Water Resources Audit has identified both the regions where soil change is of major concern (NLWRA 2001) and the relative benefits of halting or reversing current trends (NLWRA 2002). Key findings include:

- Nutrient depletion or off-site impacts of excessive fertilizer use are significant in several regions and monitoring is required to optimise economic and environmental objectives.
- Soil acidification looms as a major soil degradation issue in all states. Its economic significance is approximately six times greater than salinity. Regions at greatest risk have been identified. Monitoring pH is arguably the most straightforward of all soil properties – monitoring networks in regions

at risk are essential to confirm the severity of the problem, track changes and provide feedback on the success or otherwise of remediation strategies.

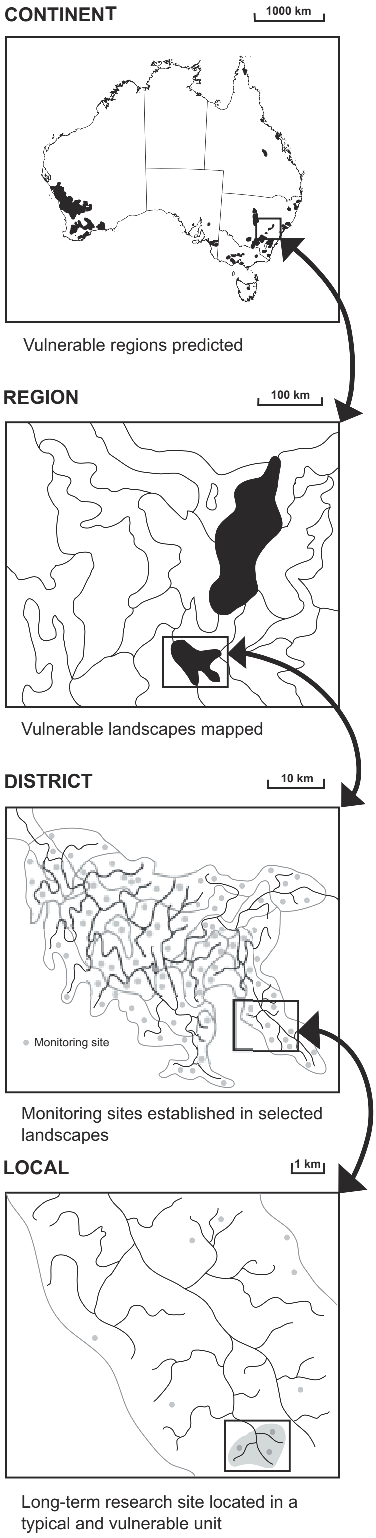
- Sodicity has been recognized as a major impediment to agricultural production. While not addressed directed by NLWRA (2002), levels of sodicity have increased in some regions, particularly in irrigated areas where waters contain appreciable levels of sodium. Well-organized programs are needed for monitoring sodicity in irrigated areas. Carefully targeted monitoring of dryland areas may be beneficial, particularly where programs of amelioration are underway.

Public investment in land resource survey has been shown to generate benefits far in excess of the costs of survey (ACIL 1996). Similar analyses are not available for soil monitoring, simulation modelling or studies of environmental history (see Figure 1) and this needs to be rectified to ensure appropriate investment. However, lack of investment in natural resource information will cause several problems.

- Resources will be poorly directed for natural resource management (e.g. Landcare activities, revegetation, support for beneficial land management activities).
- The magnitude of natural resource problems will not be appreciated – avoidable environmental degradation or low agricultural productivity being the result.

Carefully designed and targeted systems for monitoring soil change—closely linked to both land resource survey and modelling—are an essential component of the information gathering process to ensure sound natural resource management in Australia.

Figure 12: Overview of monitoring and natural resource information provision at various scales



Mapping	Modelling	Monitoring
• Synthesis • ~1:2,000,000 scale • Broad landscape types and interpreted soil properties • Predict locations of vulnerable regions	• Gross simplification of landscape processes • Broad material budgets • Exploratory analysis	• Proxy monitoring using satellite-based methods (e.g. land cover) supported by synoptic mapping and modelling.
• Soil-landscape units • 1:100,000 scale • Delineate vulnerable landscapes • Limited laboratory testing	• Generalized hydrological and simplified farming system modelling • Input data from survey and limited direct measurement • Some capacity for validation from field experiments	• Proxy monitoring of land-use and management. • Field verification of proxy measures • Survey monitoring feasible • Programs to improve land literacy
• Soil map units • 1:25,000-1:100,00 scale • Most sensitive lands identified to guide location of monitoring sites	• Farming system modelling at enterprise level and hydrological modelling at intermediate catchment scale • Input data from direct measurement • Validation from field experiments	• Simple monitoring • Network of sites for direct measurement of soil change in selected and vulnerable landscapes • Programs to improve land literacy
• Full inventory restricted to the long-term ecological research site • More detailed than 1:10,000 • Intensive field measurement to support experimental program	• Detailed deterministic modelling • Comprehensive validation of models	• Integrated monitoring • Major long-term ecological research site • One of perhaps 20 or so sites in Australia • Direct monitoring of landscape processes

Appendix 1: Checklist of design considerations

The following questions are intended to provide a general checklist of design considerations for a soil-monitoring program – they have been based loosely on Jeffers (1978) and Usher (1991). The section on defining the purpose for soil monitoring in the main report should be consulted in conjunction with the checklist.

Purpose

☐ Have the objectives of the monitoring program been stated clearly and explicitly?

☐ Does the problem require soil information that can only be provided through monitoring and have other sources of information been fully exploited (e.g. mapping, modelling and narratives)?

☐ Will the information collected during a soil-monitoring program provide valuable scientific information, or input to a decision-making process, or both?

Method

☐ Has a system narrative been prepared for the landscape or regions of interest?

☐ Are there appropriate soil and land resource maps to support all phases of the monitoring program (particularly the design and extrapolation components)?

☐ Are simulation models available for the soil and landscape processes of interest and can they be used to help design the monitoring program?

☐ Can the problem be solved by simple monitoring, survey monitoring, proxy monitoring or integrated monitoring?

☐ Are there aspects of complex behaviour due to factors such as feedback loops, and will integrated monitoring be required to gain sufficient understanding?

☐ Can the process of interest be measured within the requisite time, and are its dynamics either, very slow, episodic or controlled by rare events?

☐ What are the most appropriate scales or levels for monitoring the processes of interest, and will measurement at the site level be sufficient to capture trends and allow generalization to larger areas?

Sampling

☐ Has a comprehensive sampling plan been prepared and documented in a form that will be readily available over the full life of the monitoring program?

☐ Will purposive sampling be used, and if so, are the implications of inevitable bias fully appreciated?

☐ What is the scope of inference of the monitoring program?

☐ What is the target population?

☐ Will the planned sampled population coincide with the target population?

☐ If different combinations of soil, climate and land-use are to be monitored, will their status change during the course of the monitoring program?

☐ What is the expected magnitude of spatial and temporal variation in the soil variables being measured and is a pilot study required to design an efficient measurement program?

☐ Will a fixed location or flexible network be used?

☐ Has an unambiguous soil individual been defined and is it large enough to sustain repeated measurement?

☐ Can different operators visit the planned monitoring site at subsequent times and be able to adhere to the original sampling plan (e.g. repeat the stratification of the soil individual both vertically and laterally)?

☐ Are there clear protocols for visiting sites and have precautions (e.g. rules for traffic) been taken to avoid inadvertent disturbance that may affect later measurements?

☐ Are the dynamics of the soil process of interest understood sufficiently to allow specification of the frequency of measurement?

☐ What will be the frequency of measurement and are there issues of timing that require standardizing (e.g. time of year, soil water content)?

☐ Will specimens be bulked, and if so, are there clear protocols for mixing and homogenizing?

Measurement

☐ Has a comprehensive measurement plan been prepared and documented in a form that is readily available over the full life of the monitoring program?

☐ Do the soil variables have a direct link to the natural resource management problem or scientific issue being addressed?

☐ Can the soil variables of interest be measured accurately and reliably?

☐ Can the behaviour of the soil variables be predicted without the need for monitoring?

☐ Has the cost of soil measurement been estimated (with the input of a qualified statistician) and is it within the resources of the planned program?

☐ Are there sufficient resources to ensure both characterization of the site and profile, as well as monitoring the particular soil properties of interest?

☐ Are there appropriate measurement methods for characterizing land management?

☐ Are there appropriate measurement methods for characterizing relevant environmental variables (e.g. weather, vegetation)?

☐ Are the laboratory measurement methods capable of providing the accuracy and precision required by the monitoring program?

☐ Are there appropriate laboratory standards to ensure accurate and precise measurement over long periods of time?

☐ Does the laboratory participate in inter-laboratory comparisons and quality assurance programs (e.g. under the auspices of the Australian Soil and Plan Analysis Council (ASPAC))?

Archiving

☐ Is there a well-organized system for archiving specimens?

☐ Is the archival system connected with the data management system?

☐ Are the containers and labelling systems adequate?

☐ Is the physical environment of the soil archive appropriate for long-term storage?

Data Management

☐ Has a comprehensive data management plan been prepared and documented in a form that is readily available over the full life of the monitoring program?

☐ Is there a system for recording all relevant ancillary data collected during a monitoring program?

☐ Is there a system for defining data quality and are records updated and checked on a regular basis?

☐ Are there systems for backing up all data?

☐ What plans have been made for regular reporting of results?

Analysis

☐ Have the methods for statistical analysis been defined and is there a documented plan?

☐ Have the hypotheses to be tested in the analysis of the results been defined at the outset?

☐ Will the methods of analysis allow the detection of trends, cycles, noise and outliers?

☐ Is there access to a qualified statistician advice and will he or she be available during all phases of the monitoring program?

People and institutions

☐ Have individuals and organizations agreed to take responsibility for the monitoring program?

☐ Have appropriate staff with sufficient training available for all tasks?

☐ Are there plans for staff turnover, technological change (e.g. computer software) and institutional instability?

☐ Have reliable funding sources been secured?

Fulfilment

☐ Are there rules for stopping the monitoring program or will a regular program of review be required?

Appendix 2: Layouts for soil monitoring sites

Many layouts can be used for soil monitoring sites and some options are found in Hornung et al. (1996) and Papritz and Webster (1995b). The layout in Figure 13 is intended as a starting point for designing a soil-monitoring site. There has been no allowance for the installation of in situ measurement or collection systems (e.g. access tubes for neutron moisture meters or soil solution samplers). Figure 13 represents a 25 × 25 m soil individual subdivided into 25 cells. The design allows for five periods of sampling. For each period, five cells are randomly selected, one from each of the five blocks (i.e. columns A-E). In Figure 13, each cell is divided into four strata and a sample is randomly located in each. Bulking of soil specimens is possible at the level of the cell, block or site depending on the overall design. The rectangular areas outside the site are used for soil pits to enable profile characterization.

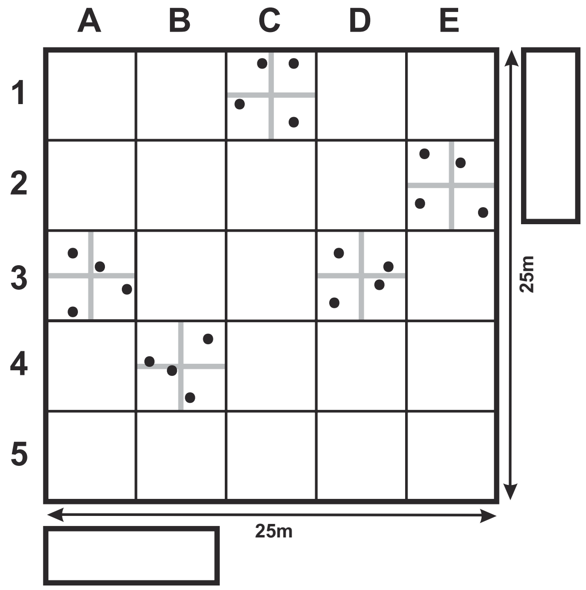


Figure 13: A possible layout for a soil-monitoring site.

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