# The relationships between land management practices and soil condition and the quality of ecosystem services delivered from agricultural land in Australia

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## Project team

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## Disclaimer

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## Questions addressed

Funded under the Caring For Our Country program by the Australian Government's Land and Coasts Division, a joint initiative between the Department of Sustainability, Environment, Water, Population and Communities and the Department of Agriculture, Fisheries and Forestry, this project addresses two key questions about relationships between land management practices, soil condition, and the quantity and quality of ecosystem services (i.e. the attributes of ecological systems that contribute to benefits for humans) delivered from agricultural land:

- What evidence exists about how improving land management practices will lead to reduced soil loss (through water and wind erosion) and improved soil condition (especially through reduced impacts of soil acidification and increased organic matter content)?
- How might reducing soil loss and improving soil condition result in improvements in the quantity and quality of ecosystem services and benefits delivered from agricultural lands, including cleaner air, improved water quality, reduced greenhouse gas emissions, and more productive soils?

## Key conclusions

The project focuses on four aspects of soil condition identified in the Program Logic for Caring for our Country's Sustainable Practices target: soil carbon; soil pH; wind erosion; and water erosion. It also focuses on four broad groupings of agricultural industries: broadacre cropping; horticulture; dairy; and grazing.

In summary, evidence in the scientific and economic literature assessed and referenced in this report finds:

- Approaches to improving the soil organic carbon (SOC) content of soils, including minimising disturbance to soils from tillage and stock and increasing inputs of carbon by retaining stubble, using perennial pastures, and adding manures and other sources of carbon, have slowed the rate of loss of SOC and show potential to increase absolute SOC over time (although predicting the outcomes of interventions precisely is still difficult due to the many variables involved). Benefits in terms of better production outcomes have been demonstrated.
- Regular monitoring of soil pH and application of lime at appropriate rates has been shown to reduce acidity in surface soils, although rates of adoption of these practices are far too low to achieve widespread benefits. Net financial benefits of controlling acidity in surface soils have been demonstrated. Build-up of acid in

subsoils is of growing concern and addressing it is likely to be unaffordable for most agricultural industries in the near future.

- Maintenance of ground cover above 50-70% has been shown to be effective in reducing wind and water erosion and to yield financial benefits to farmers across all agricultural industries.
- Addressing soil carbon, acidity and susceptibility to erosion has many public and private benefits. These include better yields of agricultural products, which have private and public benefits, and better outcomes for agricultural soils, which themselves provide a range of 'ecosystem services' and benefits to both farmers and the broader public. Better soil condition generally improves the ability of soils to support benefits to the public (both urban and rural), such as clean water for drinking and recreation, protection from wind and water erosion and floods, and reduced risks from pests and diseases and reduced need to use agricultural chemicals. They can also include a range of cultural, spiritual, and intellectual benefits such as enhancing sense of place, mental wellbeing and acquisition of knowledge. Modest improvements in soil condition might only produce modest improvements in these public services and benefits, but even these modest improvements can be significant in economic terms and often greater than the private benefits.
- One of the most substantial benefits of better management of groundcover is reductions in dust storms, which have been shown to incur very large financial costs in regional and metropolitan areas across Australia. These costs relate to damage to infrastructure and health costs, as well as clean-up costs and costs of reduced water quality. There have been substantial reductions in dust indices since the 1940s, but large and damaging dust storms have occurred recently and are likely to recur in coming years during prolonged dry periods.

## Benefits and beneficiaries from better soil management

Ecosystem services can be described as the attributes of ecological systems that contribute to benefits for humans. By ecological systems, we mean systems that involve interactions among multiple species of plants, animals, and other organisms and between those species and the non-living environment. To address the question of how improving soil condition might result in improvements in the quantity and quality of ecosystem services and benefits delivered from agricultural lands, a framework was developed that relates soil properties and processes to ecosystem services, benefits and beneficiaries. The framework, described fully in the main report, is a synthesis and modification of several published frameworks. It was developed because many of those available in the literature did not explicitly link changes in soil condition to benefits to people, and because those that addressed this link were not entirely consistent with a set of principles distilled from the most recent literature in this field. The key framework principles were:

- Contributions that ecosystems make to meeting human needs (ecosystem services) should be kept separate from the contributions made by humans that are required to turn ecosystem services into benefits (for example, ecosystems generate fertile soil but for that service to become the benefit of support for crops requires humans to plant, manage and harvest those crops);
- To avoid multiple counting of benefits, it is important to distinguish between ‘final ecosystem services’ (ones that can be turned directly into benefits) and ‘intermediate’ or ‘supporting’ ecosystem services (ones that support other services and therefore can contribute indirectly to multiple benefits).

The living and non-living components of soil ecosystems interact to mediate a range of processes that would require engineering at an unprecedented scale to replicate. These processes transform natural resources into forms that are potentially of benefit to humans and in so doing they are said to provide ‘ecosystem services’. The main report identifies 14 such services and their respective benefits from soils.

Management of land for agriculture dramatically changes the balance among ecosystem services, increasing some provisioning services, decreasing some regulating services and changing the nature of many cultural services. One aim of improved agricultural management is to adjust this balance to meet a wider range of private and public needs.

Research reviewed in this report shows that best-practice approaches to managing soil carbon, acidity and wind and water erosion are generally effective at addressing those issues and improving soil condition. Practices like minimal tillage, maintaining ground cover above 50%, adding organic matter to soil (within limits), and managing the impacts of stock and machinery on soil disturbance and compaction, have beneficial outcomes for all aspects of soil condition. These practices, therefore, potentially enhance most ecosystem services and their benefits (Box S1).

The beneficiaries include farmers, agricultural industries, communities, families and individuals in regional areas and in cities. It is possible to estimate the magnitude of these benefits under different conditions in the future, but it is not meaningful to make a single estimate of future value because of the many combinations of management practices, soil types, climatic variations, products, market opportunities, demographic changes, and demands of consumers over the coming decades.

Some general conclusions can, however, be made:

- There are achievable opportunities to address declining soil carbon and increasing acidity and reduce wind and water erosion and at the same time improve profitability of agriculture and deliver a range of public benefits (which in some cases will be worth more than the private benefits in terms of health and wellbeing outcomes);
- To do this it will be important to consider the ability of soil ecosystems to cope with ongoing and potential future shocks (i.e., their adaptive capacity and resilience), which cannot be considered in isolation from the adaptive capacity and resilience of the humans who manage agricultural landscapes;
- The resilience of soils in many parts of Australia depends strongly on building and maintaining soil carbon stocks, which affect a wide range of functions, including nutrient cycling and water infiltration and storage, and the ability of landscapes to retain topsoil;
- Another key aspect of the resilience of Australian soils is their ability to avoid passing through thresholds of change, some of which could be irreversible;
- Such thresholds include critical proportions of ground cover (50-70% depending on factors like rainfall and slope), below which erosion accelerates dramatically, carbon-content thresholds, and thresholds of acidification, especially of subsoil, which currently cannot be addressed economically by most agricultural industries.

**Box S1: An example of benefits from better management of soil condition**

Maintenance of 50-70% groundcover — a management practice shown to be effective at reducing wind and water erosion and contributing to increasing soil carbon content and, indirectly, to addressing soil acidity — will affect the texture of soil by retaining the small particles that would otherwise be lost due to water and wind erosion. Organic matter content and biodiversity of soil will be enhanced because of reduced losses of carbon by erosion, increased inputs of carbon as groundcover plants die and degrade, and enhanced habitat for soil species. This will affect soil structure, soil biological activity and cycling of organic matter, nutrients, gases and water within soil and between soils and the atmosphere. These processes combine in different ways to support the full range of ecosystem services and their potential benefits. The extent of the benefits and the beneficiaries from maintaining ground cover will depend on the demand for different ecosystem services and benefits, who needs these and at what scales of space and time. The benefits are likely to be increased production of food and other commodities as well as a range of public benefits to people from local to regional, national and international scales.

# 1. Project rationale and approach

## 1.1 Rationale

Soils are a national asset, the condition of which is integrally tied to the health of Australian industries, ecosystems and, ultimately, communities. However, for a country for which the vagaries of climate variability have been manifested in dust storms and land degradation on the one hand, and rich production and economic wealth on the other, soils remain very much taken for granted.

Funded under the Caring For Our Country program by the Australian Government's Land and Coasts Division, a joint initiative between the Department of Sustainability, Environment, Water, Population and Communities and the Department of Agriculture, Fisheries and Forestry, this project addresses two key questions about the relationships between land management practices, soil condition, and the quantity and quality of ecosystem services delivered from agricultural land:

What evidence exists about how improving land management practices will lead to reduced soil loss (through water and wind erosion) and improved soil condition (especially through reduced impacts of soil acidification and increased organic matter content)?

How might reducing soil loss and improving soil condition result in improvements in the quantity and quality of ecosystem services and benefits delivered from agricultural lands, including cleaner air, improved water quality, reduced greenhouse gas emissions, and more productive soils?

The project focuses on four aspects of soil condition identified in the Program Logic for Caring for our Country's Sustainable Practices target: soil carbon; soil pH; wind erosion; and water erosion. It also focuses on four broad groupings of agricultural industries: broadacre cropping; horticulture; dairy; and grazing.

## 1.2 Approach

### *Literature review*

This project is largely a desktop literature review, utilising some of Australia's leading soil, agricultural systems and ecosystem service researchers.

The Program Logic for Caring for our Country's Sustainable Practices target has identified four key aspects of soil condition in Australia, including carbon and pH (which are soil conditions) and water and wind erosion (which are threatening processes). Declining soil carbon and increasing acidity (which affect both the physical properties of soils and a number of the processes occurring in it), and continuing susceptibility to wind and water erosion (which affect both the loss of soil from some sights and its build up in others) have been identified as key concerns in recent comprehensive analyses of agricultural and other landscape processes in Australia (NLWRA 2001). This project focuses on how land management practices affect these aspects of soil, and in particular:

the extent to which land management practices are available that can reduce erosion, increase soil carbon and slow rates of acidification; and

the degree of change likely to be possible from plausible changes in land management over a range of land and farming systems and a range of future time periods.

A second component of the project addresses the extent to which soil condition affects the quality of the market and non-market benefits received by people (so-called ‘ecosystem services’) from agricultural land.

### *Valuation of benefits from better soil management*

The valuation of the benefits from changed land management practices is complex and requires a wide array of data on what changes might be made, who might make them and where, how those changes might affect ecological processes, and how those processes might affect ecosystem services and the benefits that flow from them. Because of this, the valuation component of the project makes assumptions and estimates upon which the valuations are contingent. The aim is to provide indications of the size of costs and benefits that might arise from improved soil management and the types of uncertainties that still remain in those estimates.

Based in the latest thinking about valuing ecosystem goods and services, the project develops a framework that makes explicit the links between:

- soil and other landscape processes
- landscape processes and ecosystem services
- benefits that potentially flow to a range of beneficiaries
- who the beneficiaries are likely to be
- how the value to those beneficiaries can be best assessed.

Valuations are based on realistic scenarios for marginal changes in land management practices in different regions and farming systems rather than any attempt to estimate the total value of all existing soil ecosystem services across Australia. Scenarios for changes in land management practices are developed from the literature, the researchers' experience with a range of land-use systems over many years, and selected contacts with key experts on different land-use systems. The three scenarios used, as far as possible, reflect business as usual, modest improvements to farm management and optimistic improvements.

# 2. Soils: the essential asset

## 2.1 Soils, life and human interaction

Soils underpin, literally and figuratively all of the processes that support human societies and economies and, indeed, all other terrestrial life on earth. The overwhelming focus of both ecology and agricultural sciences has been on what happens above ground, which can be seen and experienced directly by humans. Soils play physical roles in supporting plants and structures, including those created by humans. They contain a vast diversity of living organisms and non-living elements that interact to mediate processes as diverse as provision of raw materials, water filtration, breakdown of wastes, pest control, regulation of atmospheric composition, regulation of water and wind flows across landscapes, and maintenance of hydrological cycles (Bardgett *et al.* 2001; Nelson and Mele 2006; Barrios 2007; Mele and Crowley 2008; McAlpine and Wotton 2009; Colloff *et al.* 2010; Dominati *et al.* 2010; Robinson *et al.* 2012). Soils also contribute in important ways to cultural, spiritual, intellectual and other intangible aspects of landscapes that are important to humans in many different ways (Dominati *et al.* 2010).

We are entering an age that has been termed the Anthropocene: an age when the impacts of humans represent the most significant drivers of change in Earth systems (Steffen *et al.* 2011). Thus, it is timely to consider how the tools available to humans have been and might be used to improve the functioning of soils, including reversing the degradation caused by past human activities.

## 2.2 Living soils and determinants of soil condition

Soil condition can be defined as *the capacity of a soil to function, within land use and ecosystem boundaries, to sustain biological productivity, maintain environmental health, and promote plant, animal, and human health* (Doran and Zeiss 2000). The condition of a soil can be inferred by measuring specific soil properties (e.g., organic matter content) and by observing soil status (e.g., fertility).

Maintaining soil condition is not only important to sustaining life and ecosystems beyond the immediate physical presence of soils, but also within. Soils are the home to over a quarter of all living species on earth (Turbé *et al.* 2010). Indeed, there is a strong relationship between soil condition and the biodiversity soils support. The many organisms and micro-organisms living within soils can interact to perform three major functions required of healthy soils: chemical engineering, biological regulation and ecosystem engineering. In the case of chemical engineering, bacteria, fungi and protozoans help in the decomposition of plant organic matter into nutrients readily available for plants. In the case of biological regulation, small invertebrates, such as nematodes, pot worms, springtails, and mites, act as predators of plants and other invertebrates or microorganisms to regulate their dynamics in space and time. Finally, in the case of ecosystem engineering, earthworms, ants, termites and some small mammals help modify or create habitats for smaller soil organisms by building resistant soil aggregates and pores, thus regulating the availability of resources for other soil organisms and supporting plant systems.

Soil biodiversity is not the only determinant of soil condition. Soil can be defined as *the weathered and fragmented outer layer of the earth's terrestrial surface* (Hillel 1980), and the physical properties of soil such as particle size and mineral composition are important in its differentiation and condition. Moreover, the chemistry and nutrient status of soils are also important. However, it is the interaction of soil physics and chemistry with soil biodiversity that influences the overall condition of soils. For example, soil pH is one of the abiotic factors susceptible to influence biology and activity of biological regulators (Turbé *et al.* 2010). In every sense, the term *living soils* is a reminder that soils too have a lifespan that can either be cut short through inappropriate interaction or sustained by appropriate nurturing or remedial attention.

## 2.3 Soils and systems

This report considers the relationship between soil condition and agricultural practices in four distinct sections (i.e. sections on soil carbon, acidification, wind erosion and water erosion). These aspects of soil condition do not exist in isolation, however. For example, soil carbon content also influences susceptibility to erosion as soil carbon affects soil physical and chemical properties. Similarly many soil management practices, such as ground cover maintenance, address multiple aspects of soil condition (e.g., ground cover management can increase soil carbon and decrease soil erosion).

Across Australia many farmers and graziers face more than one form of resource degradation and most will have multiple objectives they seek to achieve. Some of these objectives will be economic, but certainly environmental and social objectives also play an important part in determining agricultural practice. Because of this, taking a systems approach to agricultural practice is not only theoretically important, but it also plays an important part in the day-to-day operations of Australian farms.

The extent to which systems approaches are well practised is an altogether different question. One of the aims of any system approach is to become efficient in achieving multiple objectives, and so in the context of this report the question arises: can good practices be combined so they are additive and multiplicative, without negative impact. An example of a systems approach in managing soil follows. The traditional response to managing soil erosion on a grain farm may be to put in contour banks to reduce the length of water flow, hence its velocity and power – this prevents rills becoming gullies. Systems thinking would suggest that erosion is caused by runoff, adding soil sediment to the runoff and then the flow moving this across the landscape. Systems practice would be to reduce runoff by increasing infiltration, hence reducing sediment concentration, and managing the flow to maintain spread across the landscape and prevent runoff concentration (where rills and gullies form). This is usually achieved by management of ground cover.

At the conclusion of each of the soil condition Sections (4-8), a box has been included to provide an example of a systems approach to managing soil C, soil pH, water erosion and wind erosion.

# 3. Linking management practices, soil quality and ecosystem services

## 3.1 The concept of ecosystem services

One key purpose of this report is to consider the links between soil condition and the benefits that soils in good condition provide for humans. There is increasing demand from the public for agricultural landscapes to be ‘clean and green’ and to meet a wide range of society’s needs (Soils Research Development and Extension Working Group 2011). Rarely, however, have these needs been fully and clearly articulated in the past, especially with respect to soils. Soils are often seen as simply the substrate in which plants grow. This narrow view has been changing over the past decade as there has been increasing focus on the roles of soils in ecosystems and their contributions to ‘ecosystem services’ and the benefits that flow from those services.

The dependence of humans on ecosystems has been the focus for a body of research over the past decade and more, under the banner of ‘ecosystem services’. Ecosystem services can be described as the attributes of ecological systems that contribute to benefits for humans (Fisher *et al.* 2009). In Section 8 we discuss in more detail how ecosystems services are defined and categorised, and how the concept can be put into practice with respect to soils. The essence of the concept is that the multitude of interactions among living organisms in ecological systems, and between those organisms and the non-living components of the environment, produce outcomes that not only have great value to humans but can potentially be more efficient and less costly than alternatives that involve humans and their technologies (Daily 1997).

The types of benefits that come from ecosystems broadly (i.e., including above and below ground ecosystems) include: support for production of food, fibre, fodder and other products of crops; provision of chemicals and genetic material that can have value in human health and/or industrial processes; clean air and water; natural pest control; disposal of wastes; and a range of cultural, intellectual, spiritual and other intangible benefits. Obtaining these benefits usually requires some final input from humans, which is why several recent approaches have explicitly separated the services from the benefits (see Section 8).

Soils are at the heart of virtually all processes leading to ecosystem services and subsequent benefits (Daily *et al.* 1997; Sparling 1997; Wall and Virginia 2000; Barrios 2007; Soils Research Development and Extension Working Group 2011). Hence, any changes in soil condition potentially affect a range of processes, services and benefits to humans. The changes in benefits are not, however, always readily attributable to soils as many involve inputs from other parts of ecosystems, such as plants, animals and atmospheric processes. As such, soils often provide ‘intermediate’ ecosystem services (i.e., services that support other services and therefore support benefits to humans indirectly rather than directly) (Fisher *et al.* 2008). In Sections 8 and 9, we explore how changes in soil quality relate to soil ecosystem services and how the value of those services can be estimated.

## 3.2 Ecosystem services and management practice

A focus of this study is the relationship between ecosystem services (their quality, quantity and diversity) and agricultural practice. We know from the history of agriculture that inappropriate practices may lead to land and water degradation and potentially to the loss of the productive resources upon which agriculture depends. Examples of this are provided in Sections 4 to 8.

It is important to note that the relationships between management practices and ecosystem services provided by soils are neither linear nor homogenous; what is a sustainable practice on one soil type within one climatic zone may not be sustainable elsewhere. Moreover, some practices may result in trade-offs between different ecosystem services. For example, tree planting to manage local erosion might enhance local productive capacity but the reduction in run-off may lead to less water being made available elsewhere. From a natural resource management perspective, this example may translate into the trade-off between managing dryland salinity and environmental river flows (van Buren and Price 2004).

The heterogeneity of Australian landscapes, Australian soils and Australian production systems demands heterogeneity in agricultural practices and policy approaches across our landscapes, our soils and our production systems. This makes determining an aggregated valuation of ecosystem services resulting from changes in practice very difficult, if not impossible, as discussed in Sections 8 and 9.

# 4. Soil Carbon

## 4.1 Nature of the issues

The global soil organic carbon (SOC) pool is estimated to be ~1,395 × $10^{15}$ g (Post *et al.* 1982) which is three times more than that found in the atmosphere or in terrestrial vegetation (Schmidt *et al.* 2011). SOC refers to the diverse range of organic material that enters (e.g. plants/ manures/ herbicides) or resides (e.g. soil animals and microbes) in soil. Soil therefore contains C in diverse structural forms and with diverse residence times, encompassing living (labile), recently dead and long-dead (non-labile and recalcitrant) forms. A comprehensive list of critical functions of soil C has been developed (Lal 2004) (Table 4.1).

**Table 4.1. List of critical functions of soil C (after Lal 2004)**

| Function |
|---|
| Source and sink of principal plant nutrients (e.g., N, P, S, Zn, Mo) |
| Source of charge density and responsible for ion exchange |
| Absorbent of water at low moisture potentials leading to increase in plant available water capacity |
| Promoter of soil aggregation that improves soil tilth |
| Cause of high water infiltration capacity and low losses due to surface runoff |
| Substrate for energy for soil biota leading to increase in soil biodiversity |
| Source of strength for soil aggregates leading to reduction in susceptibility to erosion |
| Cause of high nutrient and water use efficiency because of reduction in losses by drainage, evaporation and volatilization |
| Buffer against sudden fluctuations in soil reaction (pH) due to application of agricultural chemicals |
| Moderator of soil temperature through its effect on soil colour and albedo (reflective capacity) |

These functions of SOC can be associated with provisioning, regulating and cultural ecosystem services as well as the soil processes that support these services (MA 2005). They relate to water, air and food quality, nutrient cycling and disease control (Kibblewhite *et al.* 2008). SOC is considered a ‘headline’ soil condition indicator nationally and internationally. It is also a key component of greenhouse accounting programs used by the Australian Greenhouse Office (AGO) through the National Carbon Accounting System (NCAS) to track changes in carbon loss and storage under alternative land-use scenarios (Wilson *et al.* 2007). Further development of NCAS is supported by the Soil Carbon and Research Program (SCaRP) which examines variations in soil organic carbon (SOC) and composition under different agricultural management practices in regional Australia using a nationally consistent methodology (Sanderman *et al.* 2011).

## 4.2 Impacts of agriculture and measures that could build Soil Organic Carbon

There are many ways in which agriculture impacts on the capacity to build SOC. In principal, several factors influence this process reflecting that SOC dynamics is biologically mediated by a diversity of organisms that inhabit soils (see Section 2.2). Put simply, what determines the amount of SOC that accumulates is the balance between the amount of C added to the soil, the amount lost through microbial respiration and the capacity to build the resistance of what remains (Kirkegaard *et al.* 2007; Sanderman *et al.* 2010). Climate, and specifically precipitation and temperature, exert an overriding control whilst other regulators such as soil type, particularly particle size, nitrogen inputs, and plant biomass quality and quantity, are also important because they can be managed to some degree (Parton *et al.* 1987; Paustian *et al.* 1997).

It is also well recognised that land-use change has the most profound and enduring influence on SOC stocks. A global meta-analysis indicates declines in SOC stocks after land use changes from pasture to plantation (−10%), native forest to plantation (−13%), native forest to crop (−42%), and pasture to crop (−59%). Soil C stocks increase after land use changes from native forest to pasture (+ 8%), crop to pasture (+ 19%), crop to plantation (+ 18%), and crop to secondary forest (+ 53%) (Guo and Gifford 2002; Smith *et al.* 2012).

In Australia, clearing of native vegetation for primarily agricultural purposes has caused a 40-60% decrease in SOC stocks from pre-clearing levels. Significantly, some soils are still responding to the initial land-use change with continuing declines in SOC albeit more slowly under some management regimes (Sanderman *et al.* 2011) so it is critical that management not be considered only in relative terms (e.g. stubble retention versus stubble burning) but in the broader context of land-use change.

Also noteworthy is that while there is a strong theoretical basis for management strategies that build SOC, this is supported by a limited number of field studies (Sanderman *et al.* 2010) that generally lack management history detail (e.g. past and current management including fertiliser history, rotations etc) that is critical for estimating SOC build-up (Smith *et al.* 2012). This reduces confidence in making quantitative predictions about outcomes of interventions, but there is moderately high confidence in the efficacy of many approaches (Sanderman *et al.* 2010).

The relative efficacy of management strategies to mitigate SOC losses and to potentially build SOC, evaluated below for each of the four main industry groups.

### ***Broadacre cropping***

Broadacre cropping includes cereals, oilseeds, sugar cane, legumes, hops, cotton, hay and silage, and contributes around $13 billion or more than 50% of the gross value of agricultural production in 2009-2010 (ABS 2011b).

Figure 4.1 illustrates the crop management options that are likely to or have been shown to increase SOC.

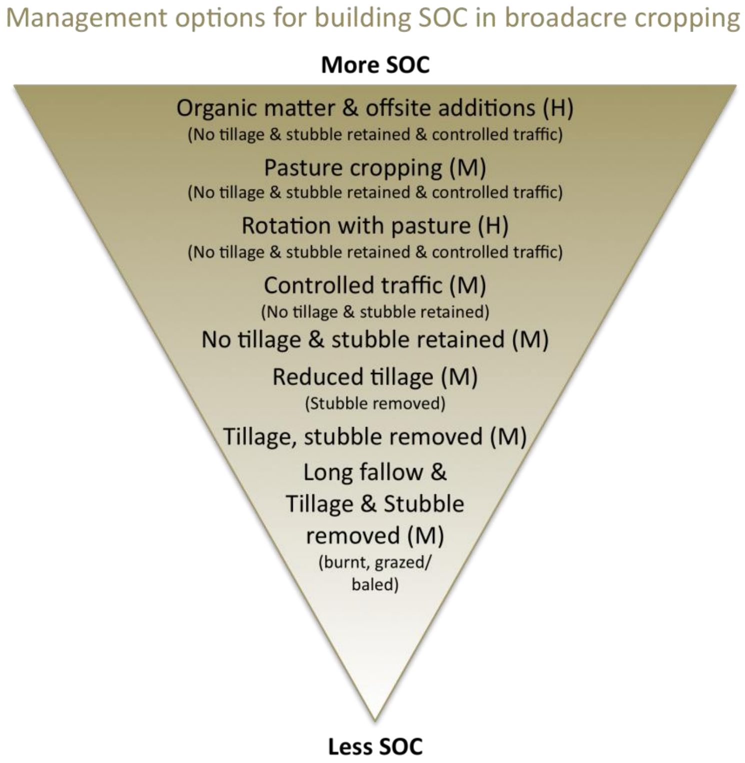

**Figure 4.1. Crop management practice and relationship with expected Soil Organic Carbon levels and benefits.**

**Confidence in SOC benefit based on qualitative assessment of theoretical and evidentiary lines; L=Low, M=Medium, H=High (figure draws on information from Sanderman *et al.* 2010, Scott *et al.* 2010 and Murphy *et al.* 2011)**

The nearly universally observed reductions in SOC that accompany clearing of native vegetation for agriculture have been attributed to two broad categories of process changes: reduced inputs due to harvest and stubble burning; and increased loss rates of carbon due to disruption of the soil surface, leading to enhancement of decomposition rates and greater risk of water and wind erosion (Sanderman *et al.* 2010). The potential approaches to increasing SOC, therefore, focus on reversing these effects (i.e., increasing inputs and/ or reducing losses). These management options include varying planting time, sowing rates, nitrogen application, cover and crop varieties, residue management (e.g. grazing and/ or burning), tillage type and depth, and length of fallow (Ugalde *et al.* 2007; Murphy *et al.* 2011). A combination of these options, and specifically tillage and stubble management practices, can determine the SOC levels (Sanderman *et al.* 2010; Scott *et al.* 2010; Murphy *et al.* 2011) – although Sanderman *et al.* (2010) warn that the outcomes of changed management practices is not always predictable quantitatively because of the many factors that need to be taken into account. Some of these choices affect the stability of soil, while others affect yield and, therefore, biomass potentially available to the soil carbon pool.

The amount of carbon available for addition to soils in the form of shoot and root residues/ exudates depends on how much is removed at harvest. A broadacre crop such as wheat would produce less than 2 $t.ha^{-1}.yr^{-1}$ compared to sugar cane which might generate inputs of 7 $t.ha^{-1}.yr^{-1}$ (Kirkegaard *et al.* 2007).

Based on Figure 4.1, long fallow is *likely* to be associated with lowest expected SOC levels, and pasture cropping is likely to support the highest *expected* levels of C. Expectations for enhanced SOC are now high due to improved adoption of relevant practices (Barson *et al.* 2012b). Between 2007-08 and 2009-10 there was a national 10% increase (from 49-59%) in the number of farmers using reduced tillage, or one pass sowing systems and a 3% increase in farmers using residue retention. This resulted in residue being left intact over 68% of cropped area or no cultivation apart from sowing over 76% of cropped area.

Interpreting research on the effects of soil management practices on SOC is complicated because many studies have not been able to control all variables (Sanderman *et al.* 2010). For example, rainfall, soil type, time since last cultivation, and the depth at which measurements are made all affect SOC accumulation (see review by Sanderman *et al.* 2010). How sustained these increases are is also subject to conjecture as there are limited long-term studies of these systems across the five broad agro-ecological cropping zones (summer rainfall, Mediterranean west, moist south east, dry marginal south east and high rainfall zone) and rates of accumulation are highest in surface soils, which are also most vulnerable to disturbance. These temporal and regional data are critical in determining the likelihood of increasing SOC under the proposed management options and explains the high variability in SOC levels reported for direct drilled, stubble-retained systems (Mele and Carter 1993; Sanderman *et al.* 2010; Scott *et al.* 2010; Dalal *et al.* 2011).

Apart from the options of direct drilling and stubble retention to build SOC in some regions, Sanderman *et al.* (2010) highlighted that the greatest theoretical potential for building SOC is the addition of organic materials such as manure and green waste and the inclusion of a pasture phase in a cropping sequence. Due to their relatively recent emergence there is very little scientific evidence that associates increased SOC in Australian broadacre cropping with practices such as organic matter amendment (e.g. manure, green waste and biochar) and pasture cropping (e.g. with perennial species). There is however strong evidence supporting the feasibility of pasture cropping in broadacre cropping systems (Bruce *et al.* 2006; Millar and Badgery 2009; Dolling *et al.* 2010) and the feasibility of biochar amendments (Chan 2008; Kimetu and Lehmann 2010; Singh *et al.* 2010) as potential strategies for increasing SOC.

If management enables SOC to build up, there is also a nutrient cost reflecting the heightened demand of soil biota for these nutrients as they decompose additional C substrates. The deficit created in nitrogen (N), phosphorus (P) and sulphur (S) over and above crop requirements is 60, 12 and 9 kg respectively per tonne of humus locked up (Passioura *et al.* 2008).

### *Horticulture*

In 2009-10 Australia's horticultural industry was the nation's third largest agricultural industry based on gross value of production (GVP) of $8.4 billion, ranking third behind the meat and grain industries (DAFF 2012b).

Horticultural industries encompass a diverse range of fruit and vegetable industries. The total area under production in Australia is around 250,000 hectares. Generally, interest in SOC is driven by the need to mitigate greenhouse gas emissions and to improve soil health and resilience (the capacity to recover after disturbance). A survey commissioned by Horticulture Australia limited (HAL) in 2000-2003 indicated that the most important building block for healthy soil, irrespective of soil type, region, or climatic conditions was SOC.

A comparison of SOC in intensively managed vegetable production sites with 'reference sites' in Tasmania and Queensland led to the conclusion that 'good farm management practices, even for intensive land use for vegetable production, can sustain soil integrity/ soil health' (HAL 2003). A recent investigation into on-farm emissions in Bundaberg regions and in the Lockyer Valley and Bowen indicated that vegetable production was the highest emitter of C from soils (3.50 $tCO_2$-e.$ha^{-1}$.$year^{-1}$) followed by tree crops (2.85 $tCO_2$-e.$ha^{-1}$.$year^{-1}$), then sugar cane (1.91 $tCO_2$-e. $ha^{-1}$.$year^{-1}$) then cane/ other crops (1.16 $tCO_2$-e.$ha^{-1}$.$year^{-1}$). This trend was reversed when calculated as emissions per unit income (e.g. vegetables 41 tCO2-e/$1 million, fruit trees 221 tCO2-e/$1 million and cane 606 tCO2-e/$1 million). It was concluded that, despite the high variability in data within a production system, there was significant scope for improvement with carbon fixed in organic matter as a recommended management option (HAL 2012b).

The vegetable industry's key management messages are to use minimum-till techniques and controlled traffic technologies and to add organic materials (such as organic mulches and biochar) to build SOC (Pattison *et al.* 2010; HAL 2010, 2011). A detailed study on the use of organic products (chicken manures, composted green wastes) for multiple benefits confirmed that additions of organic matter in these ways both offset carbon losses experienced in conventional approaches to vegetable management and increased crop productivity by up to 10% when other inputs were held constant (HAL 2011). A survey of soil management from 2007-08 to 2009-10) indicated that 28% more horticulturalists used alternate or cover crops and 33% used mulching or matting (Barson *et al.* 2012c).

### *Dairy*

In 2010-11 the farm gate value of production for the dairy industry was $3.9 billion (around 10% of the gross value of Australia's agricultural production) and the total area under production was 4 Mha (Barson *et al.* 2012a; Dairy Australia 2012). Generally, dairy systems have higher levels of SOC relative to other agricultural industries and therefore the focus is less on building SOC and more on maintenance or loss prevention (MacKenzie 2010). Higher levels of SOC are attributed to a number of factors such as: higher availability of water (as rainfall or irrigation); ready supply of nutrients (N and P); higher proportion of perennial species that grow continually rather than seasonally; minimal disturbance relative to cropping; and minimal erosion.

Loss of soil carbon from dairy soils does occur and has been attributed to loss of ground cover due to high stocking rates, leaching of organic acids below the root zone, and to cultivation associated with planting of annual grasses in dryer or drought prone regions such as in northern Victoria (MacKenzie (2010) reviewed experimental results from several countries as well as Australia). Management options to prevent loss of carbon in dairy pasture soils are: 1) to reduce decomposition; 2) to improve the rate of addition of organic materials; and 3) to reduce soil disturbance/ increase ground cover (Watson 2006; MacKenzie 2010; Barson *et al.* 2012a). These options are summarised in Table 4.2 together with the likelihood of adoption.

**Table 4.2 Dairy pasture management options to conserve soil carbon (drawing on a research review by MacKenzie (2010) and a survey of practices by Watson (2006))**

| Management option | Rationale | Current likelihood of adoption |
|---|---|---|
| **Slow the rate of decomposition of soil carbon** | Clay soil tends to protect organic matter more effectively from decomposition than sandy soil. | Unlikely; on most farms, increasing clay content through techniques such as clay spreading is prohibitively expensive. |
| | Subsoil modification of hard pan or sodic/ Al toxic layers to encourage root penetration to deeper (cooler) layers | Unlikely; Subsoil modification costs can be high despite the likely high returns in a short timeframe (MacEwan *et al.* 1992). |
| | Organic materials such as biochar, waxy plant materials, and composted manure have chemical structures can potentially reduce the rate of organic carbon decomposition in soil | Likely where material is readily available and inexpensive (i.e. where financial returns are expected to exceed the costs of purchase and application).<br>Unlikely where input material is not retained (is decomposed) and where there are other costs in terms of nutrient tie-up i.e. efficacy questionable due to scientific uncertainty (Passioura *et al*. 2008; Schmidt *et al.* 2011; Jones *et al.* 2012). |
| **Increase the rate of addition of plant biomass** | Use of ameliorants such as gypsum (for sodic soils) and lime (for acid soils) to increase plant productivity | Unlikely due to fluctuating production costs which means it is not always economically viable to correct the problems with gypsum and lime (refer Section 5); main issue is pasture utilisation rather than biomass. It should be noted that sub-soil acidity is a problem in some dairying areas (Section 5). |
| | Use of essential elements (e. g. N, P, S, K, Ca) to increase C transformations and optimise productivity | Unlikely to be viewed as a strategy to increase C build-up *per se* but as a means of increasing pasture biomass. |
| **Reduce soil disturbance (pugging, tillage) increase ground-cover** | Livestock management (stocking rates/ grazing intensity to protect ground cover) | Likely but requires pasture renovation as well |
| | Pasture renovation (increasing perennials in sward composition). | Likely but requires livestock management as well |

In terms of current trends in management (2007-08 to 2009-10), dairy farmers are increasingly monitoring ground-cover (up from 72% to 88%) but fewer are setting ground-cover targets (38% to 27%) (Barson *et al.* 2012a).

### *Grazing*

Livestock grazing is the most widespread Australian land use, covering more than 336 Mha or about 40% of the total area of Australia. Meat and wool production contribute almost 30% to the gross value of agricultural production (ABS 2011a). These enterprises encompass three broad systems; i) the native pasture dominant systems, principally occurring in the rangelands of central and northern Australia, ii) the permanent perennial grass-based pasture zones of south-eastern Australia and iii) the more intensive mixed wheat-sheep farming systems of southern Australia that are based on improved pastures and fallow rotations (Scott *et al.* 2000; Australian State of the Environment Committee 2011).

Grazing by livestock (e.g. beef and sheep) can impact directly on SOC and nitrogen cycling by modifying plant biomass inputs into soil (shoot and root material) and by reducing ground cover and thereby exposure of SOC-rich surface layers to wind and water erosion (Earl and Jones 1996). Grazing can also impact indirectly on SOC by modifying soil structure (density and aggregate stability), moisture and temperature influencing soil faunal and microbial diversity and activity (Southorn and Cattle 2004b; Teague *et al.* 2011).

Management options to increase SOC have focussed on three strategies: 1) increased productivity (irrigation and fertilisation); 2) time controlled (TC) or rotational grazing; and 3) shift to perennial species (Sanderman *et al.* 2010). Research on the impacts of these options on SOC is rare (Sanjari *et al.* 2008; Sanjari *et al.* 2009), despite the extensive research effort in sustainable grazing systems and, specifically, increasing the perenniality of pasture systems (Kemp and Dowling 2000; Mason and Kay 2000; Michalk *et al.* 2003). The emergence in the late 1980's of grazing systems referred to variously as 'cell grazing', 'savory grazing, 'short duration grazing', 'time-controlled (TC) grazing' and 'holistic management (HM) grazing' have been assessed for their impact on a range of sustainability measures including SOC (Earl and Jones 1996; McCosker 2000; Sanjari *et al.* 2008; Sanjari *et al.* 2009; Sherren *et al.* 2012). A small number of studies in south-eastern Queensland and northern NSW of TC grazing have reported increases in herbage mass, SOC, nitrogen (Sanjari *et al.* 2008), ground-litter (Earl and Jones 1996; Sanjari *et al.* 2008), and reduced runoff and soil loss (Sanjari *et al.* 2009) compared to continuous grazing. Longer monitoring periods would increase confidence in these data (Sanjari *et al.* 2008; Sanjari *et al.* 2009).

## 4.3 Evidence of the efficacy of practices to increase soil organic carbon

In theory, the two main ways to build soil C are to reduce gaseous loss as either $CO_2$ and $CH_4$ by reducing soil disturbance and to increase C inputs either in the form of more plant biomass (which may require measures to overcome other constraints to plant growth) or in the form of other organic materials (manures, biochar etc). In practice, only the cropping industries (broadacre and horticulture) have opted for reducing disturbance of surface residues and increasing inputs through plant residue retention and through the addition of organic residues as strategies to increase SOC. The grazing industries (including dairy) have focussed more on maintaining SOC through indirect means such as increasing ground cover and arresting acidification.

The efficacy of practices to increase SOC is highly variable and is dependent on soil type (particle size) and climate (regional precipitation patterns) (Smith and Belvins 1987; White 1990; Mele and Carter 1993; Kirkegaard *et al.* 2007). The consensus is that, in most of the cereal cropping areas in Australia (rainfall of 250-600 mm), the potential for reduced or no-tillage (direct-drilling) and stubble-retention to store carbon and mitigate greenhouse gas emission is limited, in contrast to areas with higher rainfall and greater biomass production (Sanderman *et al.* 2010; Chan *et al.* 2003). In a review of stubble retention systems in southern Australia, the higher SOC levels under stubble retention practices (relative to stubble burnt treatments) was not attributed to the sequestering of C but rather to the slower rate of decline under stubble retention compared to burning (Scott *et al.* 2010). The higher levels of SOC in surface soils of no-till systems can be associated with other benefits such as increased infiltration, reduced disease, conservation of nutrients and increased earthworm densities (Carter and Steed 1992; Roget 1995; Simpfendorfer *et al.* 2004; Scott *et al.* 2010) which may represent a more sensitive, yet indirect measure of the benefits of SOC increases with minimum tillage and stubble retention.

For horticulture, dairy and grazing industries, evidence of the efficacy of management strategies to increase soil C is difficult to find in the primary literature. For the grazing industries, only a very small number of studies have measured changes in SOC directly (Sanjari *et al.* 2008) and the confidence in these data was low due to the relatively short time frame for monitoring differences in TC and continuous grazing systems.

The general principles that have been demonstrated in using broadacre cropping industries as the model can also be applied more broadly. Empirical data have increased confidence in the application of models to predict soil C build up (e.g. CENTURY/ROTHC), which can be useful when it is not possible or affordable to collect SOC data.

### Box 4.1: Managing Soil C through a systems approach

**System goal**

To increase soil C or slow down its decline.

**Considerations**

1. Increase inputs by growing more biomass (relative to removal), adding fertiliser and ameliorants as required, growing perennials or increasing crop frequency, and adding organics (mulch, manure, compost). These practices are interactive and probably cumulative. Appropriate performance indicators would be water-use efficiency and nitrogen-use efficiency, as an optimal balance between carbon and nutrients improves water-holding capacity of soil, microbial involvement in carbon and nitrogen cycles, and efficiency of nitrogen use for growth by plants. These actions potentially apply to cropping, horticulture, grazing and dairy.

2. Reduce decomposition by: avoiding excessive soil moisture and waterlogging; eliminating tillage, burning and erosion; reducing $NO_3$ fertilisers, changing to NH4 fertilisers, organics or legumes; and encouraging free-living N fixation. These actions are applicable across industries.

3. With 1 and 2, operate at a stable soil C level, not increasing. This level needs to be determined but will be higher for currently degraded soils. Maintenance inputs depend on soil C levels, lower is better. Soil C also ties up large amounts of nutrients. Should our goals be equilibrium soil C and increased C cycling of the C inputs from 1 and 2? It is difficult to increase C inputs and soil C in cropping industries with the high product removal required for viability and efficiencies.

**Recommended practices**

Zero tillage, increased crop frequency or perennial pastures to increase biomass production and retention, residue retention or managed grazing pressure, improved agronomy, organic fertilisers, no burning.

**Performance indicators**

Annual water-use efficiency and nitrogen-use efficiency, carbon and nutrient cycling (most relevant at farm scale), percentage ground cover (most relevant at farm to regional scales), and productivity (relevant at farm to regional and national scales).

**Conflicts**

Availability and costs of machinery for managing minimum till can be a limiting factor. Incentives may be needed to move some farmers from traditional practices. Management inputs can be high to achieve enhanced SOC.

# 5. Soil pH

## 5.1 Nature of the issues

Soil pH (potential hydrogen) is the test used to assess the concentration of hydrogen ions in soil solutions of water ($pH_W$) or calcium chloride ($pH_{Ca}$). Ideally, soil pH for crop and pasture production should be in the range of pH 5.5 to $7.5_{Ca}$ in the top soil, and no less than pH $4.8_{Ca}$ in the subsoil (Dolling *et al.* 2001; Gazey and Davies 2009). Soil acidification, a key soil condition indicator (NLWRA 2007) is measured by a decline in pH over time. This can occur in the surface and subsurface layers of soil. There are several major causes for the acidification of agricultural soils: removal of agricultural products (most plant and animal products from farms are slightly alkaline); excessive accumulation of organic matter, which contains organic acids, in some circumstances (even though soil carbon also plays a key role in buffering against pH change); excessive use of nitrogenous fertilisers, especially those that lead to release of ammonia into the soil; leaching of fixed, fertiliser and urine-N as nitrate from surface layers to lower layers before plants can utilise it (Scott *et al.* 2000; NLWRA 2001; Gazey and Davies 2009). Understanding the causes will be critical for addressing questions on the efficacy of remedial action in different agricultural land-use scenarios.

The effects of acidification are not easily recognised and hence it is commonly described as an insidious problem in that plant symptoms are less visual and easily misdiagnosed, and production declines are gradual (Scott *et al.* 2000). Impacts can be on-site and related to plant, animal and soil biological performance or off-site, though the link to stream and groundwater acidification is speculative (Cregan and Scott 1998). On-site impacts are usually associated with increases in aluminium (Al) and manganese (Mn) levels with plant toxicity symptoms emerging and a reduction in nutrients such as calcium (Ca), Magnesium (Mg), and Potassium (K) with plant deficiency symptoms emerging (Slattery *et al.* 1989). The reduction in plant biomass production has a major knock-on effect; it reduces the quantity and quality of plant residue entering soils and hence SOC levels and all the associated critical functions (see Section 4, Table 4.1).

Acidification occurs in surface and in subsurface soils. According to the National Water and Land Resources Audit of 2001 (NWLRA 2001), half of the non-rangeland agricultural land in Australia is acidic (surface $pH_{Ca} \leq 5.5$) and below the optimal level to prevent subsurface acidification. This area, estimated to be of the order of about 49-50 Mha, is 5 times greater than the area affected by salinity. About half of this, or approximately 17 Mha, has $\mathrm{pH_{Ca}} \leq 4.8$ and requires immediate remedial action. In WA, almost 8 Mha of the 13 Mha under dryland agriculture are at risk of acidification (Holmes *et al.* 2011). In southern Australia, subsoil acidity occurs on about 24 Mha (Li *et al.* 2010).

Ten years on, the State of the Environment report (Australian State of the Environment Committee 2011) highlights that the severity and extent of acidification has increased in many regions, due, it says, to inadequate treatment, intensification of land management, or both. Although, for three of the four main agricultural industries, the number of businesses applying lime or dolomite to their holdings increased between 1995-96 and 2009-10, the totals by 2009-10 were only between 17 and 21% and most of that increase had occurred by 2001-02 (DAFF 2012a). For cropping, this increase was from 8 to 17% between 1995-96 and 2001-02, rising to 19% by 2009-10 (DAFF 2012a; Barson *et al.* 2012b). Dairy and horticulture started at higher percentages but achieved much smaller increases (DAFF 2012a).

Of even greater concern is the largely unknown extent of subsoil acidification and the intergenerational issues that will arise if this develops to levels where mineral dissolution occurs and soils are beyond remediation. It is clear that subsoil testing to raise awareness of the issue is a critical first step with early evidence of a change in attitude and intention in farmer groups (e.g. Nyabing group) in WA (Wilson *et al.* 2009; Gazey *et al.* 2012).

## 5.2 Impacts of agriculture and measures that could arrest soil acidification

Broadacre cropping, horticulture, dairy, and grazing all contribute to soil acidification. The Australian State of the Environment Committee (Australian State of the Environment Committee 2011) listed the following summary observations:

- Soil acidification is widespread in the extensive farming lands (cropping, sheep and cattle grazing) of southern Australia;
- Rates of lime application are well short of those needed to arrest the problem;
- Acidification is common in intensive systems of land use (tropical horticulture, sugar cane, dairying);
- Acidification is limiting biomass production in some regions, but the degree of restriction is difficult to estimate;
- Carbon losses are most likely occurring across regions in poor condition, and soil acidification is a major constraint on storing carbon in soils in the future.

Acidification risk areas based on topsoil data from major agricultural land-use categories have been identified (based on a 5 km grid) as a priority for remedial management (Wilson *et al.* 2009). The specific agricultural activities that increase soil acidity are the use of high-analysis nitrogen fertilisers, the large rates of product removal, and the farming of soils that have a low capacity to buffer the decrease in pH (e.g. infertile, light-textured soils) and the soil already has a low pH (Helyar *et al.* 1990; Helyar 1991; Wilson *et al.* 2009).

The five primary actions to address soil acidification are to:

- soil test for pH
- add lime at rates that are effective for arresting acidification
- add lime at high rates, sufficient to reverse acidification in soils that have already acidified
- use acid-tolerant plant species where available (as a short-medium term measure).
- land retirement (this could be considered where it is uneconomic to apply lime and where the benefits of arresting acidification are judged to be sufficiently important – this has not occurred anywhere in Australia to date to our knowledge).

Testing surface and subsurface pH by farmers, on-farm, is the precursor to implementing remedial action. The number of landholders who undertake pH testing has declined slightly (from 07-08 to 09-10) across all industries (grains, horticulture, dairy and grazing) with Queensland being the exception with slight increases in all but the grazing industries (Barson *et al.* 2011, 2102a, b, c). Lime addition and use of acid tolerant species are complementary actions with the fifth action, land-use change, being a more extreme option and not usually considered. The use of acid tolerant species, although a relatively straightforward and cost-effective option, does not address the underlying problem, proving a temporary strategy for ‘living with the problem’ and probably making it worse. The most widely used remedial action is to add lime to increase surface soil pH and gradually subsurface pH. Information on the neutralizing values of liming material (Goldspink and Howes 2001) and the recommended rates to apply in pasture and cropping systems (Slattery *et al.* 1989; Gazey and Davies 2009) are readily available and supported by online lime calculators for choice of lime, amount to add, and economic benefit (e.g. http://www.aglime.com.au/liming; http://www.soilquality.org.au).

The adoption of these five primary remedial actions is ultimately influenced by return on investment which is set by regional factors of soil type and rainfall (Helyar 1991; Gazey and Davies 2009; Holmes *et al.* 2011). The impacts of soil acidification and practices that are available to address this widespread problem will now be considered in the context of the four main industry groups.

At a national scale, protocols for monitoring soil pH are established (Grealish *et al.* 2011) but an organised national monitoring system has yet to be implemented.

### ***Broadacre cropping***

A consequence of the intensification of broadacre cropping over the past 10-15 years (see Section 4.2) is greater N-fertiliser use and greater product removal leading to increased rates of soil acidification. Liming is regarded as an economically viable option for broadacre cropping, and a lime application strategy must account for a range of factors including type of crop and level of production, type of lime and amount applied, soil texture and rainfall (Slattery *et al.* 1989; Helyar 1991; Helyar *et al.* 1992; Gazey and Davies 2009).

The key management messages for broadacre croppers are that:

- Lime rates should be matched to the soil type and soil pH. The lime requirement (as dolomite or limestone) to raise pH by about one unit varies by soil type, with rates increasing from about 1.5 to 2.5 t/ha of good quality lime on sandy soils to up to 6 t/ha on clay soils (Slattery *et al.* 1989; Aitken *et al.* 1990; Gazey and Davies 2009).
- Varying the rates of lime applied to soils has proved more cost effective than uniform application. This accounts for paddock variability in soil type (see above) and to variable rate N fertiliser applications (Bruce *et al.* 2006).
- Soil samples to assess pH should be taken to depth (down to 30 cm) and composited to account for spatial variability (Slattery *et al.* 1989; Holmes *et al.* 2011) and to assess the occurrence of subsoil acidification (Gazey et al 2012)
- Soil pH should be monitored every three to four years to assess the impact of management and amelioration treatments (Holmes *et al.* 2011).

Lime rates should also consider the crops grown to account for varying tolerances and for loss of alkalinity through product removal (Slattery *et al.* 1989) and to N fertiliser rates to account for increased acidity through nitrate-N drainage (Bruce *et al.* 2006).

### Horticulture

The use of high analysis N fertilisers and the high rate of product removal are features of most horticultural enterprises. Horticulture Australia limited (HAL) reports that 11 of the 21 horticultural industries supported by HAL have undertaken soil research (e.g. strawberries, citrus, bananas, blueberries, deciduous orchards, macadamias, and nursery, potatoes, processing tomatoes, turf and vegetables) to counter the problems associated with high fertiliser inputs and product removal. Soil acidification has been identified as one of the six main issues of concern (Horticulture Australia Ltd 2008).

The key management options for mediating soil acidification in horticulture are similar to those for broadacre cropping with liming a key strategy. Nationally about 20% of horticultural businesses apply lime/ dolomite and 25% use pH and nutrient testing (Barson *et al.* 2012c). Horticulturalists tend to use burnt lime (CaO) which reacts more quickly with water (Goldspink and Howes 2001). For intensive industries such as vegetable growing, the high N fertiliser use coupled with irrigation represents a significant risk for acidification through nitrate leaching below the root zone. In extensive perennial-based dryland systems, (e.g. orchards and vineyards), particularly those located in the high rainfall zone, the use of acid tolerant species such as chestnuts and the liming of soils for grape production is recommended (McCarthy *et al.* 1992; Scott *et al.* 2010). The recommended $pH_{Ca}$ for grapevines is 5.5 to 7.5. Outside this range they are likely to suffer toxicity (Al) or deficiency (Fe, Cu, Zn and Mn) (White 2009). Data recording the extent to which lime is applied under vine in Australia is difficult to find.

For many horticultural industries, the cost of liming is relatively small in relation to yield profit so it is more likely that the condition of these soils won’t decline from acidification compared to the broadacre cropping industry. As with broadacre industries, liming can be an effective and profitable management strategy for mitigating surface soil acidification provided appropriate rates are applied that account for regional and local (management) factors of soil and plant type and N-fertiliser regimes.

### Dairy

Eight of the major dairying areas in Australia occur in the higher rainfall zones (600 mm) of southern Australia (Southern Queensland and Northern NSW) and southern Western Australia. Around 63% of intensively managed grazing, including dairy pastures, area is at low risk of soil acidification (particularly in SA and NSW) and

21% is at high risk (particularly in WA and Vic) (Barson *et al.* 2012a; Dairy Australia 2012).

Due to diminishing returns from milk production dairy farmers nationally have intensified and diversified their production to remain profitable. This has been done by increasing stocking rates, growing irrigated annual fodder crops, moving to mixed livestock systems of beef and dairy, and increasing nutrient inputs (Gourley *et al.* 2007; Bolland and Russell 2010). Many dairy farms also report significant nutrient surpluses, either as a result of high N application rates or by importing feed on farm (Gourley *et al.* 2007). The net effect of these activities is significant acidification, particularly in light textured soils where soil buffering capacity is low. The situation is particularly serious in south-western Australia where most soils used for dairy production have acidified from $pH_{Ca}$ values 5.5–6.5 to $pH_{Ca}$ 3.7–4.5 (McArthur 2004). Aluminium toxicity, induced by soil acidification, is a major problem for dairy production (Bolland and Russell 2010) and is ameliorated by applying sufficient lime to raise the pH of the top 0.10 cm of soil to ≥5.5 (Whitten *et al.* 2000). The rate of change was slow, with $pH_{Ca}$ of 5.5 achieved in individual paddocks 9–11 years after the liming program started, with 29% of paddocks not achieving this level despite additions of between 12–21 t/ha lime (Bolland and Russell 2010).

### *Grazing*

Acidification-remediation actions for grazing lands are confined to permanent pasture and mixed farming zones, and subsequent discussion will focus on these systems.

Under grazed permanent pastures, nitrate leaching is considered to be the largest contributor to acidification (Ridley and Coventry 1995). In south eastern Australia (e.g. NSW southern Tablelands and north-eastern Victoria), Scott *et al.* (2000) highlighted three characteristics of acidification; i) the rate of pH decline is slow (50 years or more) and even slower on strongly acidic soils ii) acidity problems are more quickly apparent on light textured soil and iii) soil can be acidic to depths of 60 cm.

The options for managing acidification under grazing systems are listed in Table 5.1 together with the associated constraints (Scott *et al.* 2000). These options are related to increasing perennial pasture content for better uptake of nitrate and for better year round biomass production (Section 4). Specifically there are four listed: 1) to sow perennial grass species rather than annual to access nitrate and prevent leaching; 2) to incorporate agroforestry systems, again to increase rooting depth and nitrate uptake; and 3) to reduce stocking rates on pastures with a high component of native grasses, to maintain vigour of native grasses. This last option will only constitute a minor component of grazing systems (less than 10%) and will therefore not apply in many cases. Ultimately liming at higher rates is the major solution to reduce soil pH below 10 cm and benefit-cost scenarios for different soil types and rainfall distributions must be articulated.

**Table 5.1 Options for management of soil acidity and feasibility in permanent and mixed grazing systems (adapted from Scott *et al.* 2000)**

| Option | Feasibility | Considerations |
|---|---|---|
| 1. Modifying the grazing system<br>▪ change pasture species and/or grazing management<br>▪ use less fertiliser | Limited (in permanent pasture systems due to cost and management skills, and also limited to area). This option will also only reduce acidification | Perennial species (e.g. native grasses)<br>▪ some scope but very high establishment costs<br>Modification of animal camping behaviour<br>▪ high investment in labour, management skills and fencing<br>Increase stocking rate<br>▪ likely if farmers more able to afford lime<br>Reduce stocking rate<br>▪ likely where there is a reasonable proportion of summer-active native grasses<br>▪ profitability likely lower except maybe for fine wool production<br>Fertiliser use<br>▪ avoid elemental S and $NH_4^+$- fertilisers, otherwise must apply lime to balance (3-7 kg per kg S and N respectively) |
| 2. Breeding and selecting plants for tolerance | Feasible in permanent and mixed grazing systems but is a temporary solution only | Selection of Aluminium tolerant species - most ryegrasses, native grasses, oats and triticale are highly tolerant but can mask and intensify developing problem and does not negate need for lime<br>Breeding must consider other traits such as palatability, persistence and the response of the rhizobial symbiont to acidity.<br>Selection of aluminium tolerant plant varieties and rhizobial strains can be useful as a short –medium term solution (Ridley and Windsor 1992) but can exacerbate acidification in the long-term. |
| 3. Correcting acidity by lime application | Highly feasible but amounts required and time taken dependent on soil type and grazing system (permanent or mixed) | Lime (carbonate) movement is slow<br>▪ takes time to move into soil profile, depends on porosity, can be facilitated by tillage and/ or soil fauna<br>▪ higher clay and organic matter soils resist change<br>▪ higher lime rates increase pH to greater depth<br>▪ surface applied lime increases profile pH to greater depth than incorporated lime(Ridley 1995)<br>Response of subterranean clover-based pastures to liming is promising<br>▪ sub clover response but variable in magnitude and time;<br>▪ the required 30% increase in stocking rates for economic response has been reported (e.g. Book Book NSW)<br>▪ some nutrients less available limiting rhizobial survival<br>▪ sub clover response less reliable where lime surface applied but likely a matter of time (Ridley and Windsor 1992)<br>Response of perennial-based pastures to liming is promising<br>▪ Phalaris, cocksfoot (DM increases) (Ridley and Windsor 1992)<br>Plant yield response is often related to depth of lime incorporation and to rate of application<br>▪ the rate of lime required varies with soil type (Ridley 1995) |
| **Management option** | **Feasibility** | **Considerations** |
| 4. Changing land-use | Technically feasible, politically very difficult! | Forestry/ land retirement means acidification slowed/ less relevant<br>▪ forestry is too costly on slopes >20%, location of infrastructure for harvesting trees<br>▪ Land retirement will require public funding<br>Horticulture and cropping means lime amendment is economically achievable (refer above section) |

## 5.3 Evidence of the efficacy of practices to increase soil pH

This section will address the issue of efficacy against the 4 practices listed above.

### *Test soil for pH*

The motivation to test soil requires knowledge of the problem (why it is necessary), instruction on a statistically meaningful sampling design (how to collect the sample), awareness and instruction on best course of action to increase soil pH, and knowledge of economic benefits couched in realistic timeframes. Commercial soil testing facilities are readily available and instruction on testing design is established or under refinement to take greater account of spatial variability and temporal factors that account for the slow rate of change in soil pH (Holmes *et al.* 2011). Yet soil testing for pH (monitored since 2007/08) has declined in 2009-10 (Barson *et al.* 2011; 2012a; b; c). Reasons for this decline are unclear and are likely to be complex and multifaceted (Pannell and Vanclay 2011). Significant motivation will be generated by the promotion of regional data demonstrating the significant benefits to be derived from managing soil pH and the development of a 20-year, $75 million national soil pH monitoring program (noting that this national program is separate from programs aimed at encouraging local testing) (Grealish *et al.* 2011).

### *Add lime at rates that are effective for arresting acidification*

There is compelling evidence to support the view that the management of soil acidification by liming surface soils can yield significant benefits for broadacre cropping industries. In a long-term trial, known as 'managing acid soils through efficient rotations' (MASTER), wheat crops produced on average, 1.6 t/ha more grain on the limed (2-3.6 t/ha) treatments. Sensitive (barley and wheat) and acid tolerant cereal varieties (e.g. Dollarbird) also yield more (1.6-2 t/ha more) in limed soils (Li *et al.* 2001; Carr *et al.* 2006). Lime-induced yield increases of a similar magnitude have been reported widely in southern Australian broadacre cropping systems in plot trials (Coventry *et al.* 1987; Coventry *et al.* 1989; Slattery *et al.* 1989), even in the presence of soil borne diseases (Coventry *et al.* 1987). According to Li *et al.* (2010), this success, combined with strong grain prices resulted in anecdotal reports of exponential increases in lime applications in the area in the 1990s.

A more recent case study conducted in the Gabby Quoi Quoi Catchment of the Avon River basin in Southern WA, highlighted the increases in soil pH values measured at approximately 300 sites over a 7-year period (1999-2006) after liming (Carr *et al.* 2006). This study reported that 75% of the topsoil and 85% of the mid-soil sampled in 1999 had $pH_{Ca}$ values lower than 5.0, with 15% of these soils having pH values less than 4.0. Re-sampling in 2006 has showed an overall increase in soil $pH_{Ca}$ with

60% topsoil and 69% mid-soil being less than $5.0_{Ca}$ and no samples found to be below pH 4.0. Yield responses were also measured in wheat ($28/ha), barley ($53/ha) and lupin ($5/ha), although in the latter crop, lime costs were not covered by the increased yield.

In the diverse industries that are collectively grouped into horticulture, the addition of lime is viewed as one of the management strategies for improving the overall health of soils. There are no accessible studies available on the effects of lime rate on biomass production in this industry. The high inputs applied and the short growth phases of vegetable production systems means that the lime-induced response is difficult to assess. Lime addition is therefore seen more as a general soil health maintenance activity (AusVeg 2010).

Despite positive yield responses, national trends in lime/ dolomite use (Barson *et al.* 2011; 2012a; b; c) to manage acidification suggest that there hasn’t been much change since 2000/01 or there has been a slight decline depending on industry and state. Many suggest that this could be related to the 10 years of drought during this period. For cereals (majority of broadacre cropping) nationally there was an increase in the percentage of farmers using lime/ dolomite from 1995/96 to 2000/01 but not much change since (except in WA and Tasmania) (Barson *et al.* 2012b). A project in the WA wheatbelt (where sandy soils are at high risk) is showing that 50% of soils tested have subsoil acidification problems, around 40% of broadacre croppers in WA are liming, but lime use is less than half the amount required to manage soil acidification (Gazey *et al.* 2012; Chris Gazey, DAFWA, pers. comm.) For the dairy industry the results are similar, except that liming has decreased in Tasmania and WA since 2000/01 (Barson *et al.* 2012a). In horticulture there was little change in the percentage of farmer’s liming between 1995/96 and 2007/08 (Barson *et al.* 2012c). In the grazing industries the percentage of beef cattle/ sheep businesses (outside the rangelands) liming declined between 2007/08 and 2009/10 (Barson *et al.* 2011).

### ***Add lime at high rates, sufficient to reverse acidification in soils that have already acidified***

The target values required to arrest acidification are generally high and followed by lower maintenance levels (Li *et al.* 2010). National lime use estimates from the Australian Bureau of Statistics’ Agricultural Resource Management Survey show that a total of 4,136,312 tonnes of lime and 302,333 tonnes of dolomite were used in the broadacre cropping, dairy, horticulture and more intensively managed beef cattle/ sheep grazing industries in 2007-08 (Michele Barson, DAFF, pers. comm.) This is considerably less than the projected requirement for nine million tonnes nationally (Webb *et al.* in preparation).

It is highly likely that these estimated lime requirements reflect the response of the more recalcitrant soils in south western Australia in broadacre and dairy industries where field studies indicate that it may take in excess of 11 years (and likely much more) and between 12–21 t/ha lime to raise the $\mathrm{pH_{Ca}}$ to 5.5 (Bolland and Russell 2010).

***Use acid-tolerant plant species where available***

There is good information available about the natural acid tolerance (and associated Al and Mn tolerance) of a range of pasture and crop plants (Slattery *et al.* 1989; Duncan 1999). The DAFWA Farmnotes soil acidity series (DAFWA 2012) also contains this information. No information was available on the combined use of this acid tolerant species and liming but it could be assumed that both practices are used in many regions that are at high risk of acidifying.

## 5.4 Concluding remarks

There is compelling evidence to show that liming surface soils increases yields of a wide variety of grasses and legumes. This is based on intensive R&D effort in the 80s-90s on long-term trials in the high rainfall and temperate zones of southern Australia, and more recently in the 1990s-2000s in southern WA field trials. Examples of information packages available are the Department of Agriculture, and Food Western Australia soil acidity series (DAFWA 2012) covering issues such as lime storage, liming rates and quality and expected and actual yield responses. For broadacre cropping and high return industries such as horticulture and dairy, liming can be an effective and profitable management strategy for mitigating surface soil acidification provided appropriate rates are applied that account for regional and local (management) factors of soil and plant type and N-fertiliser regimes.

The efficacy of practices to reduce subsoil acidification is less well established and only demonstrated on a small subset of soil types, but according to Anna Roberts (pers. comm.) the principles are simple – “it is about pH gradient, soil type and rainfall and therefore could be relatively easily calculated”. Notwithstanding the extended time frame for change and the high rates required to shift pH in some soils (of heavier texture) this is a remaining challenge for achieving improvements in soil pH condition. Once subsoil pH testing is adopted more broadly, the mitigation of subsoil acidity with more appropriate lime application rates and frequencies can be implemented in the high-risk agricultural regions.

### Box 5.1: Managing Soil pH through a systems approach

**System goal**

To increase soil pH or slow its decline by managing nitrogen in plant systems.

**Considerations**

1. Reduce $NO_3$ availability by using legumes, $NH_4$ and organic forms of N fertiliser, and maximising N uptake by crops and pastures.

2. Reduce $NO_3$ leaching by maintaining drier soils and reduced fallow lengths (perennials and higher crop frequency).

3. Balance anion removal in products by liming, presumably this is forever.

Acidification is a constraint to production and C storage, there is reluctance by growers to use more lime and lime application for many farmers is driven by rules of thumb.

These responses are consistent with the soil C responses, provided lime application can be incorporated.

**Recommended practices**

Apply lime effectively, use organic and $NH_4$ fertilisers, use more legumes, perennials and increased crop frequency, test soils regularly where $pH<6$.

**Performance indicators**

Trends in soil pH (relevant to support decisions at local to national and international scales), productivity (relevant locally to nationally), leaching of nitrates to subsoil and waterways (relevant locally and regionally).

**Conflicts**

Suitable machinery for applying lime, especially at depth, higher management inputs required to apply lime at sufficient quantities in some areas and the costs of these inputs encourage some farmers to increase cropping and grazing pressure to maintain cash flow.