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Soil Health for Victoria's Agriculture
Context, Terminology and Concepts

MIS 07898 Final Report

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Victoria
The Place To Be

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Summary

This report has been prepared to provide a baseline for soil health work in DPI with respect to the use of terminology, a general understanding of soil health within agro-ecosystems and some frameworks that can be used in future work. Soil health is an essential aspect of environmental health as it supports a range of ecosystem services. This is a complex topic and a single report can do little more than indicate useful sources of literature and an outline to provide context. There is a wealth of literature on soil health and soil quality but terminology and definitions sometimes differ and therefore waylay the unwary reader. Some aspects have been dealt with in more depth than others but I have attempted to provide a balanced and comprehensive overview of soil health from a scientific point of view. The focus is particularly soil health for agriculture, but the implications of soil health for environmental health and for provision of ecosystem services are also discussed. The international context for soil health has been summarised with key references provided. Priorities for soil health are presented through a general framework that is used in landscape research and decision making. Appendices comprise a case study in extension for soil health in NE Victoria, a review of the use of remote sensing in soil health assessment, and a review of the biological aspects of soil health and research needed for soil biology.

This report should be used as the primary reference for terminology and frameworks for soil health in the DPI Healthy Soils project (MIS 03250).

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The Agriculture Division of DPI is acknowledged for funding this project. Additional funding was received from DSE, North Central Catchment Management Authority and West Gippsland Catchment Management Authority to support other aspects of soil health review or research associated with this project.

Several scientists in DPI contributed directly to the project through advice, analysis or written contributions. Pauline Mele (DPI Rutherglen) is acknowledged for contributing a soil biology perspective on soil health and James Nuttall (DPI Horsham) for his review of remote sensing as a surrogate for plant and soil health. Nathan Heath (DPI Wodonga) is acknowledged for providing a case study for soil extension based on experiences in North East Victoria. Keith Reynard (DPI Bendigo) carried out a review of data for soil and land in the North Central CMA region. Joanne McNeill and Doug Crawford compiled and analysed soil and land data for the West Gippsland CMA region, using the Land Use Impact Model (LUIM) to develop a regional soil erosion management plan. Doug Crawford (DPI Werribee) and Nathan Robinson (DPI Bendigo) carried out a review of DPI soil datasets and this is provided as a separate report. Jim Allinson (consultant) and Stuart Boucher are acknowledged for their contribution in preparing a review and report for DSE on the case for investment in soil health.

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During the course of this project, team members were involved in DPI workshops related to policy and project development, with CMAs in the development of soil health strategies and in presentations at public and scientific forums on soil health. Related projects have also helped with formulation of some of the ideas presented in this and the associated reports. In particular, the ORL 'Our Landscape' project (MIS 05188) through which the framework attributed to Carl Steinitz has been applied, and the GRDC subsoil constraints project (MIS 07541) which entailed related data analysis for soils in South East Australia especially for functional aspects of subsoils.

Soil Health for Victoria's Agriculture:,

Context, Terminology and Concepts.

Richard MacEwan

1 Introduction

This report has been prepared for the State of Victoria's Department of Primary Industries (DPI) project 'Soil Health for Victoria's Agriculture' (MIS 07898). The project was funded for one year ending in June 2006 under the Agriculture Division's key program 1.1 'Integrating Farming Systems into Landscapes'. The foundation work of this project supports implementation of the DPI 'Healthy Soils' project[1] (MIS 03250) which is funded under the Environmental Sustainability Action Statement (ESAS) until June 2010.

The 'Soil Health for Victoria's Agriculture' project had three partner agencies that provided co-funding:

1. The Department of Sustainability and Environment (DSE) paid for the preparation of a document defining the role of soil health beyond agricultural production, and the case for government investment.
2. West Gippsland Catchment Management Authority (WGCMA) commissioned land use impact assessment of current land use to assist in development of a soil erosion management plan.
3. North Central Catchment Management Authority (NCCMA) contracted the collation and review of the region's soil and land data in preparation for strategic planning for the region's soil health.

Separate reports have been provided for the partner agencies.

The purpose of this report is to provide the Department of Primary Industries (DPI) and the Department of Sustainability and Environment (DSE) with sufficient science basis to support the development of priority actions for soil health. This report focuses largely on the primary production aspects of soil health for Victorian agriculture. Whilst this does include the environmental context for agriculture, a separate companion report for DSE has been prepared that more specifically describes the case for government investment in soil health issues beyond those concerned directly with agricultural productivity.

Soils are the fundamental agricultural resource, they are variable in the qualities they offer for agriculture and they differ in their requirements for management. There is considerable history of soils research in Victoria and Australia that has resulted in a knowledge legacy that is not readily available to agricultural practitioners, land management authorities and agricultural policy makers. Since the early days of soil conservation there have also been fundamental changes in government policies concerning land degradation, with an increasing emphasis on environmental monitoring and strategic planning for protection of land and water.

1.1 Background

The management of soil for agricultural production has been fundamental to the survival and growth of human populations for the past 10,000 years. In the last century radical changes in agricultural practices have intensified the pressure on soil resources. Plant and animal improvement programs, increasing mechanisation, irrigation, artificial fertilizers and agrochemicals for weed and pathogen control have all contributed to higher production per unit area for the full range of foods and fibres produced from soil.

[1] This project also incorporates the 'Healthy Soils for Sustainable Farms' project funded by Land and Water Australia and GRDC until June 2008 and June 2009 respectively.

Concurrent with these changes in production systems there has been an unprecedented growth in human population globally and this has increased the pressure on soil and land resources to serve other needs.

Competition for land resources has resulted in loss of high quality soils and potentially productive agricultural land to urban and infrastructure development, whilst expansion of agricultural and other human activities into the 'natural' environment has generated major concerns about ecological sustainability, the role of biodiversity, and the condition of rivers, lakes, groundwater and oceans. In many instances the soil resources themselves have deteriorated or become unproductive through, for example, erosion, salinisation, fertility decline, or contamination.

Global projections for human population food requirements by 2050 indicate that these will be at least double their present levels (FAOSTAT 1998). Given the limited availability of land and water, most of the increase in production will have to be met from existing soil and water resources or from marginal agricultural land. Pressure on the soil resource will therefore inevitably increase along with associated pressures on ecosystem services that are dependent on soil. As a major exporter of agricultural produce ($17.6 billion value annually according to the National Land and Water Resources assessment in 2001) Australia makes a significant contribution to global food security. The state of Victoria substantially supports this effort as well as providing national and global food security. Agricultural sector value of Victorian exports was estimated as $7.2 billion for 2001-2001 and $5.4 billion in 2003-2004 (this decline was attributed to drought and a high Australian dollar) (Business Victoria, 2005). The state government target is for an increase in agricultural export value to $12 billion by 2010. Achieving this target as well as maintaining or improving environmental quality depends on a thorough matching of soil and land qualities to management practices and consequent pressures.

Soil is a critical ecological component that directly serves many ecological functions, supporting plant growth, absorbing and recycling nutrients, storing water, mediating as the interface between rainfall, runoff, interflow and recharge, and contributing to atmospheric regulation. In agro-ecosystems, soil is subject to greater change than in natural (non agricultural) ecosystems, the primary purpose in agro-ecosystems being to secure a carbon harvest in the form of food and fibre. Consequently, balances between inputs, outputs, storage and nutrient recycling are highly altered compared with natural systems.

Whilst there is a large body of specialised scientific knowledge to support management of soil in these systems, it is only recently that more holistic concepts embodied in terms such as 'soil quality' and 'soil health' have been seriously adopted in the scientific literature and have become part of the language of government policy. The topical nature of these terms, the mixed debate surrounding their meaning, and the urgent issues facing agriculture and the environment with respect to soil management, and the increased farmer interest in soil health, all provide timely context for this report.

This report and associated papers provide:

- discussion of the national and international context for soil health,
- definitions for terminology associated with these more holistic paradigms for soil,
- descriptions and review of the science that underlies our current understanding of soil health,
- a summary analysis of Victorian soils data pertinent to soil health
- recommended priority actions for investing in soil health

1.2 International context for soil health

Global

The leading global organisation in this area is the United Nations (UN). The UN has a history of investment in soil related issues through the Food and Agriculture Organisation and the United Nations Environmental Programme. Soil survey, land evaluation and soil conservation are the dominant themes in the work of the UN and FAO with soil quality and soil health implied rather than explicit. The FAO soils bulletins published since 1965 and the land and water bulletins published since 1995 contain substantial scientific knowledge and support for soil management. In particular, early publications on soil survey and land evaluation (FAO 1967, 1976) provided the context for more specialised advisory bulletins (FAO 1983, 1985), integrated land use planning (FAO 1995) and the use of indicators (FAO 1997). Many of these publications are available as electronic documents through the FAO web pages (http://www.fao.org/publishing/). The FAO literature is largely directed towards less developed countries, focussing on extremes of degradation, issues affecting food and water security and using land within its capability.

The UN have also been important agents for policies concerning soil and land management; significant milestones being the World Soil Charter (FAO 1982), Agenda 21, and the United Nations Environmental Programme's strategy for land use management and soil conservation (UNEP 2004). The latter proposed an ecosystem approach thus relating land and soil issues to other environmental focal areas and built on the 1982 World Soil Charter (FAO 1982) which had called for commitment by governments and international organisations to manage the land for long term advantage rather than short term expediency.

New Zealand

New Zealand has a significant history of work in soil quality and soil health. The 1991 Resource Management Act (RMA) Section 35 requires Regional Councils to report on the "life supporting capacity of soil" and whether current practices will meet the "foreseeable needs of future generations". Protocols for monitoring land and soils were established in a six year trial commonly known as the '500 Soils Project' (Sparling *et al.* 2004), and an interpretive framework for reporting at a regional scale was developed (Lilburne *et al.* 2004). The 500 soils project was evaluated by Hill *et al. (*2003) who recommended that seven soil quality properties (total C, total N, mineralisable N, pH, Olsen P, bulk density and macroporosity) validated in the work should form part of any soil quality monitoring programme. The requirements of the NZ RMA for reporting on soil quality at national and regional scales have parallels with Australian partnership agreements for NRM but, up to this point, there has not been the equivalent investment in monitoring Victorian soil condition. Lilburne *et al. (*2002) have described the strong relationship between legislation, policy and science for soil quality in New Zealand. The situation in Victoria, Australia, is such that legislation (the CaLP Act of 1994) and soil health policy (DPI 2006) are also aligning with funding to provide science to underpin implementation of that policy.

SLURI

Recent developments in New Zealand have seen a rebirth of soil science in the form of a 'Sustainable Land Use Research Initiative' (SLURI), a national centre for maintaining and managing New Zealand's soils (NZ Agencies 2004). This is effectively a collaborative venture devised by separate Commonwealth institutes (HortResearch, AgResearch, Crop and Food Research, and Landcare Research) in order to gain government support for soils research.

SLURI's five priority areas (http://www.sluri.org.nz/index/page/25) for new science are:

1. Intensification and Soil Functioning - Tools to ensure maintenance of soil services in the face of pressure from increasing inputs.
2. Managing Land-use Change – Provision of knowledge to assess the performance of land-uses now being carried out on soils not formerly used for these purposes, and the prediction of plant performance to express certain traits or qualities.
3. Resilience under Change – New system designs to sustain our existing land-uses in the face of the exigencies created by increasing climate variability and extreme weather events.
4. Valuing the Natural Capital of Soils – Research is required to assign value to the natural capital of our soils and waters to underpin rational land-use decision-making and resource allocation by industry and policy makers.
5. Landscape Designs – Tools are required to integrate and scale-up our understanding of enterprise and sector behaviours across the mosaic of land-uses to permit equitable resource allocation and sustainable coexistence of land uses.

Europe and the United Kingdom

The European Union (EU) adopted a European Soil Charter in 1972 and a revision of this charter was subsequently adopted in 2003 (Council of Europe 2003) in response to continued trends in soil loss and degradation and the need for a legal instrument across the member countries of the EU. In September 2006 the EU adopted a thematic Strategy for Soil Protection consisting of a Communication from the Commission to the other European Institutions, a proposal for a framework Directive (a European law), and an Impact Assessment (European Commission 2006a). Five technical working groups for the soil thematic strategy, comprising experts from the member countries, contributed background reports to the

Commission in 2004. Reports from these groups on erosion, organic matter, contamination and land management, monitoring, and research are all available online (European Commission 2004; European Commission 2006b). Eight principal issues identified in this strategy are erosion, organic matter decline, contamination, salinisation, compaction, soil biodiversity loss, sealing[2], landslides and flooding. One of the issues associated with soil sealing is a loss of soil diversity (pedodiversity) and this has led to proposals for soil types to be given equivalent conservation status as that given to species. The current scientific knowledge in the EU on soil biodiversity and its behaviour is regarded as too limited to allow for specific provisions in this Directive aiming at its protection.

In the United Kingdom, parallel initiatives have been developed for England and Wales, and for Scotland with strategies for soil quality or soil health being recently adopted (DEFRA 2004, SEPA 2006).

Canada

The Canadian Government have been active in the monitoring and management of soil health. Twenty-three benchmark sites were set up across Canada in 1989 to monitor soil quality under representative farming systems and landscape conditions. Measurements of key soil properties relating to land use and land management were made over several years and provided baseline data in 1995 for future monitoring. Results of the program were reported as a strategic framework for soil health in 1995 (Acton and Gregorich 1995). The report concluded that new government policy for soil conservation was needed, aimed at achieving sustainable agriculture and built on the understanding that agro-ecosystems are part of the broader environment. This reflects a change seen elsewhere in the world where, initially, soil conservation programs focussing on soil loss and erosion management have broadened in their approach. Acton and Gregorich (1995) also acknowledged the issue of scale and proposed that soil management programs are best designed at the farm level, integrating management practices to suit specific, local soil needs.

Within Canada, Alberta is the state that has shown the greatest uptake of the national strategy. Alberta has had a program of monitoring for soil health in place since 1997 and there is considerable documentation of this program available online (Alberta Government 2006). Key documents prepared recently in this program are:

- A description of site selection and sampling protocols for the Alberta benchmark sites (Cannon 2002).
- An extensive review by Winder (2003) describing 52 environmental/soil monitoring programs from around the world.
- A review synthesising literature on soil quality indices (current to December 2003) to inform recommendations for use in the Alberta Environmentally Sustainable Agriculture (AESA) Soil Quality Program (Hall 2003).
- A review of soil quality indicators with implications for Alberta's agro-ecosystems (Bremer and Ellert 2004).

United States of America

Research and extension for soil quality and soil health have been prevalent in the United States since the early 1990s and much of the early literature on soil quality has its origins in the USA. Seminal publications such as those by the Soil Science Society of America (Doran and Jones 1996; Doran *et al.* 1996) provided the foundation for much of the language and approaches to soil quality and soil health adopted internationally. At the time of these publications, the United States Department of Agriculture (USDA) Soil Quality Institute produced a range of fact sheets and technical notes on soil quality that were widely available via the world wide web. Much of the work has been highly practical in nature and geared to the development of soil quality score cards and assessments for use on farm, with several of the states developing their own applications. A recent review by Wienhold, Andrews and Karlen (2004) emphasises the potential for a broadly based soil quality index.

[2] 'Sealing' of soil refers to the sealing over of the soil surface by urban structures, such as roads or buildings, and a consequent loss of soil functions in particular those affecting hydrology.

1.3 Soil health context in Victoria, Australia

Soil protection in Victoria is historically based in soil erosion management and, subsequently, salinity. The work was led by the Soil Conservation Authority, later the Department of Conservation, Forests and Lands, and more recently the Department of Natural Resources and Environment. In 1991 the Victorian Office for the Commissioner of the Environment commissioned a substantial review of the impact of agriculture on the environment and identified a number of important soil issues (OCE 1991). The Department of Agriculture, its predecessors and successors (latterly NRE and now DPI) focussed on soil issues most affecting production (waterlogging, acidity, soil structure management) but has now taken up the lead for work on the more encompassing topic of soil health. During the development of the Victorian Catchment Indicators (Catchment and Water Division, 2001) program, a working group from government and University attempted the task of developing a soil health or soil quality index as suggested in the terms of reference provided by consultants for that project. Some progress was made towards this end but the proposed initial setup cost and ongoing monitoring costs were prohibitive within the budget of the funding division of NRE (Catchment and Water). There was also a lack of confidence in the ultimate value of such an exercise.

Recent impetus for soil health came from a government inquiry into soil acidity (ENRC 2004) and the government response to this inquiry (State of Victoria 2004) which led to development of a policy framework by DPI (DPI 2006). Planning for implementation of soil health work was carried out in parallel with the policy framework development and work commenced in the project reported here (Soil Health for Victoria's Agriculture, MIS 07898).

1.4 Developing a program for soil health in Victoria

The primary reason for this current project is to assist in setting the foundation for a program of work supporting soil health in Victoria. This is given context by the framework for soil health written by DPI's agricultural policy group (DPI 2006). The project team determined several purposes for an integrated soil health program. Such a program should:

- Be the vehicle for enactment of government policy on soil health.
- Provide a blueprint for implementation of an integrated program of soil research, extension, adoption and improvement.
- Describe the accountabilities that relate to management of the soil resource (landholder, CMAs, DPI, DSE).
- Identify the partners and funding sources for delivery of elements of the program.
- Define CMA involvement in development and implementation.
- Develop an appropriate communication plan that provides a high profile for soil health and soil management.
- Assist in the requirements of government for environmental reporting (e.g. catchment condition).
- Provide a strategic assessment of the current agricultural landscapes in relation to soil health risks and needs. (Extent and severity of soil degradation issues such as acidity, and extent of major soil constraints to production).
- Consider potential impact of future changes in land use, land use practices, and climate on soil health.
- Describe the pathways to adoption of good soil management by the users of the soil resource.
- Support appropriate data management and information delivery for soils and soil health.
- Provide measures for soil quality and soil health that represent soil functional properties.
- Provide the means for comparison of soil quality and soil health across and within soil groups.
- Identify the opportunities in new technology and methods for understanding soil health.
- Identify research gaps that exist with regard to understanding soil quality and health in the context of different land uses or enterprises (industry forums). In particular, there is a need to define 'sustainability rules' for management of the soil resource in different contexts.
- Describe how future capacity (knowledge and skills) to support soil health R, D & E should be addressed.

Analysis of current capacity to satisfy elements of the knowledge chain (Figure 11) was seen as the necessary foundation to begin with. A flow diagram to link some of the fundamental science work and audit of capacity required as a basis for the soil health program development is shown in Figure 1.

1.5 DSE, CMAs and soil health beyond agriculture

There is a broader interest in and responsibility for soil health that extends beyond the interests of primary producers. The principal difference between the interests of agriculture as a sector and of DPI, DSE and CMAs as governance bodies is one of scale. At the agricultural enterprise and paddock scale, the interest in soil health is specific to soil type and production system. Issues of soil fertility, pests and diseases, agronomic management and gross margins drive the implementation of activities directed towards improvement of soil health for a farm. At the governance (policy and planning) level, investment decisions in soil health have to resolve differences between public and private benefit, societal duty of care, and generational costs and benefits. Decisions are directed to strategic planning for whole sectors of agriculture and for large, sometimes national, regions. DSE as a co-investor in this project have been provided with a separate report (Boucher and Allinson 2006). Several CMA regions have embarked on soil health strategies although these are hampered by insufficient data on land condition. In two regions, modelling approaches have been adopted using DPI's Land Use Impact Model (McNeill and MacEwan 2007). The LUIM outputs provide assessment of risks to soil health based on interpretation of soil susceptibility to degradation and assumptions about land management practices.

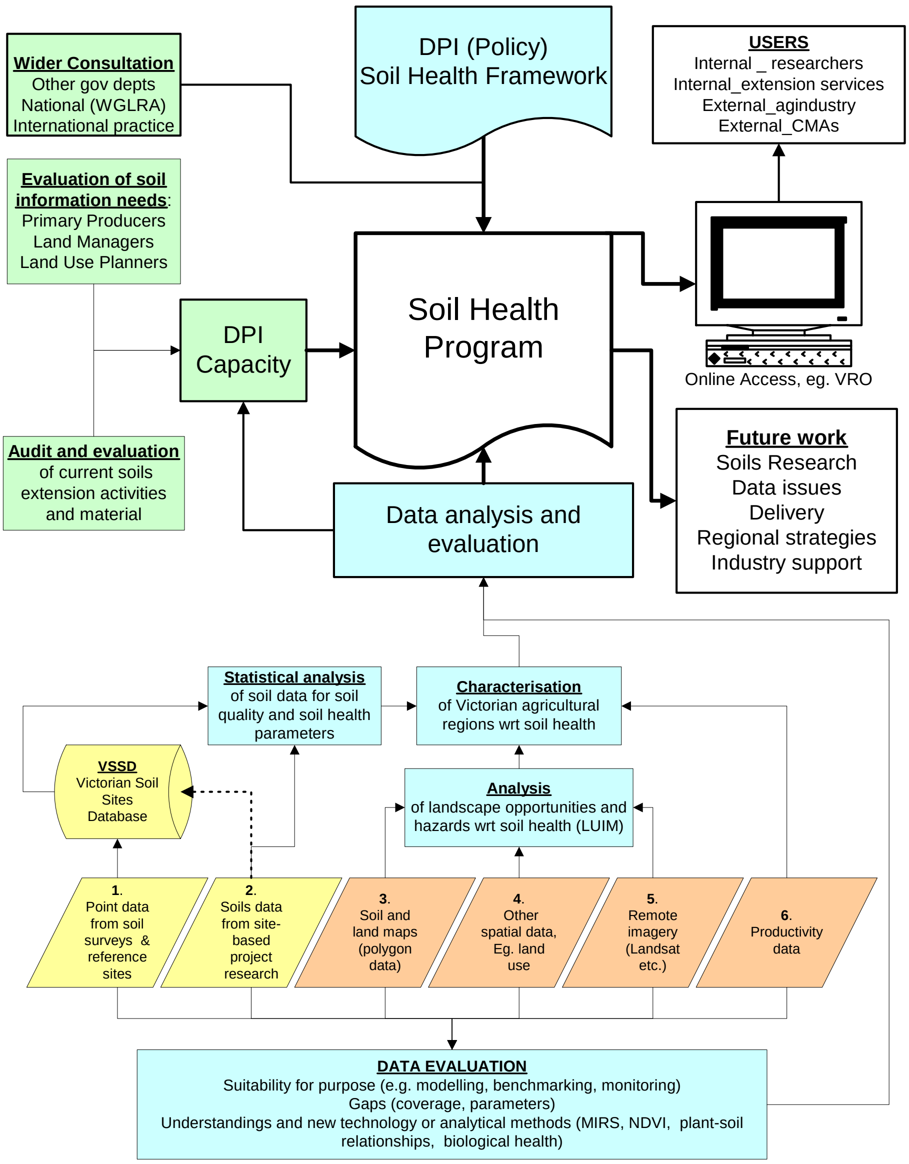

Figure 1 Flow diagram illustrating components of work in developing and delivering a soil health program.

Data analysis and evaluation

Data relevant to soil health are diverse and exist in a number of different forms. They are represented by the lozenge shaped blocks of the flow diagram in Figure 1, and have been numbered 1-6.

1. Soil point data (usually derived from auger or pit samples) have been collected as part of land resource assessment (LRA) projects and in the Reference Sites work funded previously by Agriculture Division (Mark Imhof's work). Much of the data collected in these projects is stored digitally in the Victorian Soil Sites Database (VSSD).
2. Soil point data collected at research sites. At present there is no protocol for ensuring that such data become part of statewide datasets. If readily accessible these data should be entered into the VSSD.
3. Soil and land maps. These are polygonal data sets (spatial coverages at various scales) derived from interpretation of soil point data and other land attributes. These coverages are representative of soils and landforms across Victoria and, in some instances, have been interpreted in relation to land capability and potential for soil degradation. They are particularly useful for modelling or evaluating environmental risks if used in conjunction with land use practice information.
4. Land use data. Mapping of land use is currently being completed for regions of Victoria. Australian Bureau of Statistics (ABS) also provides data on land use and practices. These data can be used in modelling the potential impact of agriculture on soil health using the Land Use Impact Model (LUIM).
5. Remotely sensed imagery such as provided by Landsat is used to assist in developing items (3) and (4) but also has potential to be applied in monitoring soil health through plant performance (see Appendix B).
6. Productivity data from ABARE and ABS sources and projects such as the Land Monitor Project can be used in conjunction with land use and soil map data to assess the relative values and threats in current agricultural enterprise distribution.

Crawford *et al.* (2006) have begun analysis of these data to:

- Assess differences in inherent soil quality between major soils and regions.
- Model landscape opportunities and hazards with respect to soil health.
- Characterise Victoria's agricultural landscapes and regions with respect to soil health.
- Determine suitability for purpose (for modelling, benchmarking and target setting).
- Identify gaps in coverages and in particular parameters that are necessary to determine soil quality.

Provision of soil information for assessment and management of soil health

Extension of soils information consists largely of publication of reports related to soils research or soil and land survey, or to components of industry focussed projects such as Topcrop and Target10. As such, there is little information that provides an integrated view of soil health and soil management except in very general terms. A more focussed approach to soil health is needed because of significant regional differences in soils and the specific demands that different enterprises impose on soil quality. The 'Healthy Soils' project (MIS 03250) provides the opportunity to complete the delivery elements of the knowledge chain, through the project's objectives which are to provide:

- Improved access to available Soil Health information.
- Improved and new Soil Health assessment tools.
- Enhanced soil health extension programs.
- A coordinated Victorian program for Soil Health.

2 Terminology and conceptual background

The terms used to describe soils and the environment range from those with precise scientific meaning to those that are more or less symbolic and defy precise definition. Consequently, the meanings for terms that fall more into a symbolic category require some discussion and, where possible, some boundaries with respect to the usage in this report. Without trying to be exhaustive, the following section provides discussion to put the terms into context and clarify their use. Further, more detailed, analysis of their application and relationships can be found in later sections of this report.

2.1 Soil quality and soil health

The principal terms that will be found in the literature and in this report are 'soil quality' and 'soil health'.

While there are many definitions in the literature, there is no argument that both terms refer to the capacity of soil to perform the functions that are demanded of it. Hence good or high quality soils and, or, healthy soils are those that perform well and are not incapacitated in any respect. In contrast, poor quality soils and those in 'poor health' exhibit various dysfunctional attributes such as erosion, retarded or zero plant growth, and other problems. 'Poor' performance of soils is a relative judgement made according to the expectations that we have of soil, thus soil quality and soil health are judged with respect to their "fitness for use". This concept, 'fitness for use', is undoubtedly the simplest representation of the meanings behind soil quality and soil health.

Soil quality, by which differences between soils are recognised, has been used as a concept for a much longer period than soil health. For example, soil quality concepts underlie rationales used in determining land capability (Klingebiel and Montgomery 1961; FAO 1976) and have existed in the literature for two millennia. Virgil (70-19 BC) wrote:

> 'before we ready to plow an unknown plain, know the winds and the different moods of weather, the forefathers' method and local traditions, what here the earth will give or refuse to yield to the farmer. Here cereals grow better, there grapevines'

Virgil even went so far as to recommend methods for determining soil quality:

> 'The method by which you can recognize their differences: Ascertain whether the soil is loose or its surface compact, because one is suitable for grains and the other for Bacchus — Dig a well in the earth and refill it entirely with the same earth, then trample it from above with the feet.
> If it lacks strength (it sinks), it is more suitable for cattle or the beneficial grapevine; if it refuses to rearrange, or the level will not fall after the whole pit has been refilled, the soil is compact.' (translation cited by Krupenikov1993)

'Quality' and 'Health' are terms that convey relative meanings, and must therefore be related to some baseline measurement and purpose (or function).

Whereas air and water 'quality' can be measured with respect to their absolute purity, and 'healthy' air and 'healthy' water have meaning with respect to supporting or threatening life, the case for soil is not so simple or clear. There is no such entity as 'pure soil' and the problem is compounded by the fact that air and water are constituents of soil. The quality of the air and water in soil has importance for life in and above the soil, so interpreted measurements of these individual constituents, along with many others, are important if we want to rate soil health.

Soil is highly complex and should in many respects be regarded as a living system in much the same way as an ecosystem is understood. There are therefore considerable challenges to the development of integrated assessment tools that are simple to apply and have useful meaning for managing or monitoring soil health. For these reasons and others some authors have refuted the whole notion of soil quality (and soil health) as having any value at all (Sojka and Upchurch 1999).

Because both terms, 'soil quality' and 'soil health', are in common use, some definitions and distinctions between the terms are adopted here.

Carter *et al.* (1997) have discussed concepts of soil quality in detail and suggest that the definitions developed by the Soil Science Society of America (1995) and Doran *et al.* (1996) are comprehensive and well accepted:

> 'Soil quality is the capacity of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation.' (SSSA 1995)

and,

> 'Soil quality is the capacity of a soil to function, within ecosystem and land use boundaries, to sustain biological productivity, maintain environmental quality, and promote plant, animal and human health.' (Doran *et al.* 1996)

The term 'soil health' has been used in many instances as synonymous with, and to replace, 'soil quality', in particular for dialogue with non-scientists. However, for some, the emphasis on 'health' has parallels with living organisms and supports the notion of soil as a living system. Consequently, much of the discussion around soil health has concerned the biological aspects of soil and there has been an increasing focus on organic and biological farming systems as the route to achieving better soil health. Doran *et al.* (1996) emphasise the living aspects of soil and its sustainability in their proposed definition for soil health:

> 'Soil health is the continued capacity of a soil to function as a vital living system, within ecosystem and land use boundaries, to sustain biological productivity, maintain the quality of air and water environments, and promote plant, animal and human health.' (Doran *et al.* 1996)

For the purposes of the Victorian soil health work, we should adopt a balanced approach that acknowledges the importance of biological, chemical and physical aspects of soil as well as the landscape and catchment context and the goals of land managers.

Additional context for the use of the term 'health' rather than 'quality' is provided by the way in which government has responded to requirements for reporting on the state of the environment. For example the Victorian Government's report 'The Health of our Catchments' (VCMC 2002) provides a snapshot of catchment condition using a range of environmental indicators.

Simplistically, health is a changing state whereas quality more closely relates to the inherent properties of the entity. Just as a cereal variety may intrinsically be good quality, the plants of a particular crop of that variety may exhibit poor health due to a stressful environment and will result in poor grain quality and, potentially, poor animal or human health. The distinction between quality, as inherent, and health, as apparent and dynamic, is a useful one. A further distinction might be made in that soil quality provides a useful paradigm for comparison between different soils, whereas soil health is more concerned with the state of a particular soil at any one time.

We recognise that there is considerable overlap between the terms, but, simply stated, the terms 'soil quality' and 'soil health' used in this report are distinguished as follows:

Soil quality is the capacity of soils within landscapes to sustain biological productivity, maintain environmental quality, and promote plant and animal health.

Soil health is the condition of the soil in relation to its inherent, or potential capability, to sustain biological productivity, maintain environmental quality, and promote plant and animal health.

Attributes that can be measured to indicate the functional performance or capacity of a soil will be the same whether we are talking about soil quality or soil health. Soil health simply has an added dimension that represents the state of the soil with respect to a scale that would encompass optimal performance (for a stated purpose) as well as degradation.

Soil health is therefore a more practical term that can be used, as an indicator of soil sustainability, when talking to managers of soil. There are widely differing philosophies with respect to what actually comprises a healthy soil and these range from the view that anything 'artificial' added to soil compromises soil health, to the view that healthy soils should be biologically sterile (for example for root-borne disease management in intensive vegetable production). However, each of these views is formed by the manager's goals, their understanding of the soil system, and the management techniques available to them. In a broader context, 'healthy' or prospering business is the manager's goal and soil management (or health) is one aspect of their business. The degree to which a biologically, self-sustaining healthy soil is required as a foundation for a healthy business is currently hotly debated, particularly by the organic and biological farming sector. Economic evaluation of the functions performed by soil and the relative costs to maintain those functions under different management regimes is needed. This also requires additional science in order to understand the interactions between the soil system and the farming system, particularly where the system is chemically, physically and biologically engineered in order to sustain production.

Resilience and resistance are terms found in the literature concerning ecological systems since the 1960s and 70s and more recently in reference to soil quality and soil health (Blum and Santelises 1994). These are terms for which there is also some overlap and ambiguity. For the purposes of the soil health work the definitions provided by Seybold, Herrick and Brejda (1999) are recommended:

Soil resistance is the capacity of the soil system to continue to function without change throughout a disturbance.

Soil resilience is the capacity of a soil to recover its structural and functional integrity after disturbance.

2.2 Ecosystem Services

The language and objectives in natural resource management (NRM) have recently become more holistically focussed than in the past. The notion of 'ecosystem service' provision now has currency as the major criterion for assessing the functional worth or capacity of the natural and the managed environment. This is in contrast to the more reactionary alternative approach in NRM that has been more focussed on negative aspects associated with environmental degradation. In the case of soils we can list issues such as erosion, acidification, structure decline, and salinisation as serious degradation issues (which they are). There are many programs and initiatives that have been, and are being, implemented to address these issues. However, the underlying reasons for dealing with them have always been positive, for example, that by addressing these issues, land management will be more productive and sustainable and water quality will be improved. The ecosystem service concept provides an integrated positive driver for NRM just as the soil health concept provides an integrated (albeit symbolic) paradigm for managing the diverse issues that arise in soil management.

The most comprehensive attempt to develop NRM priorities with respect to ecosystem services was carried out by the Goulburn Broken Catchment Management Authority and CSIRO Sustainable Ecosystems who described ecosystem services in the following way:

> 'Ecosystem services flow from natural assets (soil, water systems, plants, animals, other living organisms and the atmosphere) to provide us with financial, ecological and cultural benefits. Examples of ecosystem services include: provision of clean water, maintenance of liveable climates and fertile soil, pollination, and fulfillment of cultural and intellectual needs. If natural assets are not maintained the benefits from ecosystem services decline. Conversely, if we maintain our natural assets and use them more effectively, we will benefit from greater returns.' (Binning *et al.* 2001)

Soil Health was identified by Binning *et al. (*2001) as an ecosystem service in its own right. However, soil can be described in the context of other ecosystem services as having a functional role. For example, water filtration and regulation of river flows and groundwater levels are ecosystem services that stem in part from soil and its management. In section 6 the broader relationship between soil health and environmental health is discussed and the soil functions that support ecosystem services are summarised (Table 3).

2.3 Functions, Processes, Attributes and Indicators

The sense of the definitions discussed is that soil health is the capacity of the soil to support or supply ecosystem services. Linkages between soil health and ecosystem services can be quantified if the properties and processes controlling soil functions are known and are measurable. Carter *et al.* (1997) outlined a useful framework to evaluate soil quality that is based on the following sequence: functions, processes, attributes or properties, attribute indicators and methodology (for assessment of soil quality).

Soil Functions

Functions describe what the soil does, or is required to do, for example, support plant growth, support traffic, resist erosion. These functions belong to a suite of ecosystem services directly attributable to soil and they contribute to more global or encompassing ecosystems services such as 'produce crops', or 'provide clean water'. Whilst there are many examples of soil functions given in the literature, these can be broadly classified as:

1. Supporting life (plant growth, production, biodiversity, health)

2. Partitioning water (flows and storages: runoff, drainage, water supply to plants, retaining water in dams)
3. Resisting erosion (maintaining stability, evolving and sustaining plant growth)
4. Providing physical support (anchorage for plants, wheeled traffic, animal treading, building foundations, roads and dams)
5. Processing matter (recycling and storing nutrients, absorbing wastes, filtering water, acting as an environmental buffer).

Specific functions should be defined for any particular agro-ecosystem. An example of a soil quality approach for the dairy industry is provided in section 7.2.

Soil Processes

Processes describe what happens in the soil (fluxes of energy and matter) and determine its functional performance. A hydrological example can illustrate this. For example, water moves on and in soil and can be held in soil. This partitioning of water between runoff, infiltration, drainage and retention determines the performance of soil with respect to several functions: supplying water for plant growth, provision of clean water, resisting erosion et cetera.

Soil Attributes

Attributes are the measurable properties of the soil system or components that support or regulate processes in the soil and hence the functions of the soil. A useful distinction can be made between properties that are fixed, inherent attributes of a particular soil (e.g. texture) and properties that are changeable or dynamic (e.g. soil structure). Management of soil health is concerned with manipulating the dynamic soil properties in the context of fixed soil attributes. Attributes may be directly measured physical, chemical or biological parameters, for example, clay percentage, exchangeable sodium, number of earthworms. Attributes may also be measurable properties that are affected by other attributes. For example, saturated hydraulic conductivity (regulating the passage of water through soil) is a measurable attribute that would be affected by clay percentage (through its influence on texture and structure), by exchangeable sodium (through its affect on sodicity and soil structure), and by earthworms (through the macropores created by their burrowing activities). Attributes may also be, in some instances, estimates of properties that are based on other measured or directly observed properties, for example, hydraulic conductivity can be estimated from soil texture and descriptions of soil structure. Such estimates are referred to in the literature as **Pedotransfer Functions** and range from the conceptually simple to the mathematically complex.

The key to managing soil health lies in our ability to understand, measure, model and predict components in the simple hierarchical framework:

ECOSYSTEM SERVICES ≤ SOIL FUNCTIONS < SOIL PROCESSES < SOIL ATTRIBUTES

There is a deceptive simplicity to this framework which belies the natural complexity of the system. Interactions between components and processes mean that the realities behind the framework are rarely linear or simple. Soil differences and inherent variability at pedon[3], paddock, landscape and regional scales compound the problems of measurement (Wilding and Drees 1983). Sensitivity of soil properties and functions to seasonal changes (e.g. shrinking and swelling of soil as it dries or wets) and to seasonal differences (e.g. wind erosion during droughts) exacerbate the task of assessing soil health with respect to management alone and independently of other external influences.

2.4 Indicator, index and monitoring

An **indicator** is a measurable parameter of a system that can be used to represent the condition of the system or its ability to perform system functions. An indicator could therefore be a measure of the functional performance itself (e.g. crop production and plant health), a measure of or surrogate for a process affecting function (e.g. seasonal water use consumption and conversion to dry matter), or a time

[3] A pedon is the smallest three-dimensional volume of soil can be used to describe the soil properties at a particular location. It is the equivalent of a soil profile but takes into account lateral variability in soil profile properties.

sensitive attribute of the soil (e.g. depth of water extraction, amount of stored water, pH). A good indicator is sensitive to change, easily measured, has a clearly defined and repeatable methodology, is easily interpreted (not subject to system 'noise') and ideally, is reversible (sensitive to improvement as well as decay). Thus pH is an example of a good soil indicator as it is sensitive to change, can be measured consistently and easily and can be related to the soil's capacity to support plant growth.

Indicators for soil quality or soil health cover a range of physical, chemical and biological soil properties (Brussard *et al.* 2002; Doran, Molina and Harris 1994; Gregorich and Carter 1997; Hamblin 1998, 1999; Pankhurst 1999; MacEwan and Carter 1996; Walker and Reuter 1996). The debate has been broad but reasonable agreement appears to exist about the suite of indicators, a **minimum dataset**, and methods for measurement. However, baseline data are lacking and, although there is recognition of the importance of preferred indicators, there is little knowledge of **thresholds** or rates of change, particularly with respect to biological indicators of soil health. There is therefore a need for research in some disciplines to determine the relationships between indicator values and performance of soil functions.

An **index** is usually a value on a relative scale that has no meaning *per se* but can be used to judge system conditions comparatively in space or time. For example, students are graded by summing marks achieved in assignments and exams but the grade awarded to a student does not give an indication of what precisely the student knows or does not know. It merely indicates their overall performance relative to other students and to a pass level.

In recent years there have been many attempts to derive an index for soil health or soil quality (e.g. Andrews and Carroll 2001; Andrews *et al.* 2002; Barbiroli *et al.* 2004; Hatcher 2002; Jaenicke and Lengnick 1999; Wienhold *et al.* 2004; Xu *et al.* 2006). Combining measures into a single index that can be used as a long term monitoring aid is an attractive proposition and has been achieved to a degree in other fields. The index of stream condition (ISC), which aggregates a number of individual indicators of stream condition, is a good Victorian example (Catchment and Water Division, 2001). Such an index would appear to work well where individual indicators are related but is difficult to interpret when they are not. If the former is the case, an improvement in score always correlates with improvement in overall condition, if the latter is the case, a score improvement could be achieved if a single factor increases sufficiently to outweigh decreases in other factor conditions. Single combination indices are therefore dogged by problems associated with methods of combination of parameters (e.g. summative, divisive) and weights applied to individual factors. Such is the case with the search for a soil index.

Monitoring is the periodic repetition of measurements made on a site or population in order to track any changes that occur in condition of the system being monitored. Monitoring is necessary to provide evidence of the impacts of management and other environmental factors on soil and land condition. Soils are extremely complex systems, variable in space and time, sensitive to management (land use and associated practices) and to weather conditions. McKenzie, Henderson and McDonald (2002) have comprehensively summarised the issues associated with soil monitoring, given sound recommendations with respect to implementation in Australia and stressed the need to define the purpose for monitoring in contrasting two purposes:

1. reducing risk in decision making
2. improving process understanding.

Monitoring must be given context. Selection of monitoring parameters (indicators) and sites requires recognition of spatial relevance (land and land use that each monitoring site represents) and understanding of processes that influence soil change at this site (including rate, sensitivity, reversibility).

3 Soil health in agro-ecosystems

The primary function of soil in agro-ecosystems is to support plant growth. This is a complex function that depends on many soil processes and properties. Plants integrate all of these as well as many other factors that are not directly related to soil. The plant can be used as the indicator of successful soil management or healthy soil provided the agro-ecosystem is appraised in order to identify all of the influences (edaphic and other environmental aspects) that affect plant performance. Agronomic choices determine; species and variety selection, rotations, fertilizer regime, pest and disease management, weed control, timing of operations, machinery and tillage, and the role of animals in the system. In animal production systems, plant production (quantity and quality) still serves as a suitable integrator of the system's components.

Figure 2 illustrates the major components of the soil-plant system in an agricultural context with a focus on food products (rather than fibres or timber). Soil health, as the condition of the soil with respect to its capacity to support healthy plant growth, encompasses agronomic as well as soil quality factors. Soil-borne pests and pathogens, weeds, soil structure and fertility are all factors that can be managed directly by soil management and agronomic practices.

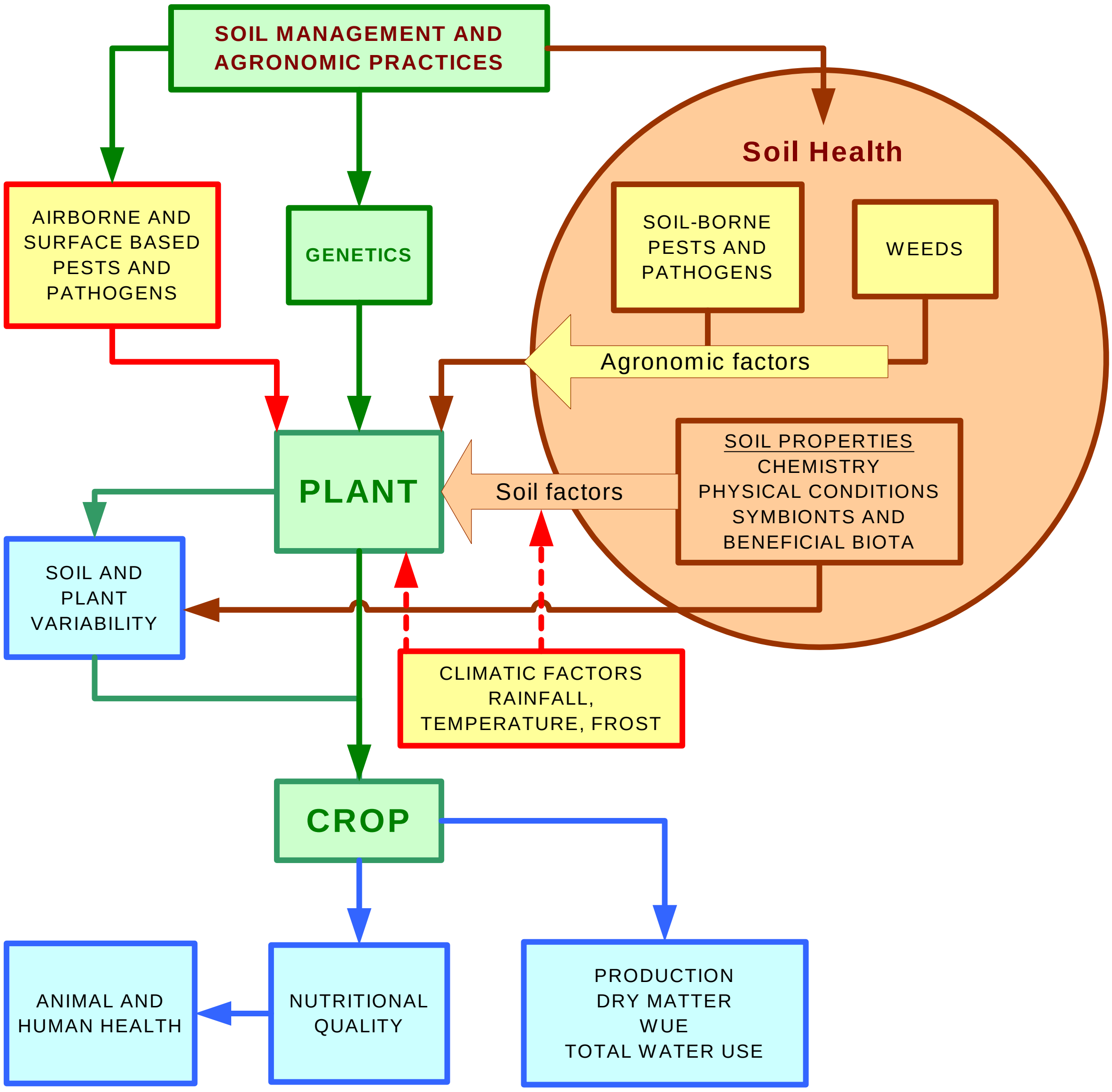

Figure 2 Diagram illustrating the relationships between agronomic and environmental factors affecting soil, plant, crop and animal health. (WUE = water use efficiency)

The aim of management is to create optimal soil conditions for plant growth but there are many examples of practices that have beneficial as well as negative effects. Balancing these effects to achieve optimal soil health is a major challenge and selection of appropriate indicators for soil health is confounded by this complexity. What can or should we monitor in order to indicate soil health through plant performance?

3.1 Production

Total dry matter production per unit input or economic yield for a particular plant species does not depend on soil condition alone but also depends on genetics (vigour, susceptibility or resistance to disease, environmental suitability), seasonal characteristics (rainfall amount and timing, frost incidence, growing season temperatures) and other external factors such as airborne diseases and pests. Plant performance may be measured for individuals in a stand but is more commonly assessed at a plot, paddock, or even regional level. Airborne or satellite remotely sensed imagery can be analysed for spectral signatures that indicate plant performance at regional, paddock and sub-paddock scales. These approaches and the application of Normalised Difference Vegetation Index (NDVI) in particular are described in Appendix A.

3.2 Variability

At the stand level, crop variability may be due to abiotic soil factors (soil variability, depth, texture, water availability), as well as soil borne pathogens, airborne pathogens, insect attack, grazing, rabbits, frost prone areas, weed competition, spray misses or other management variations. Consistent patterns of crop variability in different seasons are more likely to be a reflection of differences in soil type and quality rather than in soil health, so comparison of high and low yielding areas need to be interpreted carefully. In such cases, paddock zoning to vary inputs is an important aspect of management for soil health as well as economic farm management.

3.3 Food quality

Nutritional quality (protein and digestibility) is positively related to soil quality and soil health. Differences in nutritional quality within a stand may be the result of soil type (and therefore quality) differences but could also be a reflection of differences in soil condition (and therefore soil health). An aspect of healthy soil is its capacity to produce high quality feed (for stock animals or for human consumption), having the optimal combinations of digestible carbohydrate, protein and fats, balanced mineral composition, appropriate fibre, and lack of toxins or contaminants.

3.4 Soil biology and soil health

Soil biology is extremely complex. In many respects soil biology is regarded as the key to soil health – it is the life in the soil and a regulator of many processes that affect soil chemistry and soil physics. However, because of its complexity, there are few certainties that can be derived from our knowledge of soil biology to provide quantitative indicators of soil health. Most of the claims regarding optimal soil biological constitution and the interactions between agricultural management, soil biology and soil health are found at or beyond the fringes of agricultural research. New methods in biological research, particularly molecular techniques (Johnson, Lee and Scow 2003) offer some promise of precision in the identification of microbial communities. The Soil Biology subplatform of PIRVic, DPI is currently pursuing this line of research.

Soil organic matter is universally accepted as the major indicator of soil biological health. The function that soil organic matter performs for soil structure has been extensively reviewed by Carter and Stewart (1996). Magdoff and Weil (2004) provide a more recent review of the management of soil organic matter. A perspective on the state of knowledge regarding indicators appropriate for soil biological health is included as Appendix C to this report.

Summaries of the functions of soil organisms can be found in standard texts. A useful review is provided by Brussard (1998) who has reviewed some of these functions and explained how the plant plays a central role in governing, and providing a biological assessment of, the roles soil fauna play in ecosystem processes. In his review Brussard (1998) describes these roles and proposes a framework for understanding the ecological interactions between food webs, the plant, soil organic matter and the soil ecosystem. Simple frameworks that illustrate the principal interactions are shown in Figure 3 and Figure 4.

There are five main criteria that have been used to group assemblages of soil organisms: life-history tactics, microhabitat, principal food, feeding mode and ecophysiology. Brussaard (1998) presented an evaluation of the functional classification of soil organisms and described three 'guilds' of soil organisms: root biota, decomposers and ecosystem engineers. Figure 3 illustrates the central place of the plant in soil ecosystem functioning. The micro-predators comprise a fourth group (not described by Brussaard). These have an indirect impact on the plant through regulation of populations of other soil micro-biota.

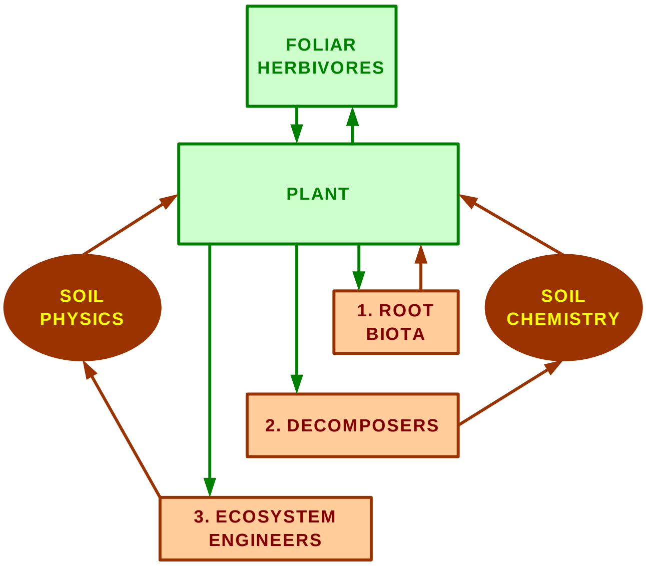

Figure 3 Conceptual diagram of an interactive web, showing main interactions between plants and biotic and abiotic constituents (from Brussaard 1998).

The interactions between plant and root biota (1) are instantaneous and may be positive symbioses such as occur between the plant and mycorrizhae, or they may be deleterious to the plant due to root diseases or pests. The plant affects decomposers (2) by supplying organic matter as a substrate that is subsequently recycled as nutrients via the soil solution to be taken up by the plant. Earthworms, ants and termites are examples of 'ecosystem engineers' (3) that also receive their substrate from the plant but affect the plant largely through the modified physical environment, in particular by changes to macro-porosity and aggregation of soil components. The foliar herbivores feeding on aerial portions of the plant interact directly with the plant but also interact indirectly, through the plant's response to soil conditions (see, for example, Altieri and Nicholls 2003). Feedback mechanisms between root and foliage with respect to herbivory are illustrated simply in Figure 4.

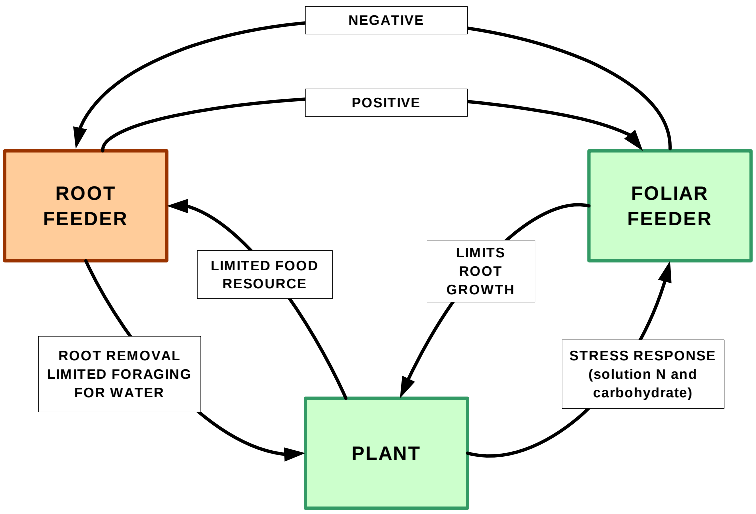

Figure 4 Conceptual model of interactions between above- and below-ground herbivores (after Masters *et al.* 1993, reproduced in Brussaard 1998).

3.5 Soil health and plant health – resistance to pests and diseases

Insect pests and soil health

Plant nutrition can affect plant pest problems (Altieri and Nicholls 2003) by altering plant tissue nutrient levels. There is evidence that lesser incidence of disease and attack by insect pests is associated with soil quality or optimal physical, chemical and biological conditions. There are strong proponents of alternative farming methods who emphasise the importance of organic matter and the need to reduce or eliminate the use of inorganic fertilizers. In particular, high N rates have been shown to increase aphid and mite numbers in most studies. However, as a minority of these studies were field-based, the results may not be indicative of field crop performance. More research is needed to confirm causal relationships and to identify critical values or ranges for key properties, should they exist. Altieri and Nicholls (2003) observe that despite the potential relationships between crop protection and soil management, there has been no combined development to link integrated pest management with management of soil fertility.

Nematodes and soil health

Nematodes in soil belong to several different groups: plant-parasitic and plant-pathogenic nematodes, fungi and bacteria-feeding nematodes, and predatory nematodes. The latter two groups are considered to be beneficial or harmless to plants. Functionally, the nematodes have direct and indirect impacts on organic matter decomposition, nitrogen mineralisation and dispersal of both beneficial and harmful bacteria. Kimpinski and Sturz (2003) have reviewed what is known of the dynamics of nematode populations and conclude that system complexity and population fluctuations confound the use of nematodes as indicators, except for extreme situations. Understanding of these dynamics and the environmental factors controlling them is a critical area for future research. Recent work by the DPI in Queensland has compared nematode populations in bananas treated with different mulch materials (Cobon and Pattison 2006). This work has shown promise in modifying the proportions of the major nematode groups and reducing the populations of harmful nematodes. They also suggest that nematodes are excellent bio-indicators because of their position in the food web and their relatively stable numbers over time compared to microbial dynamics.

Weed- and disease-suppressive soils

Kremer and Li (2003) investigated soil microbial activity in seven cropping systems and compared weed-suppressive bacteria and soil enzyme activity in these systems. They found general associations between weed-suppressive activity and disease-suppressive soils (associated with high soil enzyme activity), high organic matter content and increased water-stable aggregation.

3.6 Soil health, nutrient cycling, crop residue and organic matter

Cycling of nutrients is a primary function of soil necessary to sustain plant growth. The cycling that takes place through the breakdown and incorporation of plant and animal residues also has important impacts on soil structure at macro and micro-scales. The roles of soil biota across all scales of the food web (Appendix C) are critical to these processes. In dryland cropping systems (grains) there are widely different management practices dealing with plant residues between harvest and sowing. Crop residue (stubble) is a valuable source of nutrients, a potential protection for the soil surface, habitat and food supply for a range of animals and an important soil conditioner. Retention of residue is not simple and can cause problems. Build up of slugs and pests, interference with sowing and depth control, uneven germination, and lock up of nitrogen are some examples of issues that can arise. Incorporation of crop residues, through tillage, exposes the soil to the elements, can lead to net loss of soil carbon and may damage soil structure. Burning of residues releases nutrients but deprives the soil of bulky organic matter, exposes the soil and contributes to atmospheric pollution. Consistently reliable systems for managing crop residues to maximise their benefits to soil are needed. While design of farm machinery is a major factor that can assist with this, there is also a role for biological improvements. Spraying of stubble with cellulose-digesting fungi is an option, but natural populations of arthropods, in particular, depend on the presence of organic material (Blumberg and Crossley 1983) and can serve as useful indicators of soil health (Olfert *et al*. 2002).

4 The soil system and soil health monitoring

Earlier discussion and explanation of terminology (Section 2.3) presented a simple framework for soil health that linked the provision of ecosystem services to functions, processes, and attributes of soil. An indicator of health can be selected from any level. Ecosystem service provision may be inferred from favourable properties (e.g. infiltration rate) or may be directly monitored (e.g. water quality and quantity in runoff). Soil monitoring is a periodic rather than continuous activity and may entail annual site assessments or longer intervals between visits. Direct measurement of soil properties and soil condition is time consuming and appropriate indicators and methods need to be selected. Minimum datasets (MDS) comprising biological, chemical and physical measurements have been proposed in several sources and may be combined into a single index (for example, Andrews *et al.* 2002; Barbiroli *et al.* 2004). The extensive review by Hall (2003) on this topic is invaluable. Measurement and interpretation can be a job for experts or can be simplified for implementation by farmers themselves, as exemplified by the USDA's soil quality test kit (USDA 1999).

Understanding the soil system is an essential precursor to selection, application and interpretation of appropriate indicators and methods. In particular, the inherent physical qualities of soil have a profound influence on the expected range of dynamic properties (physical, chemical or biological) in different soils.

4.1 Physics - the soil as a three phase system

Soil is a complex medium with components existing as solids, liquids or gas (Figure 5). The solid matter is primarily mineral with a small organic component. The mineral content of soils depends on their parent rock material and the degree of weathering. In turn this affects the soil's ability to supply and store exchangeable cations and anions essential for, or sometimes, toxic to, plant growth. Grain size of the solids ranges from sub-micron (very fine clays) to centimetres (cobbles and boulders) and the fine earth or sub 2 mm fraction is assessed as soil texture. Texture, determined by hand, includes the influence of the soil organic fraction. Soil textures are broadly classified into sands, loams or clays. These principal classes are qualified by the amount of sand, silt and clay present (for example; sandy loam, clayey sand, silty clay loam). The solids may be aggregated (pedal) into structural units (peds), or they may have no identifiable structural units (apedal), being loose (single grain sands) or massive (a dense assembly of primary particles).

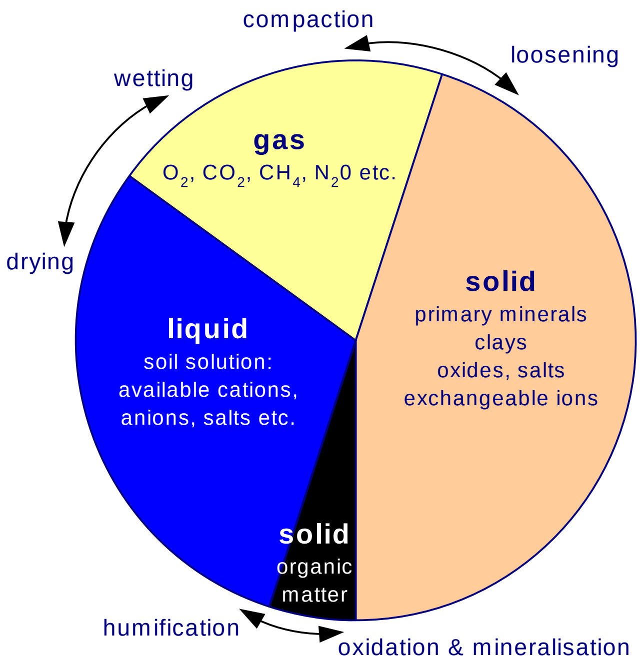

Figure 5 Representation of the bulk soil composition in relation to the three phases of matter: solid, liquid and gaseous.

The bulk relationships between these phases, particularly those between liquid and gas in the soil pore space, are critical with respect to plant growth. Figure 5 illustrates the way in which management can influence total porosity, whilst Figure 6 illustrates examples of the way in which porosity can differ widely between soils of different texture and density and the influence that this has on water availability and soil aeration.

Spaces between the solids constitute the soil porosity which has unique size and spatial properties. The spatial arrangement of solids and spaces and the stability and strength of the solids is referred to as structure. Soil structure is a critical aspect of soil quality as it controls or regulates soil functions such as water retention, water supply to plants, drainage, and aeration. Porosity has two components related to soil quality; textural and structural (Dexter 2004a). The textural component of porosity is determined by the grain size or soil texture and the way in which the primary soil particles naturally pack together. Structural porosity consists of microcracks, cracks, biopores and voids within and between soil aggregates. Textural porosity is largely unaffected by soil management, whereas structural porosity is readily influenced by tillage, compaction and biological activity. Structural porosity is therefore more relevant as an indicator of soil health whereas textural porosity affects only the inherent soil quality.

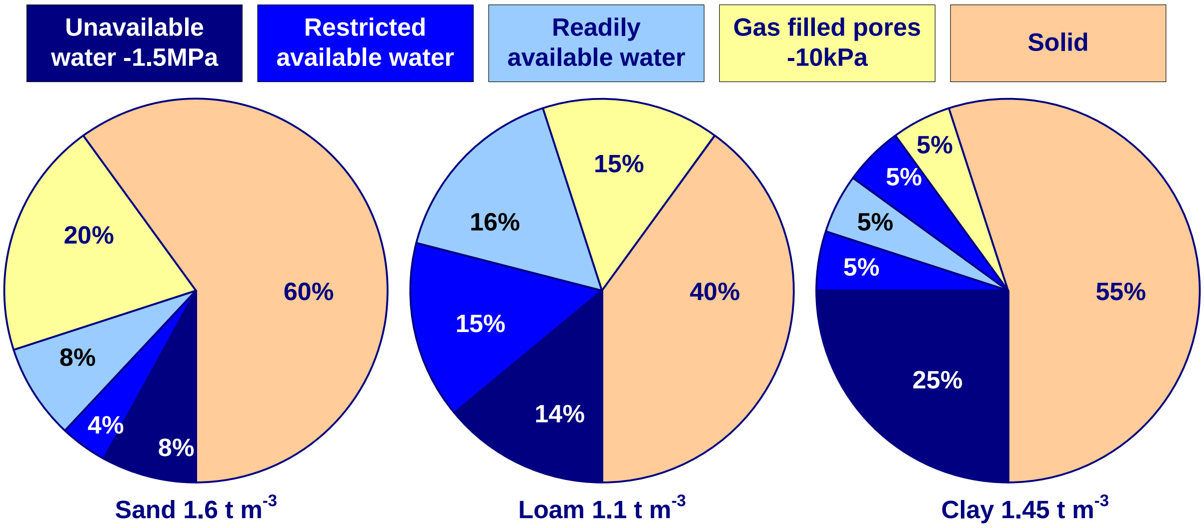

Figure 6 Water availability and volumetric relationships between solid, liquid and gaseous phases for three soils of different texture and density.

Differences in soil structure are to be expected between soils of different texture and are illustrated by the differences in bulk density, macroporosity (>30 µm, holding water at tensions above -10 kPa), residual porosity (<0.2 µm, holding water below -1.5 Mpa) and available water capacity (between -10 kPa and -1.5 Mpa) for three soils in Figure 6. Examples are shown for a sand, loam and clay. Sand readily compacts to a packing density dictated by the primary sand particles. However, it has relatively few pores that are <0.2 µm and a high proportion that are >30 µm, and therefore most of the water stored is available to plants. The loam example represents a finely-tilled surface with high total porosity (60%) and low bulk density. The loam in the example presents the best soil quality of the three, but its condition could readily change through compaction. The clay, though not as dense as the sand, provides less support for plant growth, with respect to water supply, than either the sand or the loam. Water is readily available if there is sufficient aeration and the water is in larger micropores that are well connected. As soils dry, water is confined to smaller pores and the pathways for water movement become more tortuous and slow. Hence availability of water can be restricted at the dry and wet ends of the available range (assuming a critical air filled porosity of 10%). This situation is illustrated in Figure 6 by the pie diagram for clay.

Interpreting texture, density and compaction

Assessments and comparisons of soil health (actual condition relative to potential condition) must be made within texture groups and cannot easily be made between texture groups. Comparisons of soil quality (capacity to perform functions) can legitimately be made between as well as within texture groups.

Bulk density is a useful measure of soil physical quality but has little value unless related in some way to functional properties of the soil. It should be used as an indicator of degree of soil compaction only if reported as a ratio. For example, field bulk density can be compared with the maximum bulk density achievable with a Proctor compaction test for that soil. Håkansson and Lipiec (2000) have provided a useful analysis of the relation between crop response and degree of compactness for a range of soil types and have proposed an optimal degree of compaction or *D*-value that is independent of soil texture. Compaction can also be indicated by ped shape, distorted surfaces of peds (clays), reduction in percentage of macropores, and the relationship between moisture content and mechanical strength. Dexter (2004a, 2004b) has proposed an index of soil physical quality, *S*[4], that is positively correlated with soil workability and is independent of texture.

Least limiting water range, soil texture, growth limiting bulk density and soil quality

The soil water holding characteristic (volume of water held vs. pore size or matric tension) is a useful indicator of soil health and quality. Many workers have proposed the Least Limiting Water Range (LLWR) as an important integrator of factors affecting root growth. The LLWR serves as an index of soil structural quality that integrates values of soil matrix potential, aeration and soil strength (da Silva *et al.* 1994). Quantification of LLWR requires knowledge of soil moisture contents for the following four limiting states:

1. Wilting point or physical lower limit of water available to plants (-1.5 MPa); θ_{wp}
2. Field capacity or drained upper limit water content of the soil (nominally -0.01 MPa); θ_{fc}
3. Critical air filled porosity to maintain adequate oxygen in the root zone (10%); θ_{afp}
4. Critical soil strength at which root penetration is restricted (2 MPa); θ_{sr}

The upper limit for the LLWR is equal to θ_{afp} if $<\theta_{fc}$, otherwise it is equal to θ_{fc}. The lower limit for the LLWR is equal to θ_{sr} if $>\theta_{wp}$, otherwise it is equal to θ_{wp}.

The application of this concept has been the subject of several papers in the last five years (Zou *et al.* 2000; Benjamin *et al.* 2003; Wu *et al.* 2003; Lapen *et al.* 2004; Leao *et al.* 2006). Groenevelt *et al.* (2001) went further and proposed the term 'integrated water capacity' (IWC) as a development from LLWR, introducing overburden pressure as another factor and integrating changes in bulk density of swelling soils to allow for better estimation of water availability.

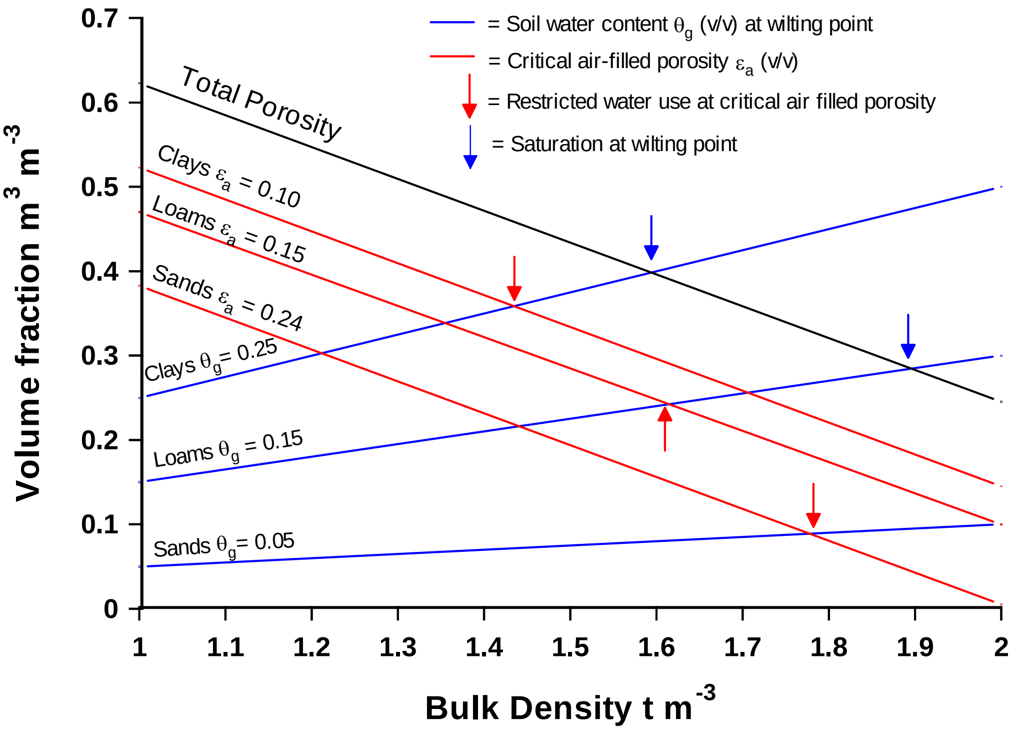

Figure 7 Relationship between bulk density, porosity and water content, illustrating critical limits for air filled porosity (red lines) and wilting point water contents (blue lines) for sands, loams and clays (Generalised data from various literature sources).

[4] *S* is equal to the slope of the water retention curve at its inflection point. The moisture retention curve is plotted as logarithm (to base e) of the water potential against gravimetric water content kg kg^{-1}. (Dexter 2004a)

Generalised data for wilting point moisture contents and theoretical relationship between particle density, bulk density and porosity (porosity = 1 – bulk density/particle density) have been plotted in Figure 7 for three soil textures. Critical air-filled porosity fractions for different soil textures adapted from Pierce *et al.* (1983) have also been plotted in Figure 7 and indicate the upper limit of LLWR for any bulk density and texture. The bulk density value at the intersection of critical air-filled porosity and wilting point water content represents the growth limiting bulk density (GLBD) for that texture. These theoretical values correspond well with those given in the Soil Quality Institute's soil quality test kit guide (USDA 1999). GLBD values may be lower if critical soil strength is exceeded at moisture contents above wilting point.

The soil profile – variability of the physical system with depth

The physical properties affecting soil functions are not uniform with depth. Differences in texture and structure with depth are normal features in most natural soils. These differences are recognised as 'soil horizons' and result from soil formation processes (pedogenesis) over decades and millennia. While most assessments of agricultural soils concentrate on the surface horizon (or topsoil), differences in material below the surface affect many soil functions at the surface. Interpretation of the whole profile is therefore necessary for optimal soil management.

4.2 The physico-chemical system

Chemical properties of the soil material are an essential aspect of soil fertility and plant nutrition. There are complex relationships that exist between plant nutritional requirements, soil solution, pH, nutrient availability and soil composition. Interpretation of chemical properties is confounded by differences in analytical methods, plant species requirements and tolerances and variable production responses in different soils. Generalised rules concerning soil chemical properties can be applied with regard to many soil properties (Peverill, Sparrow and Reuter 1999):

- pH has a reasonable relationship to nutrient availability and metal toxicity.
- EC is strongly correlated with water availability, and yield of salt sensitive plant species.
- Nitrogen, Phosphorus, Sulfur, Calcium, Magnesium and Potassium levels can all be directly related to crop production.
- Cation balances between Calcium, Magnesium, Potassium and Sodium have variable relationships to soil structure and animal health.
- Micro-nutrient levels of Copper, Zinc, and Boron are related to plant health.
- Some micro-nutrient levels such as Aluminium, Chloride, Manganese and Boron can be related to plant toxicity.

However, the degree of confidence for prescribed optimum values depends upon regional and specific crop evidence and experience. For example, although there is strong advocacy by some advisers for very specific cation ratios, particularly for Calcium, Magnesium and Potassium, there is no evidence that supports such recommendations (Kopittke and Menzies 2007).

Chemical properties and mineralogical composition also affect a number of physical functions, for example:

- Clay type determines the amount of swelling or shrinkage of soil as it wets or dries, and so affects creation of structural cracks, regeneration of structure after compaction, and soil aeration or waterlogging.
- Soluble salts affect the osmotic strength of the soil solution and therefore limit water uptake before the physical lower limit of water availability (permanent wilting point) is reached.
- Exchangeable sodium at modest levels[5] affects the swelling and dispersion of clays and deterioration of soil structure by clogging pores, restricting air movement and drainage.

[5] Soil material with >6% exchangeable sodium is classified as 'sodic' in Australia. Many Victorian soils have sodic subsoils and suffer from poor drainage. There are also substantial areas of soil in the state that have sodic surface horizons and are very prone to waterlogging.

Physical indices and soil biology

Theoretical values for GLBD provide a simple indicator of soil physical health. Whilst the GLBD is a useful indicator of a poorly structured soil with respect to restricted LLWR and low potential for root growth, there are other aspects of structure that should be considered. Bulk density is, as it sounds, a measurement applied to bulk soil and does not reveal aspects of pore geometry that would affect root growth. The number, volume, connectivity and orientation of macropores are particularly important in dense soils as they determine air and water movement to a limited rhizosphere. In structured clay soils, roots are usually observed in fissures, interpedal pores and biopores. Whilst the volume occupied by roots in such soils may be small, the physical environment is quite different to that measured in the bulk soil.

Whalley *et al.* (2005) have demonstrated that water retention and aeration properties of the rhizosphere soil are enhanced with respect to root growth compared to the properties of the bulk soil. Passioura (2002) describes the many interactions between root and soil that demonstrate the ability of plants to adapt to and survive in stressed situations.

While high bulk density has a significant negative influence on soil aeration, mechanical strength and root growth, equivalent effects have not been observed in biological properties. Shestak and Busse (2005) studied the effect of increased bulk density on biological indices of soil health (although the imposed densities were not high). They found that there was no negative effect on microbial communities but that in some instances there were increases in activity (fungal hyphae, carbon use, total phospholipid fatty acids). The compaction experiments resulted in decreases of 50 to 90% in macroporosity (>30 μm) whereas habitable pores for microbes (0.2 to 30 μm) increased by at least 40%. Microbial activity is positively correlated with water content (matric potential) and soil health tests comparing microbial activity should be carried out at equivalent moisture potentials.

5 Soils in the landscape, scale and soil quality

It is well known that soils vary locally and that this variability is often strongly related to landscape position. Local (paddock and catchment scale) assessment of soil quality and health must take note of such variability and the role that landscape plays, not only in its relationship to distribution of soils, but also in the influence it has on soil functions (particularly hydrological functions). Interactions between soil type, landscape position and land management can confound comparisons of soil condition and these interactions need to be understood in any monitoring of soil health.

On a global scale differences in soil type can be explained, to various degrees, by the soil forming factors proposed by Hans Jenny (1941, 1980). Just as there are differences in some basic physical properties and behaviour for soils of different texture, there are fundamental qualitative differences between soil types. Processes that affect the pedological constitution of a soil occur at a range of spatial and temporal scales and these have been summarised in Table 1 by MacEwan (1997). Scale and rate of change are significant aspects of the soil system and soil in the landscape that affect choice and interpretation of indicators. Suitable indicators for reporting on soil health at a regional scale are related more to land qualities than to soil type (e.g. erosion). Indicators appropriate to soil management at the paddock scale should be carefully considered in relation to soil type and inherent soil quality.

Soil characterisation routinely carried out for soil survey and mapping follows agreed data standards (McDonald *et al.* 1990) but most of the data collected are non-quantitative and only change subtly in response to management. While they are good indicators of inherent soil quality they are not well suited to monitoring of soil condition or soil health.

Field pedological data have been classified by MacEwan and Fitzpatrick (1996) as nominal, ordinal, interval or ratio (Table 2). Nominal data are simply named and put into non quantitative classes, e.g. horizon designations. Ordinal data can be ranked, more or less, in semi-quantitative classes, e.g. air dry consistency. Interval data can be quantified in terms of equal intervals on a scale having no zero, or only a relative zero, e.g. Munsell colour. Ratio data can be quantified in relation to a true zero, e.g. horizon thickness. Most pedological attributes are recorded in a qualitative (nominal), or semi quantitative (ordinal), way. Such data are easily obtainable but are useful as indicators only when gross differences exist between the value of a parameter prior to, and following a period of management. Inherent high variability of these properties, even within a relatively pure soil mapping unit (Wilding and Drees, 1983), means that there is unlikely to be any improvement in assessment of soil quality by finding more precise quantitative methods for most field observed pedological attributes. The attributes in Table 2 have been ranked in approximate order of their sensitivity to management and, by implication, their relative usefulness as indicators of soil health (dynamic soil attributes).

Table 1 Soil modifying and soil forming processes: their relationship to spatial and temporal scale, and suggested indicators for their recognition. (from MacEwan 1997)

Scale	Processes	†	‡	Sensitivity (years)	Indicators
Global and Continental Extremely small scale <1:5 000 000	Plate tectonics	U	I	10^3 - 10^6	Vulcanism, continental changes
	Soil formation	U	I	10^2 - 10^4	Degree of soil development
	Erosion	U	I	10^2 - 10^6	Valley form, river development
	Salinisation	U	R	10^2 - 10^4	Halophytic ecosystems
	Urbanisation	C	I	10 - 10^2	Loss of agricultural land ('sealing')
Regional, catchment or catena Small scale <1:100 000	Soil formation	U	I	10^2 - 10^4	Soil types
	Erosion	C	I	10^{-1}-10^3	Gullies, tunnels, etc.
	Salinisation	C	R	10 - 10^3	Area of discharge/salt affected land
	Acidification	U	I	10 - 10^3	Restricted crop and pasture species
	Waterlogging	U	R	Seasonal	Area with slow surface drainage
Paddock or polypedon Large scale >1:25 000	Erosion, deposition	C	I	10^{-2} - 1	Surface features
	Salinisation	C	R	10 - 10^2	Discharge features
	Acidification	C	R	10 - 10^3	pH
	Waterlogging	C	R	Seasonal	Ponding, pugging, sealing
Pedon (3D Profile) Human scale 1:1	Erosion, deposition	C	R	10^{-2} - 1	pedestals, rills, layering
	Profile development	C	R	10 - 10^4	Depth, horizons
	Salinisation	C	R	10 - 10^2	Vegetation response
	Acidification	C	R	10^2 - 10^4	pH
	Waterlogging	C	R	Seasonal	surface features (pugging, seals), colour
	Sodification	C	R	10 - 10^4	soil dispersion in rain water
	Root penetration and water use	C	R	1 - 10^2	depth and pattern of roots vs textures
Horizon (Pedon in detail)	Erosion, deposition	C	R	10^{-3} - 10^2	Surface features
	O.M. accumulation/depletion	C	R	1 - 10^2	L,F,H.Consistency (hard setting), OC
	Thickening, thinning	C	R	10 - 10^2	Native site comparison
	Leaching, acidification	C	R	10 - 10^2	pH
	Clay translocation	C	I	10 - 10^2	Coatings, turbidity of run off
	Soluble salt accumulation	C	R	10 - 10^2	EC, visible crystals
	Carbonate, gypsum accumulation	U	I	10 - 10^3	Nodules etc.
	Gleying	C	I	1 - 10^2	Colour, mottling
	Iron enrichment	U	I	10^2 - 10^4	iron pans, buckshot, pore linings, Bs
	Compaction	C	R	Seasonal	Ped shape, pores, bulk density, roots
	Loosening	C	R	Seasonal	Ease of tillage, cloddiness
	Root penetration, water use	C	R	Seasonal	Roots vs. pores vs texture
	Animal activity, burrowing, etc.	C	R	Seasonal	Number/area(vol)
Ped	Aggregation	C	R	1 - 10^2	Water stability
	Cementation	U	I	10 - 10^3	Consistency, grain coatings
	Slaking§	C§	R§	10^{-4} - 10^{-2}	Crusts, seals
	Dispersion§	C§	I§	10^{-4} - 10^{-3}	Cutans, turbidity
	Compaction	C	R	seasonal	Pores, ped/clod density
Mineral	Hydration, hydrolysis, solution	U	I	10^{-4} - 10^4	%unweathered minerals
	Salts (formation/ transformation)	U	I	10^{-3} - 10^2	EC, visible crystals (halite)
	Clay formation	U	I	millenia	%clay and 2:1 vs 1:1 layer silicates
	Clay degradation	U/C	I	10^2 - 10^4	low pH, water logging, bleached colour
	Fe/Mn oxide formation	U	I	10^{-3} - 10^4	Colours: red/ yellow (formation)
	Fe/Mn oxide transformation	C/U	R	10^{-3} - 10^4	bleached/ grey colour (transformation).

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

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

Table 2 Data recorded during profile characterisation (McDonald *et al.* 1990), classified according to data type and sensitivity to change (from MacEwan and Fitzpatrick 1996).

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

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

6 Soil health, ecosystem services and environmental health

Ecosystem services have been broadly defined in other literature (for example by Binning *et al.* 2001) but most of them have some relationship to soil and soil health. Table 3 provides example of the functions that soil performs to support more general ecosystem services.

Table 3 Ecosystem services (from Binning *et al.* 2001) and relationship to soil functions and soil health.

Ecosystem Service	Relationship to soil functions and soil health
Pollination	Soil does not have a direct role in pollination, although undisturbed soil can provide habitat for many insect pollinators that pupate, nest or raise larvae underground.
Fulfillment of people's cultural spiritual and intellectual needs	Soil provides general ecological functions that sustain diverse vegetation, habitats, gardens and sports fields.
Regulation of climate	Soil plays an integral role in the global climate, indirectly through supporting vegetation and C-fixation, and directly through C-sequestration in soil and gaseous emissions from soil. The latter are significant in some agro-ecosystems. Soil also influences the microclimate close to the ground through albedo and heat storage which are affected by surface soil conditions, organic matter and moisture content.
Insect pest control	Soil borne insect pests may be regulated through complex biological systems in soil. Airborne pests (eg Aphids) may be encouraged or discouraged depending on soil fertility and plant nutrition.
Maintenance and provision of genetic resources	Soil health has an indirect role in supporting genetic variety of plants and animals, but is itself also a store of unique genetic resources, many of which are undocumented at this time.
Maintenance and regeneration of habitat	Soil supports vegetation as habitat. Soil health (or soil quality) is critical in the restoration of habitat. Management of soil for ecological restoration after mining operations, urban reclamation and post agricultural land use change is a critical area for the science of soil and soil health.
Provision of shade and shelter	Through supporting and maintaining vegetation, soil serves a primary function in the provision of shade and shelter.
Prevention of soil erosion	'Resist erosion' is a primary function of soil described in the soil health / soil quality literature. Soil structural stability and strength, ground cover, roots and vegetation all interact to provide this ecosystem service.
Maintenance of soil fertility	'Store and cycle nutrients' and 'support plant growth and productivity' are two primary functions of soil described in the soil health / soil quality literature.
Maintenance of soil health	This becomes tautological, however that 'maintenance of soil health' is recognised as a primary ecosystem service only serves to emphasise the importance of soil and soil health. This ecosystem service links the soil back to the ecosystem as a whole or the agro-ecosystem and a requirement for appropriate system dynamics that serve the objective 'soil health'.
Maintenance of healthy waterways	'Filter and absorb wastes', 'act as an environmental buffer', 'resist erosion', and 'partition and regulate flows of water' are all primary functions of soil that assist in the provision of the ecosystem service, 'maintenance of healthy waterways'.
Water filtration	Comments made with respect to healthy waterways apply here too.
Regulation of river flows and groundwater levels	Comments made with respect to healthy waterways apply here too.
Waste absorption and breakdown	The soil ecosystem is the single most important processor of waste in the environment and this is recognised in the soil quality literature through primary functions such as 'filter and absorb wastes' and 'store and recycle nutrients'.

There are many ways in which soil health and environmental health are linked. Examples relating to salinity and impacts on urban infrastructure are well known and documented sufficiently elsewhere.

6.1 Soils and animal and human health

Soil quality affects animal and human health directly and indirectly. Reviews by Oliver (1997) and by Abrahams (2002) have summarised the many impacts that soil can have on human health. Relationships can be identified between soils and human health, but these might not depend on soil health. Biological, chemical and mineral components of soils can either be directly beneficial or detrimental to human health if ingested, inhaled or absorbed through the skin. The detrimental impacts do not necessarily represent 'unhealthy' soil, but this serves to illustrate some of the difficulties surrounding the 'health' terminology and positive functions of soil (supporting animal and human health). Serious contamination (for example, lead in urban soils in the UK) can result in severe human physical effects.

In the course of this project I have been unable to find any review of direct relationships between soil and animal health, although there is certainly a large body of knowledge in the veterinary and animal husbandry professions that could be summarised. Deficiencies and toxicities resulting from nutrient imbalances in forage are the most common soil health factors affecting animal health. Soil ingestion may be of concern (e.g. long-term persistence of sheep dip spillage) or of benefit (e.g. salt licks). Animal lameness is often related to soil conditions, particularly to waterlogging and to uneven ground following soil surface disturbance or damage (pugging and poaching by hooves or wheels). Flukes and other parasites may persist in ponded soil. Spores of lethal bacteria can persist for decades in soil (e.g. Anthrax) and can be directly ingested. Prions, the infectious agents thought to be responsible for transmissible spongiform encephalitis, can contaminate soils, being absorbed onto clay surfaces where they persist in a viable state (Rigou *et al.* 2006).

One of the much debated issues around soil and animal health concerns the ratio of exchangeable calcium or potassium and magnesium in soil. While hypomagnesemia or grass tetany in cattle is a common effect of low Mg in forage, the occurrence of this is not precisely predictable from the Ca to Mg or K to Mg ratios in soil. For example, there is little refereed research in the Ca to Mg topic but the importance of a ratio in the order of 6.5-7:1 is strongly promoted by 'biological' farmers. Different species of plants have different nutritional requirements and there is no evidence that yield is affected by soils with widely different Ca to Mg ratios.

Animals may amplify any effects of soil chemistry by reacting to imbalance in their nutrition but there is little reliable guidance to link measurable soil fertility factors to animal health. Trace and macro element deficiencies or toxicities are more reliably determined from animal blood tests than from soil tests.

6.2 Soil erosion

Soil erosion by wind or by water has major environmental health and economic impacts. Loss of topsoil has onsite consequences for soil health which, in some instances (loss of weed seed load in wind erosion), has been seen as positive by the landholder, but is invariably also an economic loss due to loss of nutrients and soil fertility. The offsite impacts of wind erosion in the form of human health due to dust, and obstruction of infrastructure due to drifting sand, have been estimated as ten times greater than the economic losses due to fertility losses from wind-affected paddocks (John Leys, personal communication[6]). Loss of soil organic matter from erosion can lead to degraded surface structure and consequent problems of reduced water infiltration and impaired seedling emergence. Water erosion has major consequences on river health and on silting of infrastructure. Both wind and water erosion are significant soil health issues in Victoria.

6.3 Land contamination and soil health

Soil and land contamination has resulted from agricultural chemicals, poor handling of overburden during mining operations and poor rehabilitation and soil reinstatement following trenching operations and installation of infrastructure. Soil management is a critical component throughout all urban, industrial or mining operations if soil is to be satisfactorily reinstated in a healthy condition. Soil scientists and agronomists therefore have important roles to play in planning and supervising soil handling and

[6] John Leys is a national authority on wind erosion with the NSW DPNR at Gunnedah.

rehabilitation. The soil management issues and unique classification systems for non agricultural soils are summarised well in 'Soils and the Urban Environment' (Bullock and Gregory 1991).

Soil contamination may be assessed through chemical analyses and there are many registered laboratories able to provide this service. However, multi-parameter screening of soil contaminants is expensive and there may be more economic ways to assess the potential impact of contaminants by assessing plant health and soil biota.

Madejón *et al.* (2006) argue that the use of plants as biomonitors of soil quality has advantages over soil analyses, particularly on a large scale. Their emphasis is on contaminants and metals associated with mined land, but they suggest that plants with a high root-shoot transfer would be important biomonitors for land destined for agriculture, as the worst case scenario for risks to health would be indicated by such plants. In an ecological restoration project the most significant primary producer (start of the food chain) would be the most appropriate biomonitor.

Hatcher (2002) describes a health index approach using abiotic and biotic factors to assess contaminated sites and their remediation. Abiotic assessment includes parameters likely to affect organisms' physical tolerances (for example; pH, EC and texture). The biological assessment encompasses responses of species at different trophic levels (microbes, plants, invertebrates, and community processes such as CO_2 evolution). Different media are also tested. Solid phase tests expose test organisms to soil as received. Aqueous extracts indicate water soluble toxicities. Methanol extracts test for non-polar hydrophobic organic contaminants that would not be detected in aqueous extracts. Each test result is ranked on a normalized scale of 1 to 5 (1 non toxic, 5 worst case), values are averaged and a single health index between 1 and 5 reflects all the components of the health index.

6.4 Climate and soil health

Climate has a direct impact on soil health and has its most severe impacts in extremes of dryness leading to wind erosion and, in extremes of wetness leading to sheet, rill and gully erosion. Soil health is also linked to climate benefits on a global scale because soils can store carbon, improving soil quality and reducing greenhouse impacts. Studies on the actual storage of carbon in different systems, and modelling to predict the amount of C that can be sequestered in soil, present a somewhat limited prospect for a net long-term positive impact on climate. Soil management practices underpin the capacity of these activities to sequester carbon. However, under Australian conditions, soils have a poor capacity to store large quantities of carbon and, once soil carbon has been built up, practices must be put in place to prevent its release (AGO 2002).

Chan, Heenan and So (2003) have reviewed sequestration of carbon in relation to conservation tillage in light-textured soils in Southern Australia. They found that significant improvement in carbon levels were only found in the higher rainfall (>500 mm) cropping areas. They also suggest that data from trials over 3-19 year periods indicate that carbon levels continue to decline under continuous cropping even where conservation tillage is used. They concluded that other soil quality attributes associated with conservation tillage (macroporosity, aggregate stability, infiltration and water holding capacity) depend on organic carbon levels, and therefore these attributes may also have limited long-term sustainability. They advocate that long-term continuous monitoring of soil carbon and soil quality is needed for different agro-ecological zones.

A more significant and potentially manageable relationship between soil quality and climate impacts resides in the production of nitrous oxide, a major greenhouse gas. N_2O production is related to soil moisture, N levels and soil temperature, and is therefore a feature of irrigated pastures. Recent work by DPI at Kyabram indicates that some of the modelling used up to now overestimates N_2O in temperate irrigated agriculture by about 70%. A better understanding of the dynamics of N_2O in these systems can lead to positive outcomes for soil fertility, water and fertiliser management and greenhouse mitigation. Dalal *et al.* (2003) stress the need for long term research into the relationships between CO_2 and CH_4 emissions and sinks and N_2O emissions as these interact strongly.

7 Frameworks for decision-making and soil health

Although not a goal in itself, soil health affects all areas of society through food and fibre production and relationships to environmental health. There are many papers now in the literature that present this standpoint (for example, Karlen *et al.* 2003; Doran 2002) as well as those that refute the value of the concept (Sojka and Upchurch 1999). The debate on both sides is driven by the recognition of complexity, on the one hand leading to arguments that 'soil quality is humankind's foundation for survival' (Karlen *et al.* 2002) and, on the other hand, that the concept is too vague, cannot be quantified and raises more questions than can be answered. Definition of terms (Section 2) and agreement concerning their meaning is a necessary starting point in resolving differences. From this starting point we need frameworks that support the concept of soil health and enable its integration into planning and management activities. Three examples are given here: a decision making framework (after Steinitz 1993, Section 7.1), integration of soil quality objectives (Section 7.2), and delivery of knowledge (Section 7.3). These examples are followed by a simple presentation of the diversity of stakeholders and issues concerned with soil health (Section 7.4).

Soil management is carried out on the basis of judgements that range from those that are based on trust and tradition (things have always been done that way) to those that are scientifically informed. Management may also be based on other judgements that are neither blind, in the sense of following a tradition, nor scientific, but are based on ethical or philosophical views about what is 'good' for the soil.

7.1 Application of the Steinitz framework to soil health

A systematic approach to the data, information and knowledge required for soil health management can be adapted from the landscape design framework of Carl Steinitz (1993). This framework is illustrated in Figure 8. The framework identifies six types of questions, each of which is pertinent to decision making. Steinitz focuses his work on the use of GIS and the modelling needs for spatial decision making (landscape analysis, scenarios and design solutions) but the framework structure has universal applicability. The logic of Steintitz's approach to landscape design has been applied to soil health in Figure 8.

A simple sequence is as follows. The soil system must be described by appropriate qualities (attributes); the system must be understood in terms of its dynamics (processes and functions); and it must be evaluated with regard to how well it is working (functional capacity, monitoring and indicators). The system and its management can be changed or may be changing because of external influences (change and scenarios), and this is an important area for modelling that is linked to understanding the differences that the changes may make to the soil system (impact). Decisions are informed by the sequence described but may be tempered by a lack of sufficient data, information or knowledge.

The framework therefore provides a structure by which the adequacy of any of these may be judged. For example, if the representation questions concerning properties of the soil cannot be answered (such as insufficient data concerning particular soil parameters, scale of data or accuracy of mapping) then acquisition of data may be a priority. If the processes are not fully understood or cannot be modelled then empirical research into some aspect of soil system dynamics is required. If differences exist between judgements about how well the system is working then it may be necessary to defer to a political decision, or to pursue better knowledge of the link between indicators, functions and processes (a better monitoring program).

The process of using the framework is iterative. At any point it may be necessary to move back to a previous level to refine the data, information or knowledge for that level. Practically, the requirements for each level depend on the type of decision that is being made.

The six types of questions are a useful audit for any decision making process and have been used in section 8 to structure the discussion around recommendations for priorities for soil health data, information and knowledge.

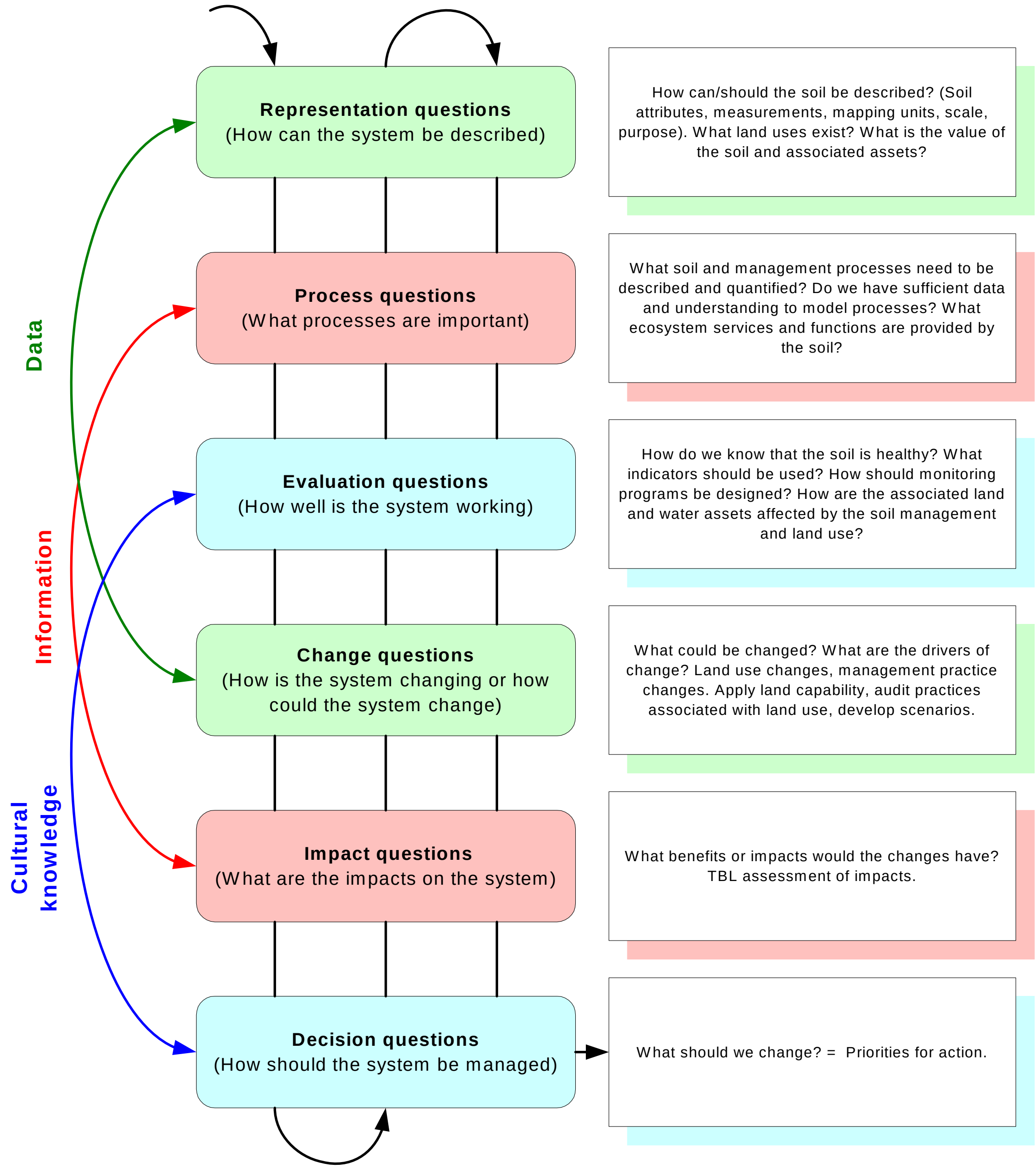

Figure 8 A framework relating data, information and knowledge needs for decision making (after Steinitz 1993) illustrated with some example questions that need to be answered for management of soil health.

7.2 Integration of issues for soil quality, an example

Soil health issues do not exist in isolation from each other or from other environmental issues. In fact, the soil health paradigm is useful because it places soil processes in this larger context. Examples of some of these inter-relationships are shown in Figure 9 and Figure 10 based on requirements of the Australian dairy industry's 'Protection and Management of the Dairy Landscape Program'. This program had five sub-programs, three of which were biophysical and had obvious synergies between them (Soil Management; Efficient water use; Nutrient management and movement). Six objectives had been set by the DRDC for soil management and a seventh (chemical fertility) was added:

1. Minimal loss of soil from dairy farms.
2. Either pasture systems that reduce rates of acidification, or the regular use of lime to correct pH.
3. Well-structured soils.
4. Specific practices and guidelines for managing wet soils.

5. Minimal build-up of chemical residues (or other undesirables such as sodium).
6. Large and active populations of soil biota so that organic matter breaks down rapidly, releasing nutrients for pastures, and maintaining soil structure.
7. Chemically fertile soils with appropriate balances of essential macro and micro nutrients to maintain quality of pasture and support animal health.

A soil quality approach was proposed which could provide an overarching framework for achievement of these objectives. Maintenance of six soil functions was seen as relevant to achieving these outcomes, as well as influencing the success of the water use and nutrient movement sub-programs (Figure 9).

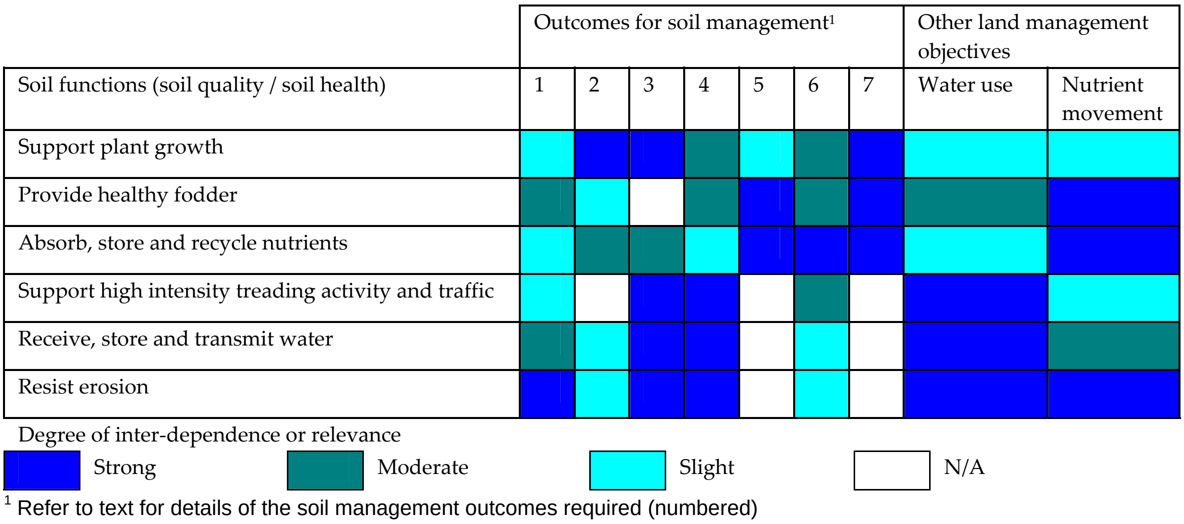

Figure 9 Relationship between soil functions and some key soil management and environmental management objectives (MacEwan 1998).

Inter-relationships between the required soil management outcomes are illustrated in Figure 10. Detailed discussion of the inter-relationships between these outcomes and soil quality is given in MacEwan (1998).

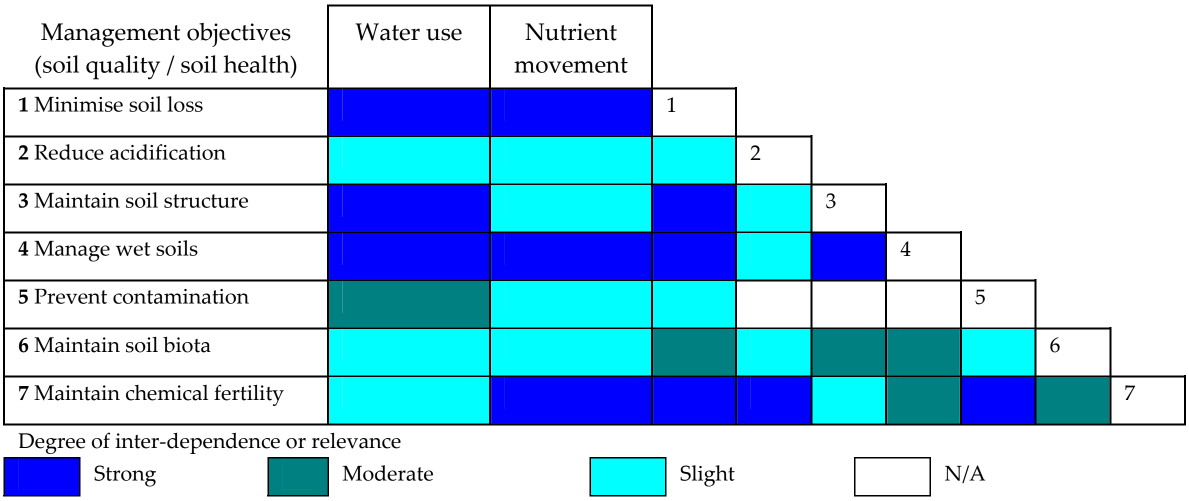

Figure 10 Interrelationships between soil management objectives (example from priorities for the Australian dairy industry, MacEwan 1998)

7.3 Soil health and the delivery of knowledge

Knowledge creation, management and delivery is a complex subject in itself that can only be superficially addressed here. However, a useful framework is provided by viewing these as related in a business chain linking data collection, knowledge creation and implementation of knowledge (Figure 11).

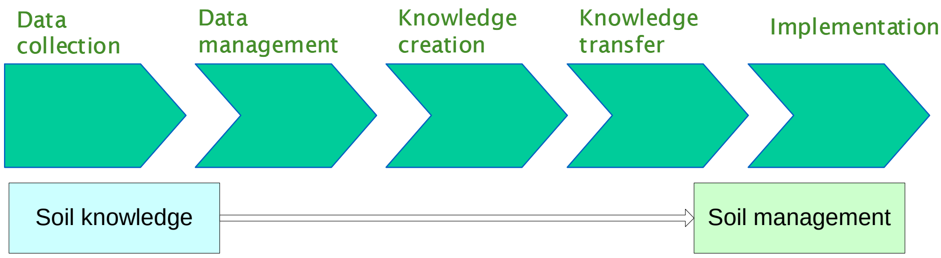

Figure 11 Soil knowledge chain, from data collection to implementation of understandings.

Activities associated with this chain are provided in Table 4. Although represented as a linear process from data to implementation, in practice, the requirements for data, knowledge creation and management are driven by a need to implement better-informed management. There are parallels with the iterative process described in the context of the Steinitz framework (section 7.1).

Table 4 Phases in knowledge creation and implementation for soil health

Data Collection	Data Management	Knowledge Creation	Knowledge Transfer	Knowledge Implementation
Soil Surveys Site characterisations (reference sites) Yield data Soil condition	Storage and archiving Systems for data access. Custodians and accountability for data systems.	Description of processes and relationships. Conceptual and mathematical modelling.	Publications: reports, papers, technical notes, articles, fact sheets. Education, extension, training, demonstration	Research and trials based on new knowledge. Hypothesis testing. Practice change. (link back to data collection through monitoring and reporting)

7.4 Stakeholders in soil health

There is a diversity of interest in soil health held by a range of stakeholders and these are summarised in Table 5. The issues or areas of concern have been separated into five topics: policy, ecosystem services provided by soil, understanding of soil processes, knowledge management, and primary production. Key stakeholders are the government departments (DPI and DSE), regional Catchment Management Authorities, farmers and farmer groups and the rural industry research corporations. Issues of concern for soil health are different for each of these groups and this has relevance to any communication planning with respect to soil health work.

Table 5 Stakeholder groups and relationship to areas of concern for soil health

	Issue / area of concern				
Stakeholder	Policies related to soil health or management.	Soil as a functional component in the provision of Ecosystem Services / Catchment management	Understanding the soil resource, processes in the soil, and responses of soil to management.	Knowledge Management and extension services.	Production issues : using soil to make money.
DPI	Soil Health Policy Framework development by Agriculture Policy Group.	Through production systems DPI has a role in determining sustainability of agriculture and the associated resource base (soil and water).	PIRVic is the lead body responsible for adding knowledge about soil process. Soil and Water platform is the lead platform but soil research will also occur in other areas. Work is often collaborative with other agencies (CSIRO, Universities).	Extension of soil knowledge primarily sits within CAS division in DPI. Knowledge management roles include those for text, data, maps etc., and reside principally in KIT branch and PIRVic.	Research and extension efforts are directed from DPI to develop more productive agricultural systems.
DSE	Cathcment and Land Protection Act accountability.	Lead agency with respect to ecosystem services, land stewardship and catchment management.	Insofar as the knowledge will support decision making for catchment protection DSE is a stakeholder in this area.	Insofar as the knowledge will support decision making for catchment protection DSE is a stakeholder in this area.	Of no interest.
CMAs	No accountability for policy development. May implement policy.	Lead regional authority responsible for catchment management, condition and reporting.	In particular CMAs need to know how to set targets and monitor soil health for catchment condition reporting.	Through soil health strategies, action plans and monitoring activities, CMAs will disseminate and collect knowledge about soil health and soil management in their regions.	Of some interest wrt regional sustainability.
Farmers and farming groups	Minor importance.	Increasingly involved in catchment and landscape issues related to farming.	Through partnerships in research and demonstration projects, these groups are adding to the understanding of soil responses to management.	Main clients for knowledge management and knowledge supply for soil management.	Most significant stakeholders are those involved in soil-based primary production systems.
RIRFs	Minor importance	Minor interest	Invest in research providers (government, universities and consultants) to acquire new knowledge about soil insofar as it affects the industry.	Invest in service providers.	Most significant decision makers for investment in research, development and extension activities.

8 Priorities for soil health

Priorities for soil health depend on the stakeholder and area of concern (Section 7.4). DPI Agriculture Division have prepared a theory of action for soil health after consultation through workshops for the soil health policy framework (DPI 2006). This sets the high level objectives, theoretical process and accountability for soil health. The discussion that follows in this section is more focussed on the science requirements to support a soil health program and is structured around the six thematic questions of the Steinitz framework (Section 7.1).

8.1 Representation: data needs and data management

Analysis of the soils data available through the Victorian Soil Sites Database (VSSD) and GIS layers held by DPI PIRVic has provided some insight into soil quality variability across soil groups (Crawford *et al.* 2006). However, there is a paucity of sites entered into the database compared to the total of Victorian sites documented in reports. It should be a priority to enter relevant site data into the VSSD wherever they can supplement the existing dataset with useful reference data. There are several soil parameters that are unavailable or have only limited availability, particularly quantitative physical properties important for understanding and modelling soil hydrology. Crawford *et al.* (2006) have made several recommendations for the improvement in soil data. The 'Datatrack' project funded by DPI from July 2006 will serve to identify the required business processes and accountabilities to address these needs. Appendix C has outlined the case with respect to biological data for which there is currently no database. Given the high level of interest by the farming community in soil biology, meeting the data requirements in this area is also a priority.

The spatial extent or coverage of soil data is limited to coarse scale (1:250,000 land systems) for the whole state. At this scale only the broadest indication of soil type can be given. Some regions have soil-landform maps at 1:100,000 scale, but because of soil variability within the map units, these too are limited and have little application at farm or paddock level. These issues are discussed more fully in Crawford *et al.* (2006) but it is worth emphasising here that a full inventory of soils and properties is a necessary basis for any advisory work or soil-correlation for agricultural research and extension. Mapping also needs to be at a resolution appropriate to modelling needs but this is a point that is invariably overlooked by the end users of model outputs. The work that has been carried out in revising land systems in the new Victorian Geomorphological Framework is a significant step in working towards an integrated multi-scale mapping approach for soil and land in Victoria. This work will need to be continued through soil correlation from older surveys and augmentation with new land resource surveys and site data.

Data access is limited by the lack of a user-friendly, web-based interface to the VSSD but this is being addressed through the newly funded soil health project (ESAS and LWA MIS 03250) which will commission the database scripting work As well as access to data, there is a generally limited understanding in DPI concerning what data are available and where they can be obtained. This also applies to map data. This general problem of access to, and knowledge of, data and modelling requirements has been tackled in part under the ORL project 'Our Landscape' through the MIKE conceptual tool (Models, Information and Knowledge Environment) but needs to be continued through other initiatives.

Soil data that have been collected in the past have either been collected as part of mapping programs or have been related to particular soil management or comparison objectives in research projects. The VSSD has not in the past been able to accommodate time series data records for monitoring at a site, though recent redesign of the VSSD by the Spatial Sciences subplatform of DPI for the Victorian Earth Information System (VEIS) may address this issue. There is no history of systematic data collection for soil quality or soil health attributes per se, so the need for this needs serious consideration. The Healthy Soils for Sustainable Farms project (Land and Water Australia, MIS 03250) has an objective centred on the use of paired sites for comparison and demonstration of soil management. Soil monitoring at these sites will require a system for data collection, storage and analysis.

8.2 Processes: understanding of soil processes

There is a broad body of literature on soil processes that can be used to inform understanding in this area. Application of the general understanding to specific soils and management situations is restricted both by the limited locally focussed research and the knowledge (training) base of staff in DPI for basic soil science. Specialists in the department can be called on to interpret specific situations but without hard data, much of this interpretation remains in the realm of educated guess work. There are many questions raised in the farming community as well as in the science community concerning the relationships between crop production and the soil system. In a broader context there are questions concerning the relationship between actions at a paddock scale and interaction with processes at a catchment (e.g. groundwater, nutrient movement) or even global (greenhouse gases, carbon sequestration) scale. These broader scale questions generate their own data needs related to landscape structure and conceptual models that link soil to groundwater systems, and climate models that link land use management to global atmospheric systems.

Soil biological processes consistently emerge as a major area for advice that can only be given in a very general way. The growing interest in 'biological' farming is a significant external driver for research that can provide scientifically defensible advice for the management of soil biology in crops and pastures. There is also limited readily available understanding of processes in the rhizosphere (the soil environment immediately related to root growth and root-soil interactions) although a recent publication (Zobel and Wright 2005) has brought together a lot of knowledge on this topic. Most soil analyses and interpretations are made on the basis of samples of soil that are bulked in order to represent the whole soil horizon of interest. However, the properties (biological, physical and chemical) of the rhizosphere are very different to those of the bulk soil matrix (Whalley *et al.* 2005; Gregory 2006). Rhizosphere studies are needed in order to provide better interpretation of soil quality attributes and the relationship between soil health and plant growth.

8.3 Evaluation: methods for evaluation of soil health

Probably the greatest limitation to assessment of how well the soil system is working is the lack of basic data on soil and land condition and the minimal application of monitoring tools. At the paddock scale this can be effectively addressed by individual landholders, provided soil variability is taken into account. Soil health scoring systems can be devised based on quantitative and qualitative assessments of soil function. However, recommendations for appropriate indicators and methods are currently not available from DPI and in some instances (e.g. biology) are challenged by the lack of useable indicators. The DPI Healthy Soil project commencing this year (2006) will review, recommend and trial tools for soil health assessment with participating farmer groups so the need for paddock scale evaluation of soil health will be addressed.

Soil assessment at one time gives an indication of how well the soil can perform its required functions at that time, but serial assessment over several seasons is need in order to provide trend data that would indicate how well the system is working. McKenzie, Henderson and McDonald (2002) have proposed methods for soil monitoring but these have not been applied in Victoria. There is potential through the Healthy Soils project to test the feasibility of setting up Victorian reference sites for long term monitoring in key agricultural landscapes.

At regional, state and national levels there are requirements to report on the state of the environment and in particular on land and soil condition. Baseline data were provided for the National Land and Water Resources Audit based on available information or interpretation by the States at that time (2000). General recommendations were made nationally that soil condition should be monitored for acidification, organic carbon, wind erosion and water erosion. Recent work commissioned by the Audit office through the National Committee for Soil and Terrain has resulted in recommendations from working groups for each of these indicators (McKenzie and Dixon 2006). In Victoria several CMAs have developed, or are developing, soil health strategies with resource condition targets (RCTs) and management action targets (MATs) but these strategies have had insufficient baseline data and little information to guide the setting of targets. There is therefore a strong need for regionally based assessment methods to enable reporting on soil and land condition. The Agriculture Division's 'Triple Bottom Line Indicators' project is currently reviewing approaches to this problem, and the DSE have also expressed intentions to develop a "Land Health Index" that would incorporate soil health.

In the absence of hard data on soil condition it is still possible to evaluate how well the system is working. Land use and land management (land use practices) have been used at the regional level to model the likelihood of a range of threats to soil health. Relationships between land use management and soil susceptibility (based on soil landform descriptions) have been incorporated in the Land Use Impact Model (LUIM) to develop a soil health strategy for the Corangamite region (MacEwan, McNeill and Clarkson 2004). The LUIM approach is useful for identifying areas that are likely hotspots based on the threats posed by land use management (McNeill and MacEwan 2007). This is a good surrogate for monitoring soil condition, provided the relationships are sound and spatial information on land use can be updated. A similar approach is being advocated in Europe in a report by Eckelmann *et al.* (2006) which presents an overview of common criteria and approaches to identify risk areas for soil organic matter decline, soil erosion, soil compaction, salinization and landslides.

Direct monitoring of soil condition may be prohibitive at a regional scale simply because of the diversity[7] of combinations that can occur between soils, landscapes and agricultural practices. If this is the case and we continue to rely on surrogates and assumptions concerning best management of land, then it is a priority to test these assumptions in order to provide more confidence in the modelling. This could be carried out across Victorian agricultural landscapes using a series of reference sites, perhaps along the lines that have been adopted by the State of Alberta in Canada (Cannon 2002; Bremer and Ellert 2004).

8.4 Change: land management and land use scenarios

Changes to the system may occur in a number of ways. Land use and enterprises may change under the influence of economics for different agricultural commodities, or competition for land for other uses than agriculture. Within a particular land use the management practices affecting soil health may change in many ways, through intensification, irrigation, tillage practices, traffic control, rotations, fertilizer usage, grazing management, weed management and disease control. Climate variability or trends in climate directly affect crop production, soil wetness or dryness, frequency of waterlogging, vulnerability to erosion by wind and water, accumulation or loss of organic matter, prevalence of soil borne pathogens, and persistence beneficial soil organisms.

8.5 Impacts: understanding and predicting impacts on soil health

The potential impacts of changes on soil condition need to be modelled so that risks to soil health can be managed. There are many different types of models used at different scales; from those that provide general assessment of risks to soil to those that specifically model soil and soil-plant processes. Models such as LUIM can incorporate scenarios for land use and map changes in likelihood of degradation and level of risk to soil at a regional scale. Carbon models such as RothC can be used to predict changes resulting from cropping practices and climate, and the Revised Universal Soil Loss Equation (RUSLE) can be used to predict erosion losses under different scenarios. All models need some validation, especially when they are being applied in new environments and new situations. Many of the poorly modelled predictions versus actual crop performance are the result of insufficient soil data to provide reliable modelling of water use (e.g APSIM), and in some instances the models are simply not designed to deal effectively with constraints in the rootzone. The support of soil modelling and the validation of outputs is a priority, if the models in question are to be used to set targets for regional strategies or to determine changes in management for soil health objectives. Modellers and the users of model outputs should be consulted to determine priorities in this area.

8.6 Decisions: support for soil health management

Decision support for soil managers requires integration of all of the aspects described in Sections 8.1 to 8.5: characterisation of the soil or soils, knowledge or modelling of processes, evaluation of relationship between current management and soil condition, development of change options or drivers, and their likely impacts. Decisions vary in their complexity, from those that require little guidance to those that require specialists for analysis and advice. Data needs are driven by the issue in question (for example; soil

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[7] New Zealand instigated a '500 Soils' program to complement their '100 Rivers' monitoring program to cope with diversity of agriculture and soils.

fertility management, acidification, erosion, soil biological health) and consequently need to be determined by the questions of end users, whether planners or farmers.

8.7 Decision making and knowledge of soil change

All the foregoing discussion implies the need for knowledge of the dynamics of soils, the types of change that can occur, and the rates of change. There are few soil properties for which we have specific knowledge although there are generalisations that can be made (for example, Table 1). Tugel *et al.* (2005) have analysed the current situation in the USA with respect to soil survey data and knowledge of soil dynamics and rates of change under natural and human influences. They proposed six actions to provide the information that land managers and decision makers need. These actions have been listed in Table 6 along with summary comments pertinent to the Victorian (DPI) situation.

Table 6 Actions needed to support soil information needs of decision makers (after Tugel *et al.* 2005) and responses from a Victorian DPI point of view.

Blueprint actions after Tugel *et al.* (2005)	Response
Identify user needs	Demands for modeling and for land use planning (capability and suitability) are mostly understood. Soil data are frequently highlighted as the gap in many landscape analysis and planning projects. However, much soil data is in forms that are not readily useful. Soil maps based on soil type have only general applicability although they can be interpreted in many ways. Soil attribute maps (for example, pH, texture, depth) would have much greater utility for models.
Conduct interdisciplinary research and long-term studies	This should encompass the regolith processes, hydrology and agronomy. The long term agro-ecological experiments are important resources that need to have greater assessment with respect to the soil properties at these sites and soil changes that have occurred.
Develop an organizing framework that relates data, processes and soil function	This work has commenced with this project and should continue in the Healthy Soils projects. However, this work will not fill any gaps in knowledge as its focus is on delivery of existing knowledge.
Select and prioritize soil change data and information requirements	This is required. The most substantial work has been on soil pH with respect to acidification. Biological data are being collected at a base level and the interpretation of change and soil ecosystem dynamics will be needed beyond this basic inventory.
Develop procedures for data collection and interpretation	Data collection protocols for standard soil characterization are well established. More work is needed to collect data on soil condition and performance of soil functions.
Design an integrated soil-ecosystem-management information system	Work has commenced in this area with the Victorian Soil Sites Database (VSSD) which is envisaged as a component of a more comprehensive Victorian Earth Information System (VEIS).

8.8 Theory of action for knowledge delivery in the ESAS health soils project

A theory of action flow diagram developed for the ESAS Healthy Soils project is shown in Figure 12 and this summarises the general relationship between many of the issues discussed in this report. The DPI Healthy Soils project (MIS 03250) provides the basis for comprehensive knowledge management and delivery for soil health with respect to existing data and understandings, but it will need to be complemented by projects in related areas that can support fundamental research into processes and soil management.

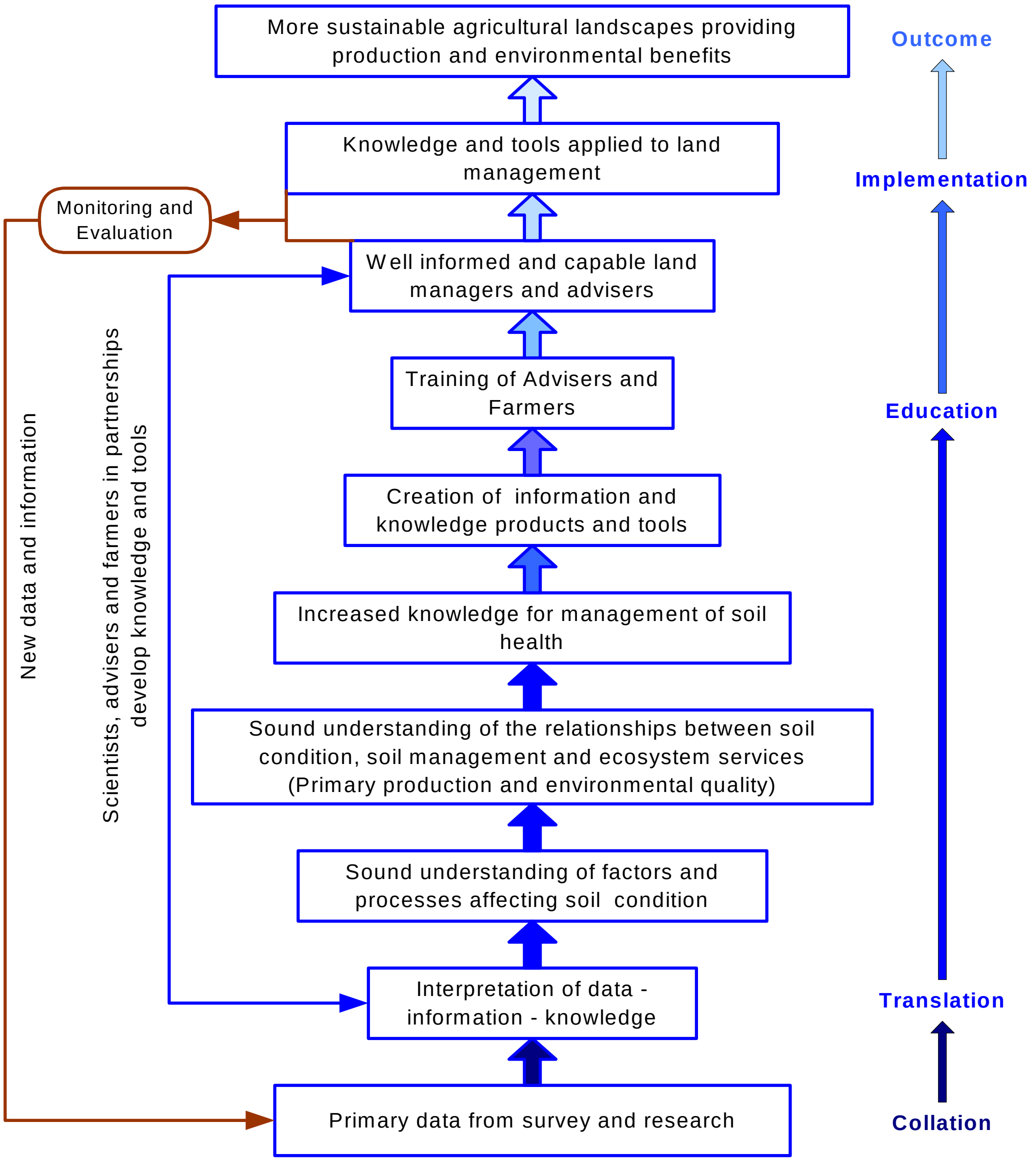

Figure 12 Theory of action developed for Healthy Soils project showing relationship between data, information, knowledge, training, implementation and desired outcomes.

9 Conclusion

Soil health is a concern worldwide and affects matters of food security, environmental protection, water quality, and infrastructure. Examples of policies (charters, agreements, memorandi of understanding) and programs for soil health (or, more generally, soil management) exist in the United States, United Kingdom, Canada, New Zealand and the European Union. Principal documents have been cited in this report and can be accessed on the world wide web (section 1.2).

Terminology (section 2) has been explained and should be used consistently in future work, using the definitions here as a basis. Scientific literature on soil health (or soil quality) is substantial and many key sources have been cited in this report. There are also many frameworks that can be used to organise complex components of knowledge associated with soils and some examples of these have also been given. The agro-ecosystem framework for soil health (Figure 2) and the landscape design research framework (Figure 8) are the most important in this respect.

The DPI initiatives in soil health (LWA and ESAS projects) represent a significant contribution to the efforts that are needed to address improvements in soil management in the dryland cropping areas of the Mallee, Wimmera and south-west Victoria. Experience gained in, and evaluation of, these projects should serve to support expansion of soil health activity in other parts of Victoria and for other agricultural industries.

Environmental implications of soil health and the wider provision of ecosystem services need to be considered in the development of initiatives that will augment and complement those in agricultural production. This report and, in particular, the summary descriptions of relationships between soil functions and ecosystem services (section 6) should be used to inform the development of the 'Land Health and Biodiversity' white paper currently in preparation by DSE.

Empirical research into the interactions between soil and management practices is critically needed in particular with respect to soil functions, soil biology and the agro-ecosystem. Questions are frequently asked about the impact that herbicides, fungicides, nematocides and insecticides may be having on soil biology, and whether these inputs compromise soil health. At this time there is insufficient knowledge of this subject to provide satisfactory answers.

There have been many changes in agricultural management in recent decades, and while these have resulted in very positive soil health outcomes there is still a need to broaden the adoption of practices that protect and improve soil. In particular, reduction in tillage, retention of organic residues and control of traffic play key roles in improving soil structure and hydrological properties as well as maintaining or increasing yields. Adoption of these practices more widely will be supported by better information but there are areas where long-established practices work against these principles. Cultivation to 'ridge' soils and protect them from wind erosion and cultivation to control summer weeds are widespread practices in the north west of the state and advocated as best practice by some DPI agronomists. While this may work from an enterprise perspective there are no gains being made in soil improvement through such practices.

Data and knowledge management for soils remains a priority but this is being tackled with funding in the Healthy Soils and Datatrack projects.

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