Priorities for improving soil condition across Australia's agricultural landscapes

Report prepared for the Australian Government Department of Agriculture and Water Resources

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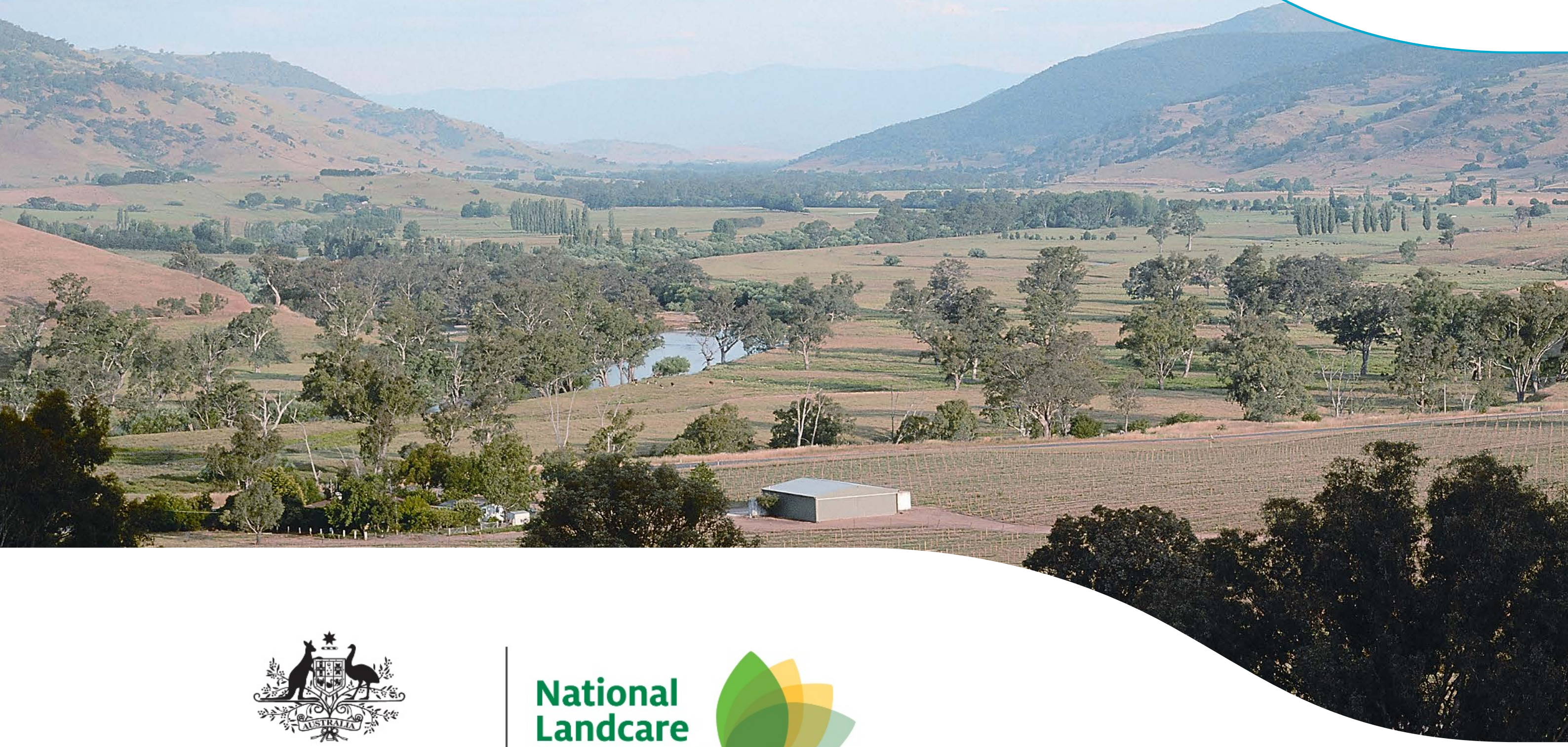

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Cover image

This picturesque rural landscape in North Eastern Victoria is vulnerable to several threats to soil function including acidification, erosion, nutrient imbalances, compaction and carbon loss. These widespread and chronic problems are typically 'half-solved' and not immediately obvious.

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Executive summary

There is a renewed international focus on soil management because of increasing concerns about the implications of current trends in soil condition. In Australia, soil acidification, unsustainable rates of soil erosion, loss of soil organic carbon and nutrient imbalances (deficiencies and excesses) are recognized as significant threats to soil function. If left unchecked, these problems will constrain Australia's ability to take advantage of agricultural opportunities created by a growing population and demand for exports. The threats have the potential to impose significant costs because ecosystem services provided by soils will be impaired.

This report provides an overview of trends in soil condition across Australia's agricultural landscapes. It has been prepared to assist the Australian Government design the next phase of the National Landcare Program and in so doing, meet its international obligations relating to sustainable development, climate change, biodiversity and sustainable soil management.

Soil acidification: The extent and severity of soil acidification is much greater than previous assessments have indicated. The intensification of cropping, and in particular the increase in nitrogen fertiliser usage and product removal, combined with inadequate liming, are causing significant acidification across large areas that were previously considered to be unaffected.

Soil carbon: Arresting declines or increasing soil carbon stocks has the potential to maintain or enhance soil resilience, sustainability and productivity as well as provide opportunities to mitigate greenhouse gas emissions. This highlights that increasing soil carbon stocks will be challenging across many agricultural landscapes in Australia. Success will depend heavily on the way individual landowners implement soil management measures (e.g. through the timing of cropping and grazing operations). The regions with the greatest potential for increasing soil carbon stocks are in the south east of Australia.

Soil erosion by water[1]: The control of soil erosion by water has the potential to preserve the soil resource and have a major influence on other soil attributes including soil organic matter, nutrient status and rates of acidification. Soil erosion is tightly linked with downstream water quality both within the rural enterprise (e.g. stock watering points and farm dams) and off-site (e.g. in rivers, reservoirs, estuaries and the ocean). The erosion of surface soils is a long-standing problem in Australia. Although there are regional success stories, the rates of hillslope erosion across Australia's rural landscapes are still much greater than the rates of soil formation so a net run-down of the soil resource is occurring. The report emphasizes that the intensification of land use in Northern Australia should avoid areas with erodible and dispersive soils if extensive gully erosion and the mistakes of the past are to be avoided.

Nutrient imbalances: Nutrient decline is an ongoing concern but Australian agriculture has a long history of responding to deficiencies as they emerge. Despite this history, chronic and possibly irreversible nutrient decline is occurring across large tracts of once naturally fertile soils,

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[1] See Leys et al. (2017) for the companion report on soil erosion by wind across Australia.

particularly in the northern cereal growing areas of eastern Australia. The situation for nutrient excess is more complex and less certain. A large and ongoing increase in the use of nitrogen fertiliser is occurring and this has implications both on-site (e.g. acidification, emergence of other nutrient deficiencies) and off-site (e.g. nitrate in groundwater, greenhouse gas emissions). A better understanding of the consequences of this intensification is required.

Achieving sustainable soil management is complex and commentary is provided on key factors for success. These include: (1) coordinated programs of soil research, development and extension; (2) experienced and highly motivated specialists; (3) up-to-date soil mapping and monitoring at resolutions relevant to farm management; and (4) technical solutions for erosion control, sequestering carbon and sustainable farming. Of critical importance is the need to integrate public sector and private sector data streams so that farmers, industries and governments are aware of the key threats to soil function.

Rankings are provided for addressing soil acidification, increasing soil carbon, controlling hillslope erosion by water and managing nutrient deficiencies and excesses. These rankings provide a framework for prioritizing investments across NRM regions. It is emphasized that prioritization is also required within regions. The project has produced several fine-resolution data sets that can be used for district planning within each NRM region.

1 Introduction

This report provides an update on priorities for improving soil condition across Australia's agricultural landscapes. The latter are interpreted broadly and include lands used for irrigation, horticulture, cropping, grazing and forestry. The report builds directly on previous assessments of priorities for the Australian Government's Caring for Our Country Program (e.g. Baldock et al. 2010, Bui et al. 2010, Wilson et al. 2009) and the Australian State of Environment Reports in 2011 and 2016 (SoE 2011, SoE 2016). The focus is on the following aspects of soil condition:

- Soil acidification
- Soil carbon
- Soil erosion by water
- Soil nutrient imbalances.

The analysis of soil erosion by water is restricted to hillslope erosion (i.e. sheet and rill erosion but not gully and streambank erosion). A companion study has been commissioned on wind erosion. (Leys et al. 2017). While there are other important aspects of soil condition (e.g. compaction, salinity, sodicity, sealing, biodiversity, contamination), the scope of this assessment was constrained to aspects that are considered to be the highest priority across the agricultural landscapes of Australia.

1.1 International context for sustainable soil management

The foundational agreements and documents of the Global Soil Partnership provide the international context for sustainable soil management. Most significant are the Revised World Soil Charter (FAO 2015), the Status of the World's Soil Resources report (ITPS 2015a) and the Voluntary Guidelines on Sustainable Soil Management (FAO 2017). These assert that soils are an essential and non-renewable natural resource hosting goods and services vital to ecosystems and human life. Soils are fundamental for producing crops, feed, fibre, fuel, and globally they filter and clean tens of thousands of cubic kilometres of water each year. As a major storehouse for carbon, soils also help regulate emissions of carbon dioxide and other greenhouse gases, which is fundamental for regulating climate. Ecosystem services provided by soils can be further elaborated into the following:

- *Supporting* services include primary production, nutrient cycling and soil formation;
- *Provisioning* services comprise the supply of food, fibre, fuel, timber and water; raw earth material; surface stability; habitat and genetic resources;
- *Regulating* services imply the regulation of aspects such as water supply and quality, carbon sequestration, climate regulation, control of floods and erosion; and
- *Cultural* services denote the aesthetic and cultural benefits derived from soil use.

Within this framework, sustainable soil management is defined according to Principle 5 in the Revised World Soil Charter as follows:

> *"Soil management is sustainable if the supporting, provisioning, regulating, and cultural services provided by soil are maintained or enhanced without significantly impairing either the soil functions that enable those services or biodiversity. The balance between the supporting and provisioning services for plant production and the regulating services the soil provides for water quality and availability and for atmospheric greenhouse gas composition is a particular concern".*

Sustainable soil management has the following characteristics (FAO 2017).

1. The rates of soil erosion by water and wind are minimal.
2. The soil structure is not degraded (e.g. through soil compaction) and provides a stable physical context for movement of air, water, and heat, as well as root growth.
3. Sufficient surface cover (e.g. from growing plants, plant residues, etc.) is present to protect the soil.
4. The store of soil organic matter is stable or increasing and ideally close to the optimal level for the local environment.
5. The availability and flows of nutrients are appropriate to maintain or improve soil fertility and productivity, and to reduce their losses to the environment.
6. Soil salinization, sodification and alkalinization are minimal.
7. Water (e.g. from precipitation and supplementary water sources such as irrigation) is efficiently infiltrated and stored to meet the requirements of plants and ensure the drainage of any excess.
8. Contaminants are below toxic levels (i.e. those which would cause harm to plants, animals, humans and the environment).
9. Soil biodiversity provides a full range of biological functions.
10. The soil management systems for producing food, feed, fuel, timber, and fibre rely on optimized and safe use of inputs.
11. Soil sealing is minimized through responsible land use planning.

The renewed international focus on soil management has occurred because of increasing concerns about the implications of current trends in soil condition. The first Status of the World's Soil Resources Report by the Intergovernmental Technical Panel on Soils (ITPS 2015a) concluded that

> *'human pressures on soil resources are reaching critical limits. Further loss of productive soils will amplify food-price volatility and potentially send millions of people into poverty. This loss is avoidable. Careful soil management can increase the food supply, and provides a valuable lever for climate regulation and a pathway for safeguarding ecosystem services.'*

The ITPS went onto to state that

> *'while there is cause for optimism in some regions, the overwhelming conclusion from the report is that the majority of the world's soil resources are in only fair, poor or very poor condition. The most significant threats to soil function at the global scale are soil erosion, loss of soil organic carbon, and nutrient imbalance. The current outlook is for the situation to worsen unless concerted actions are taken by individuals, the private sector, governments and international organizations.'*

Australia is one of the countries that gave the ITPS some cause for optimism. However, even in Australia, soil acidification, unsustainable rates of soil erosion, loss of soil organic carbon and nutrient imbalances (deficiencies and excesses) are recognized as significant threats to soil function and remain difficult to ameliorate (ITPS 2015b, SoE 2016). If left unchecked, these problems will constrain Australia's ability to take advantage of agricultural opportunities created by a growing population and demand for exports. A concerted effort to further improve soil management is required and this needs to not only include better diagnostic systems for determining when and where soil function is being compromised but also effective systems for developing and implementing farm management practices that restore or enhance soil function (McKenzie 2017).

The increasing awareness of the need for sustainable soil management has led to a range of international agreements and commitments that reference soil resources in some way. The Australian Government has a range of obligations under several of these and they include the following:

- the 2030 Agenda for Sustainable Development, where sustainable soil management could directly or indirectly contribute to achieving several of the agreed goals and targets (e.g. Sustainable Development Goal 15.3),
- the Zero Hunger Challenge (to end hunger and malnutrition and assure food security for a growing population),
- climate change adaptation and mitigation, especially in the light of the Paris Agreement adopted at the UNFCCC COP21, which embodies a strong commitment to address climate change and give agriculture a prominent role in that process,
- the commitment to combat desertification and mitigate effects of drought, especially the intention to achieve a land degradation neutral world (e.g. the outcomes of UNCCD COP12),
- the Aichi targets which underline an important agenda to preserve biodiversity and the provision of ecosystem services,
- the voluntary commitments under the Revised World Soil Charter (see below and Table 1.1), and
- as a member state of the UN FAO, support for the new arrangement for the establishment of the Global Soil Information System including the International Network of Soil Information Institutions (INSII).[2]

Of particular relevance to this report are the actions requested of governments under Section C of the Revised World Soil Charter adopted by the 21st Conference of the UN FAO in 2015 (FAO 2015). These actions are presented in Table 1.1.

The Australian Government's funding for the National Landcare Program (NLP) is a key mechanism for Australia to meet its international obligations in relation to sustainable soil management. The NLP has adopted the same ecosystem services framework used by the Global Soil Partnership and there is good agreement between Australian and international objectives. Of particular

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[2] http://www.fao.org/3/a-bs974e.pdf

importance is the recognition that funding is required to improve the ecosystem services that can be delivered from agricultural lands, especially those relating to clean air, water and biodiversity protection. This report aims to identify priorities for improving soil condition across Australia’s agricultural landscapes. As such, it should help the Australian Government meet its international obligations.

Table 1.1: Extract from the Revised World Soil Charter (FAO 2015) that outlines the expected actions by governments. The Charter was adopted by the 21st Conference of the UN FAO of which Australia is a supporting member.

Section C: Actions by Governments

I. Promote sustainable soil management that is relevant to the range of soils present and the needs of the country.

II. Strive to create socio-economic and institutional conditions favourable to sustainable soil management by removal of obstacles. Ways and means should be pursued to overcome obstacles to the adoption of sustainable soil management associated with land tenure, the rights of users, access to financial services and educational programmes. Reference is made to the Voluntary Guidelines on the Responsible Governance of Tenure of Land, Forests and Fisheries in the Context of National Food Security adopted by the Committee on World Food Security in May 2012.

III. Participate in the development of multi-level, interdisciplinary educational and capacity-building initiatives that promote the adoption of sustainable soil management by land users.

IV. Support research programmes that will provide sound scientific backing for development and implementation of sustainable soil management relevant to end-users.

V. Incorporate the principles and practices of sustainable soil management into policy guidance and legislation at all levels of government, ideally leading to the development of a national soil policy.

VI. Explicitly consider the role of soil management practices in planning for adaptation to and mitigation of climate change and maintaining biodiversity.

VII. Establish and implement regulations to limit the accumulation of contaminants beyond established levels to safeguard human health and wellbeing and facilitate remediation of contaminated soils that exceed these levels where they pose a threat to humans, plants, and animals.

VIII. Develop and maintain a national soil information system and contribute to the development of a global soil information system.

IX. Develop a national institutional framework for monitoring implementation of sustainable soil management and overall state of soil resources.

1.2 Overview of the approach

1.2.1 Sources of information

The assessment in this report has drawn on information from a wide range of sources with diverse spatial and temporal referencing systems. The sources include the following.

- **Field experiments**. Long-term field experiments provide the most reliable insights into biophysical processes and mechanisms of soil change, however they tend to be highly site-specific. The latest results from such experiments have been incorporated into the assessment via the qualitative rankings for the relevant natural resource management regions (see below). Experimental results have also been considered in the short literature reviews at the beginning of each thematic section.
- **Monitoring sites**. The number of soil monitoring sites across Australia has increased but most are less than 20 years old and this is often the minimum period for the detection of soil change. However, initial results are providing important insights into baseline conditions and soil change in some parts of the country (e.g. Wilson and Lonergan 2014, Grose 2015). These results have been incorporated into the assessment of status and trend for the relevant natural resource management regions.
- **The Agricultural Census and land management surveys**. These provide information on agricultural land management practices across Australia. Land management is often the primary driver of soil change (other drivers include climate change, fires, and extreme events such as intense storms). The Australian Bureau of Statistics (ABS) Agricultural Census is the most significant source of information because of the time-series data on: the frequency of tillage, management of stubble, application rates for a wide range of fertilisers and soil ameliorants (including lime), and rates of soil testing. These data can be obtained in a wide range of formats from the Department of Agriculture and Water Resources through *The Monitor* website hosted by the Australian Bureau of Agricultural and Resource Economic Sciences (ABARES). As discussed below, several factors have reduced the utility of the latest results from the Agricultural Census and most of the information in this assessment had to be drawn from data collected in 2012 or earlier.

  Land management surveys commissioned by other agencies (e.g. the Rural Industry Research and Development Corporations) are also useful. However, these surveys often have a specific purpose and use a variety of sampling and reporting frames. As a consequence, it is challenging to develop a consistent characterization of land management and its impact on soil condition. The assessment of land management practices by Unkovich and Baldock (in press) integrates information from the ABS and several of these specific-purpose surveys. Their assessment has the potential to help identify areas where soil carbon content can be increased and to update the estimates of the net acid addition rate for individual systems of land management.
- **Conventional maps of soils and land use.** Interpretations of these information sources are by necessity qualitative but they provide valuable information on constraints to land use and management (e.g. van Gool 2016). It is rarely possible to draw strong conclusions on soil change based only such sources. However, conventional maps provide a useful means for

classifying the rate or type of soil change because they are often conditional on soil type and climate. The Physiographic Regions of Australia (Pain et al. 2011) have provided a general spatial framework for integrating the multiple lines of evidence relevant to soil condition and it has been used in recent national state of the environment reports. These results have been incorporated into the qualitative assessments for each natural resource management region.

- **Scientific papers.** While often taken for granted, peer-reviewed scientific papers still provide the single most important source of information on soil change in Australia. These papers often present results from field experiments and monitoring sites but they also provide insights in biophysical processes responsible for soil change. In this report, the analysis of nutrient balances relies almost entirely on scientific papers (e.g. Simpson et al. 2014, Weaver and Wong 2011, Gourley et al. 2015) because other sources of information (e.g. spatial data sets) are less readily available. In other instances scientific papers provide the details of supporting methodologies. For example, Teng et al. 2016 outlines a method for estimating the mean annual rates of soil erosion by water and these were used here to calculate the associated loss of nutrients.

Several advances have occurred in recent years that allow improvements to previous assessments of soil condition at relatively low cost. These new sources of information include the following.

- **Soil and Landscape Grid of Australia (SLGA)**: The release of this product for the continent is a world first (Grundy et al. 2015, Arrouays et al. 2014). It provides a solution to some of the inconsistencies and problems that beset previous assessments. The SLGA provides estimates of functional soil properties on a fine-resolution spatial grid and at set depths. It is a much more flexible data product in comparison to conventional digital soil maps. The latter rely on polygon mapping and the depiction of soil types often with an estimate of the area occupied by each soil type in the polygon. As such, it is a difficult data model for spatial analysis, especially when integration with other data sets is required (e.g. grid-based data on land use, land cover and climate).

  More complex analyses (e.g. simulation modelling) that use the SLGA as an input are also possible. However, these require resources that are well beyond those available to this study (e.g. updates to the carbon sequestration analysis undertaken by Wang et al. (2015) or rerunning continental assessments of soil erosion (e.g. Teng et al. 2015) under a range of potential future climates).

  The SLGA was developed using the best available soil and land resource information, most notably from the relevant state and territory agencies. While it represents a great advance, it requires regular updating as better data become available. A key issue identified in this report is the underestimation of the extent of acidity in some states. This arises because of inevitable compromises that had to be made during the production of the consistent national data set and also because of the availability of more recent data on pH, particularly in South Australia and Western Australia (see Section 2.7).

- **Recent scientific studies and technical assessments**: Several research programs and technical assessments provided valuable inputs to this assessment. Most notable were: the National Soil Carbon Program (and its precursor programs), the National Agricultural Nitrous Oxide Research Program, the Western Australian report on sustainable natural resource use in agriculture (DAFWA 2013), the regional assessment for the Southwest Pacific in the Status of the World's Soil Resources report (ITPS 2015) and the latest state of the environment report for Australia (SoE 2016). A substantial number of peer-reviewed scientific studies on soil constraints to agricultural production, environmental impacts (e.g. Great Barrier Reef) and nutrient management have also provided important benchmarks or insights relating to soil change across particular parts of the continent. Examples include revised assessments of soil erosion (e.g. Teng et al., 2016, Chappell and Webb 2016, Chappell et al. 2017) and soil-carbon dynamics (Wang et al. 2015, Chappell et al. 2015).

- **Advances in time-series remote sensing and high-performance computing**: The production of a long-term (30 years) time-series of fractional soil-cover has opened a new way to assess the condition of soil and land resources, and in particular the status and risks of soil erosion by water and wind. The ability to differentiate between bare soil, living plant cover and dead plant cover, provides a measure of the degree to which the soil surface is protected from the erosive force of wind, rainfall and the surface flow of water. The new fractional-cover data sets (Guerschman et al. 2015) help to identify districts with a significant risk of soil erosion and the trend of this risk through time. This information is of direct benefit to the wind erosion component of the current NLP project. The new long-term time-series of surface cover is yet to be used in a quantitative continental assessment of hillslope and rill erosion. As noted above, a reanalysis of the last update by Teng et al. (2016) was beyond the scope of the current study but the fractional cover data were used to support the qualitative rankings of hillslope and rill erosion across Australia.

Another source of information used in this report is expert opinion. Its importance in developing a balanced understanding of environmental change has been recognized for decades (e.g. Munn et al. 1988, Vaughan et al. 2001, McKenzie et al. 2002). The quality of expert input to any assessment depends heavily on: how the elicitation process is organized; on the degree of social cohesion and scientific consensus within the relevant community of practice; and on the procedures used to present and comment on the evidence and conclusions. Each theme in this report was reviewed by relevant domain experts. A final review was undertaken by members of the National Committee on Soil and Terrain.

1.2.2 Reporting framework

A simplified version of the popular DPSIR framework (Drivers, Pressures, States, Impacts and Responses) has been employed here to structure the report. The approach has been widely used for analysing the interactions between society and the environment (OECD 1991, EEA 1999) and the format used here is based on recent Australian reports on the state of the environment (e.g. SoE 2011, 2016).

Various formal frameworks for combining mixes of qualitative and quantitative information (e.g. Delphi techniques, Bayesian networks) were considered during the initial stages of the project. However, undertaking such an analysis would require significant additional project resources (e.g. specialists in Bayesian analysis, multi-day workshops, additional data analysis) and was therefore out of scope. However, it would be desirable to pursue such an approach if a more comprehensive assessment is undertaken in the future (e.g. a follow-up to the National Land and Water Resources Audit).

Instead, we have opted for an approach of qualitative ranking supported wherever possible by quantitative spatial analysis using the Multi-Criteria Analysis Shell for Spatial Decision Support (MCAS-S) (ABARES 2017). Analyses involving the SLGA were undertaken using Google Earth Engine because of the large size of the data sets. As such, the approach represents an incremental improvement over methods used in recent assessments (e.g. SoE 2011, SoE 2016, DAFWA 2013, ITPS 2015).

1.2.3 Spatial units and ratings

The general approach has been to use, wherever possible, gridded data at the finest possible spatial resolution to generate layers of evidence relating to the key biophysical processes affecting soil status. These layers of evidence are comprised of co-registered grid and polygon data. While the data on soil properties and land use are available nationally in grid format, most land management data are available in a polygon format. These are often combined with other lines of evidence to produce assessments that are most commonly presented as qualitative ratings of the status in soil condition at the district level (mapped as polygons). In this report the degree of spatial generalization has been matched with the quality of information available.

A significant challenge for this type of spatial analysis is the calculation of a meaningful spatially-weighted mean. For example, information on soil testing, stubble management, fertiliser usage and liming rates may be available for a statistical district (i.e. a polygon format). Determining where these practices occur within the statistical district can be achieved to some extent by using the gridded land-use data. In this case, stubble management, liming and fertiliser application could be assumed to take place only on farming lands within the polygon and be absent from areas used for production forestry. However, determining exactly where the practices apply within these farming lands can be problematic particularly in larger statistical districts that have substantial variations in climate and soil conditions.

As noted earlier, the polygons used for reporting on soil condition are Australia's NRM Regions.[3] In many instances, summaries of soil condition are presented in further detail by providing estimates for the main land uses present within a particular region (ABARES 2016a). A map of these regions is presented in Section 4 (Figure 4.7).

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[3] We have restricted our analysis to the 56 NRM mainland regions (i.e. including Tasmania) where agricultural activities take place. The five other NRM regions that include remote islands, external territories and marine areas have not been considered.

Table 1.2: Summary of data sources, analyses, significance and opportunities addressed by the study.

Theme	New data sources	Type of analysis	Significance	Opportunity
Acidity	Improved national grid of pH and pH buffering capacity Improved land management data New data sets for some regions (e.g. WA and SA)	Continental analysis via GIS with improved spatial data inputs Incorporation of results from district-scale studies on current extent and severity of acidification	Very large and widespread impacts on agricultural production in many districts Impacts are occurring now and are likely to increase substantially over the next decade	Experience in some jurisdictions indicates the situation can be improved by supplying better information on acidification risk and appropriate responses. Identification of where investment into such activities is needed.
Soil carbon	Results from the National Soil Carbon Program (NSCP) New continental simulation studies of the potential for sequestering carbon Improved land management information Improved estimates of net primary productivity and carbon stocks	District and industry specific findings from the NSCP Review and update the previous assessment of soil carbon using improved data on land management, net primary productivity and carbon stocks	The importance of soil carbon in maintaining soil health and addressing climate change is widely recognized. The results of the NSCP and related studies are highlighting major constraints and trade-offs involved in increasing or maintaining soil carbon.	Extension of results from recent studies and large programs (particularly the NSCP) Refinement of the previous analysis prepared for CfOC provides an incremental improvement in identifying affected areas.
Soil erosion by water	Improved continental assessment of hillslope and rill erosion. Improved understanding of soil erosion processes in some regions (e.g. GBR catchments, Northern Australia) Improved time-series of surface cover	Review of recent soil erosion research and the emerging consensus on the importance of different forms of soil erosion. Critical analysis of the current continental estimates with a view to guiding future assessments	Improvements to grazing and cropping practices have already occurred in many industries and districts. In many parts of the country, soil erosion by water is a chronic problem of major significance in the medium to long-term	More detailed studies of erosion and sediment transport are required to formulate optimal responses in many districts (e.g. identification of hotspots, optimizing local land management). Specification of methods needed for more robust continental assessments.
Nutrient imbalance	Significant projects on both nutrient decline and excess have been completed and these allow general conclusions on the significance and location of the problems. Comprehensive national spatial data sets are not readily available	Literature review Qualitative rankings of condition and trend at the district level. Qualitative assessment of management responses and risks at the jurisdictional and industry scale.	Nutrient decline can occur as a widespread and chronic problem (e.g. Central Queensland cropping lands) that can threaten viability Nutrient excesses are usually more localized and associated with high input systems (e.g. dairy, sugar cane, intensive livestock production)	The large environmental and economic costs involved have led to significant investments by industry groups and government Affected areas can be readily mapped if land use is used as a proxy but identifying effective interventions and investment opportunities is a complex undertaking

2 Soil acidification

2.1 Significance, causes and consequences

Assessments of soil acidification during recent decades (e.g. AACM 1995, NLWRA 2001, SoE 2011, Baldock et al. 2010) have concluded that about half of Australia's agriculturally productive soils are affected by acidification.[4] The problem is considered to be increasing in severity and extent due to either inadequate treatment, intensification of land management, or both.

The cost of soil acidification is large and the NLWRA (2001) estimated that the value of lost agricultural production was about $1.6 billion per annum. Subsequent studies confirmed the scale of the problem (e.g. Lockwood et al. 2003, Wilson et al. 2009, Gazey et al. 2013, Forward and Dutkiewicz 2012) but, as discussed below, a comprehensive national economic analysis is yet to be done.

Soil acidification is of greatest concern in situations where:

- agricultural practices have a positive net acid addition rate (e.g. due to large rates of product removal, application of high-analysis nitrogen fertilisers, use of legumes, and limited amelioration with lime)
- the soil has a low capacity to buffer the decrease in pH (e.g. infertile, light-textured soils)
- the soil is naturally acid or it has a low pH due to past land management.

It is possible to reverse soil acidification through the application of lime. However, the chemistry of soil acidification and the neutralization reactions associated with liming are complex (Slattery et al. 1999, Rayment and Lyons 2011). It is much harder to reverse the problem if the acidity has advanced deeper into the soil profile because lime is sparingly soluble and incorporation at depth is more expensive. Prevention rather than cure is desirable (SoE 2011).

The main onsite effects of acidification include:

- induced nutrient deficiencies or toxicities leading to a reduction in net primary production
- accelerated leaching of plant nutrients (manganese, calcium, magnesium, potassium and anions)
- loss or changes in soil biota involved in nitrification
- reduced carbon sequestration
- erosion as a result of decreased groundcover
- fewer options for land management and decreasing land value.

The potential off-site effects are less-well understood and they may include:

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[4] The process of acidification considered here is distinct from that associated with acid sulfate soils. These soils occur mainly in coastal settings, and they contain iron sulfides that severely acidify when oxidised. This can occur through drainage of coastal wetlands, or through exposure due to drought of normally wet acid sulfate soils.

- mobilisation of heavy metals into water resources and the food chain
- acidification of waterways as a result of leaching of acidic ions
- increased sediment transport and eutrophication of streams and water bodies.

2.2 Target area

In this report the target area for the analysis of acidification includes all agricultural lands where net acid addition rates have potentially changed through: the modification of vegetation (e.g. through clearing, the establishment of particular pasture species); the addition of agricultural inputs; and nutrient export (either as product removal or via other pathways such as leaching).

The target area shown in Figure 2.1 has been defined using the National Land Use Map (ABARES 2016a) and it involved masking out of native vegetation, built-up areas, water bodies, and swamps/saline areas.

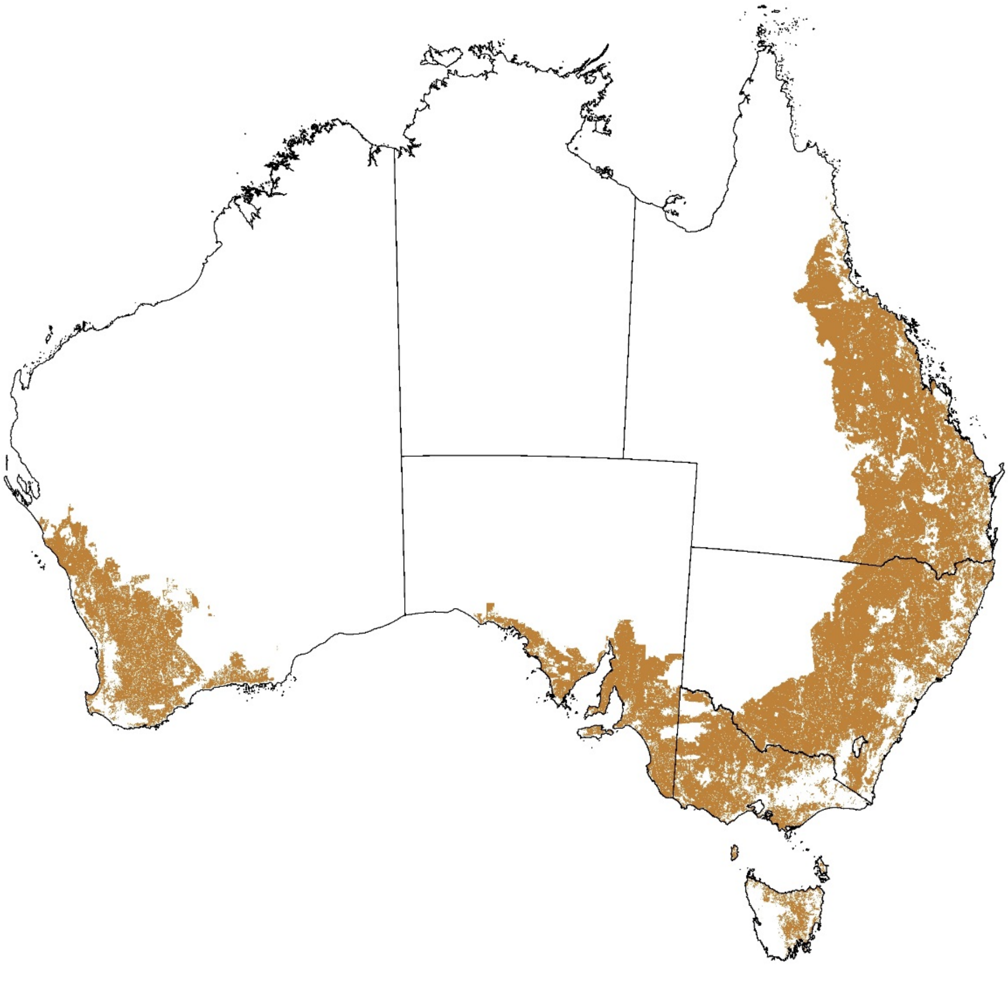


Figure 2.1: The agricultural lands of Australia analysed for soil acidification.

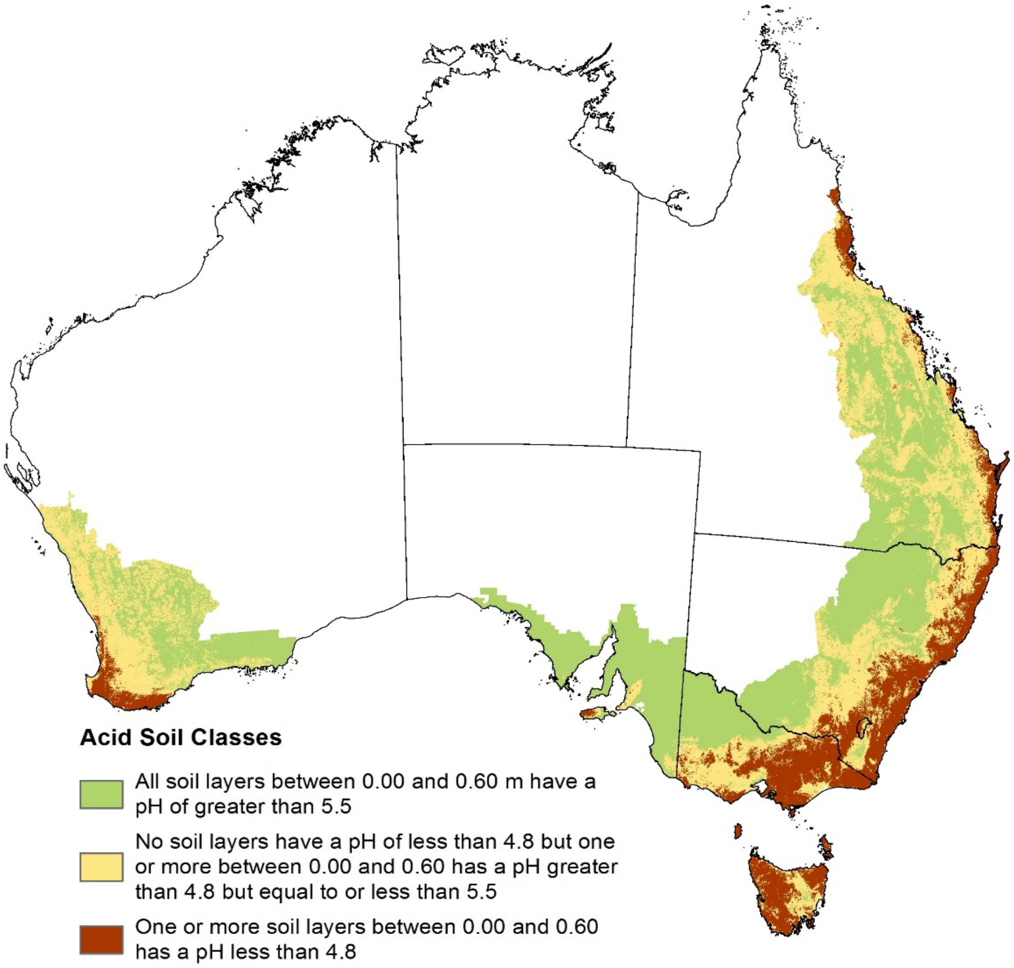
2.3 Status of acidification

Understanding the status of soil acidification for any location requires information on:

- the soil's current pH and associated buffering capacity
- the current rate of soil acidification, and
- whether management responses are adequate.

In the following sections we attempt to quantify these three aspects but acknowledge that they are progressively more difficult to determine.

Data on current soil pH[5] have been sourced from the Soil and Landscape Grid of Australia. A simple classification of soils with or without acidic layers is provided in Figure 2.2. The selected thresholds for pH of 4.8 and 5.5 have physical significance. In acidic soils with clay minerals susceptible to weathering, a pH of less than 4.8 is the point at which cations such as aluminium and manganese become more soluble and toxic to plant growth. Moderately acidic soils have a pH between 4.8 and 5.5 and this can adversely affect the growth of sensitive plants (e.g. canola, lucerne, barley).



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[5] All references to pH in this report are to measurements in a 1:5 soil/0.01M calcium chloride extract.

Figure 2.2: Distribution of acid soils in Australia – note the significant differences with more recent maps shown in Figures 2.12 to 2.15.

2.3.1 Lime requirement

The amount of lime required to increase pH to a target value provides a useful indicator of the severity of soil acidification and a guide to the cost of amelioration. While it has been common practice to calculate the time in years to reach a critical pH (often 4.8), such estimates are problematic because reliable information on the likely net acid addition rate is required (including the likely rate of lime application). In reality, soil management is adaptive and it is difficult to represent an 'average response' to ongoing acidification. It is more useful to simply present the results as lime requirements in tonnes to achieve a target pH.

The lime requirement was calculated for the depth intervals of 0–0.05m, 0.05–0.15m and 0.15–0.30m and then summed (negative values are ignored). These intervals correspond to those currently available in the Soil and Landscape Grid of Australia (SLGA) and are based on the *GlobalSoilMap* standards (Arrouays et al. 2014).

The lime requirement to achieve a pH of 5.5 was calculated using Equation 2.1. The derivation of this equation is presented in Appendix 1.

$$LR = \sum(pHBC \times 5 \times T_c \times BD) \times (T_{pH} - C_{pH}) \times \frac{100}{NV} \times (1 - \frac{CF}{100}) \quad [2.1]$$

Where

- LR is lime requirement (Mg/ha) for the relevant soil layer
- $pHBC$ is in units (cmol$^+$/kg soil/pH unit)
- T_c is the thickness of the layer (m)
- BD is the bulk density of the soil layer (Mg/m^3)
- T_{pH} is target pH (5.5 in this instance)
- C_{pH} is current pH
- NV is neutralising value of the liming product compared to pure $CaCO_3$ (%). A conservative value of 85% was used here (based on Upjohn et al. 2005).
- CF is the percentage of coarse fragments (i.e. particle size >2mm)[6]
- 5 is a conversion factor that enables the translation from moles of charge to a mass basis, the conversion from a gravimetric to a volumetric basis, and division by 100 (moles to centimoles) (see Appendix 1).

pH Buffering Capacity

Soils differ in their response to the addition of lime. Soils without much clay or organic matter will normally exhibit a larger increase in pH than those with more clay and organic matter. This

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[6] Data on coarse fragment contents are not yet available via the Soil and Landscape Grid of Australia. In this study, *CF* has been set to zero and this will cause overestimation of the lime requirement in areas with gravelly soils. The main areas where this is likely to have some impact on the results are in south-west Western Australia.

difference in response is determined primarily by the soil's pH Buffering Capacity (pHBC) which is often expressed as the amount of lime per unit area required to achieve a stated increase in pH. In Equation 2.1, the units are expressed as the amount of charge per unit mass of soil to achieve a unit change in pH (this is a simplification given that pHBC is nonlinear across the full range of pH typically encountered in field soils).

As noted earlier, the buffering capacity of a soil is dependent on a range of factors including the amount of organic carbon, clay percentage, clay mineralogy and the pH value. Various methods for estimating pHBC have been proposed but the only feasible option in this assessment was to use a pedotransfer function. Several such functions have been developed for different groups of soils in various parts of Australia (e.g. Hochman et al. 1989, 1995; Aitken et al. 1990, 1995; Noble et al. 1997; Moore et al. 1998). Most pedotransfer functions take the general form of Equation 2.2 where: *a*, *b*, and *c* are constants.

$$\text{pHBC} = a + b*OC + c*Clay \qquad [2.2]$$

and where:

- pHBC is the pH Buffering Capacity expressed as cmol^+/kg soil/pH unit
- *OC* is the gravimetric percent organic carbon in the soil
- *Clay* is the gravimetric percent clay in the soil.

However, published functions vary according to location, are generally based on small sample sizes, and rely on different methods of measurement (Table 2.1). There has been limited testing or evaluation of pedotransfer functions for pHBC[7] and applying the relationships within the relevant jurisdictions leads to pronounced mismatches at the state and territory borders. For example, estimates of pHBC based on Helyar et al. (1990) and Aitken et al. (1990) (Table 2.1) are larger than those estimated by other functions, especially for soils with significant quantities of clay and organic carbon. The Merry (pers. comm.) and Moore et al. (1998) functions are more consistent, particularly when spatial patterns are considered.

While it is a far-from-perfect solution, we have used the Merry (pers. comm.) function nationally in full knowledge that it probably underestimates pHBC in Queensland and parts of New South Wales (assuming the functions of Helyar et al. (1990) and Aitken et al. (1990) are comparable). It may also over-estimate pHBC in soils with significant concentrations of organic carbon. The reason for using a single equation across the country is that the spatial pattern and relative values are more important than the absolute values of pHBC. In the final analysis used here, the estimates of lime requirements are scaled between zero and one and the rank order is more important than the physical magnitude. Furthermore, the parameters for clay and organic carbon make physical sense and both return an increase in pHBC with increasing clay and carbon.

Our approach to scaling pHBC is pragmatic but far from adequate. It highlights the need for a coordinated scientific and technical program to improve our understanding of some of the fundamental variables that control soil acidification across Australia.

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[7] Given the importance of the parameter, it would be prudent to undertake a meta-analysis of existing functions and, if necessary, commission a comprehensive study that could include direct measurement of pHBC on a representative range of soils from the National Soil Archive along with the use of NIR/MIR spectra as a basis for prediction. These spectra have already been collected for specimens in the National Soil Archive and most of the factors controlling pHBC are readily estimated using NIR/MIR spectroscopy.

Table 2.1: Parameters for predicting pHBC – the Merry equation was used for the whole continent.

State/Territory	*A*	*b*	*c*	Reference
WA	0.48	0.54	0.000	Moore et al. (1998)
QLD	0.00	1.91	0.022	Aitken et al. (1990)
NSW	0.00	0.52	0.140	Helyar et al. (1990)
NSW, SA, VIC, TAS, ACT	0.29	0.52	0.030	Richard Merry (pers. comm.)

The map of pH buffering capacity for the 0–0.05 m layer is shown in Figure 2.3. The estimate of lime required to increase the pH to 5.5 to a depth of 0.60 m (if the current pH is less than 5.5) is shown in Figure 2.4. In most circumstances it would be impractical to apply the estimated amount because it doesn’t take into account the challenge of incorporating the lime to the required depths. However, the map gives an indication of the challenges involved in ameliorating soil acidity.

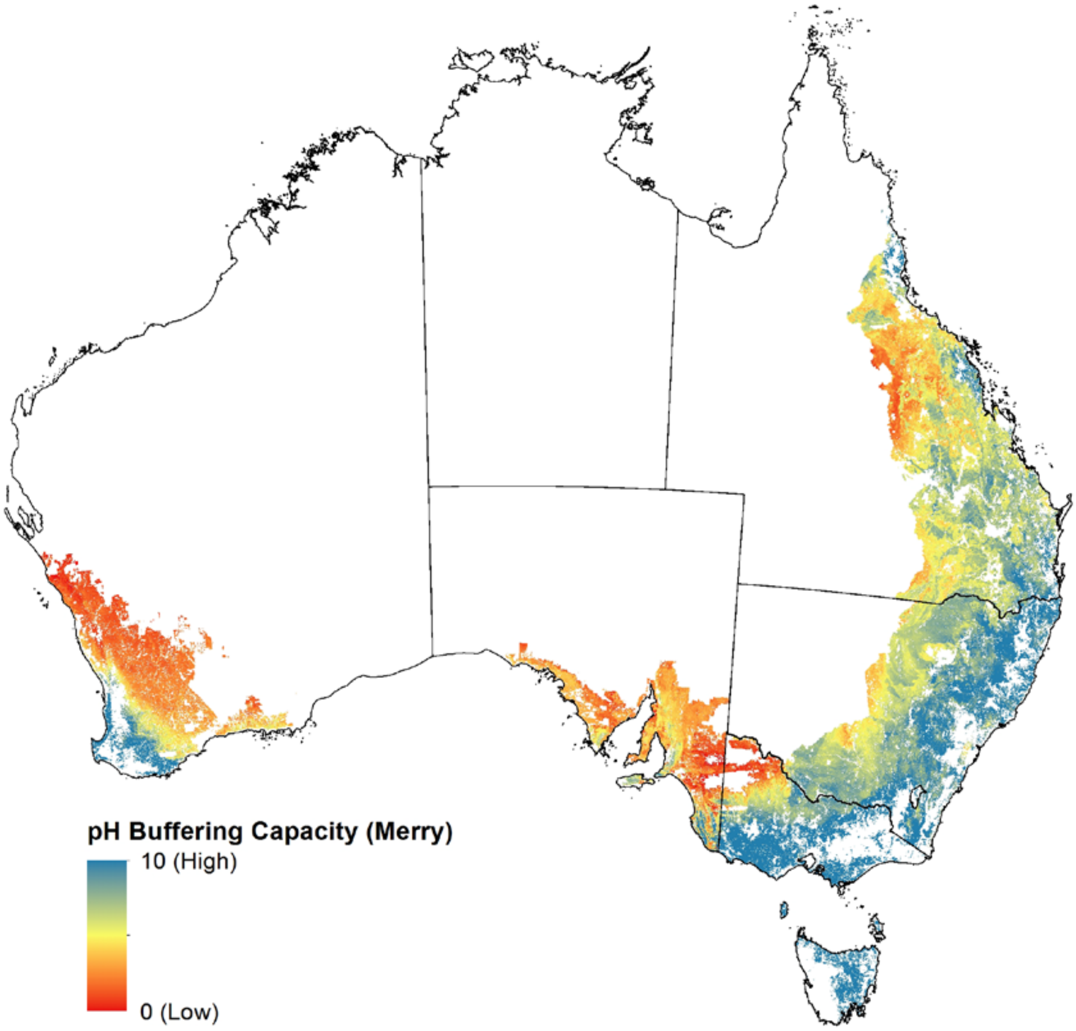

Figure 2.3: pHBC map of the 0 to 0.05 m layer (estimates for deeper layers were also used to calculate lime requirements).

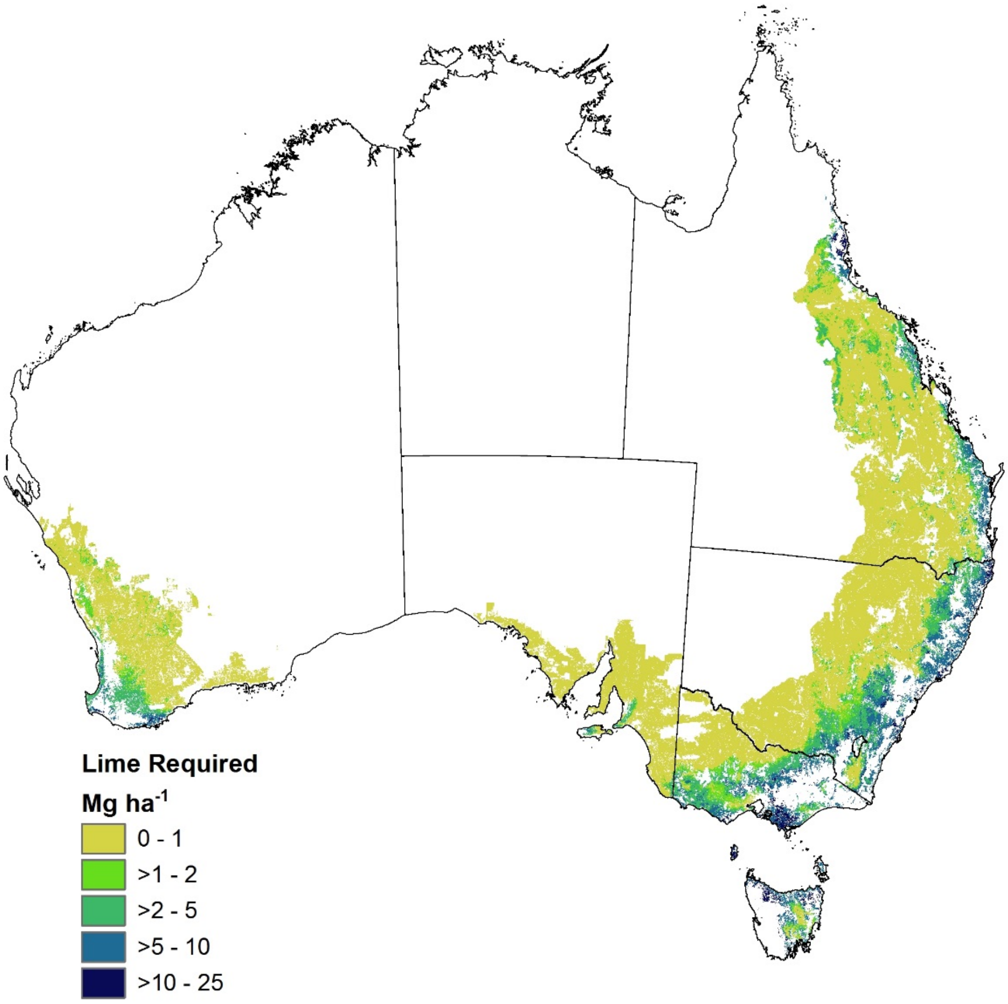

Figure 2.4: Lime required (Mg ha^{-1}) to increase the pH to 5.5 down to 0.60m if the current pH of any layer is less than 5.5. Such tonnages are unlikely to be applied at one time to ameliorate acidification because the economically optimal rate will be less. However, the map provides an indication of the distribution and intensity of acidification. Note that some areas are known to be underestimated (see Figures 2.12 to 2.14).

2.4 Pressures

The Net Acid Addition Rate (NAAR) and the associated maintenance lime requirement (MLR) are convenient measures of the pressures that cause acidification. The MLR is the amount of lime required to keep the soil pH at its current value (i.e. the amount required to neutralize the Net Acid Addition Rate (NAAR).

Despite its apparent simplicity, complex processes determine the NAAR at any given location in the landscape. As noted earlier, the main factors controlling the NAAR are:

- the rate at which alkalinity is lost because of product removal
- the application of some forms of nitrogen fertiliser
- the rate of biological nitrogen fixation
- leaching (both within and beyond the profile).

As a consequence, any spatial analysis of the NAAR requires detailed information on land management. A simple ranking of NAAR is presented in Table 2.2 and each class of the Australian

Land Use and Management Classification was given a provisional rank based on the information compiled by Baldock et al. (2010, Appendix 4) (Table 2.3).

Improvements to this very coarse measure of NAAR are planned and they will draw on the more detailed land management information compiled by Unkovich and Baldock (in press). These improved estimates will be spatially weighted averages for land management classes (defined by the Australian Land Use and Management Classification) compiled for Statistical Areas at the SA2 level. These will be supported by improved estimates of pasture production, crop yield, nitrogen use and nutrient balances. While the updated estimates provide an improved input to the analysis, further refinement is still required.

Table 2.2: Ranking system for Net Acid Addition Rate.

Ranking	Descriptor	NAAR Range ($Mg\ CaCO_3\ ha^{-1}yr^{-1}$)
1	Very Low	0.000–0.050
2	Low	0.051–0.100
3	Moderate	0.101–0.200
4	High	0.201–0.400
5	Very High	>0.4

Table 2.3: Provisional NAAR ranking for the relevant classes of the Australian Land Use and Management Classification. Some extensive classes will vary according to local rates of nutrient input and product removal (e.g. Class 3.3.1 may have a high (4) rather than a moderate (3) ranking in districts where N-fertiliser use has increased in recent years). Rankings for forested lands are included (based on Baldock et al. (2010), Appendix Four) for completeness but these lands are excluded from the spatial analysis presented below.

Land-Use Code	Land use and management	NAAR Ranking	Land-Use Code	Land use and management	NAAR Ranking
2	Production from Relatively Natural Environments		4	Production from Irrigated Agriculture and Plantations	
2.1.0	Grazing native vegetation	1	4.1.0	Irrigated plantation forests	2
2.2.0	Production native forests	1	4.1.1	Irrigated hardwood plantation forestry	2
2.2.1	Wood production forestry	1	4.1.2	Irrigated softwood plantation forestry	2
2.2.2	Other forest production	1	4.1.3	Irrigated other forest plantation	2
3	Production from Dryland Agriculture and Plantations		4.1.4	Irrigated environmental forest plantation	1
3.1.0	Plantation forests	1	4.2.0	Grazing irrigated modified pastures	4

Land-Use Code	Land use and management	NAAR Ranking	Land-Use Code	Land use and management	NAAR Ranking
3.1.1	Hardwood plantation forestry	1	4.2.1	Irrigated woody fodder plants	3
3.1.2	Softwood plantation forestry	1	4.2.2	Irrigated pasture legumes	5
3.1.3	Other forest plantation	1	4.2.3	Irrigated legume/grass mixtures	4
3.1.4	Environmental forest plantation	1	4.2.4	Irrigated sown grasses	4
3.2.0	Grazing modified pastures	3	4.3.0	Irrigated cropping	4
3.2.1	Native/exotic pasture mosaic	2	4.3.1	Irrigated cereals	4
3.2.2	Woody fodder plants	2	4.3.2	Irrigated beverage and spice crops	3
3.2.3	Pasture legumes	4	4.3.3	Irrigated hay and silage	4
3.2.4	Pasture legume/grass mixtures	3	4.3.4	Irrigated oilseeds	4
3.2.5	Sown grasses	3	4.3.5	Irrigated sugar	4
3.3.0	Cropping	3	4.3.6	Irrigated cotton	3
3.3.1	Cereals	3	4.3.7	Irrigated alkaloid poppies	3
3.3.2	Beverage and spice crops	3	4.3.8	Irrigated pulses	4
3.3.3	Hay and silage	4	4.3.9	Irrigated rice	4
3.3.4	Oilseeds	3	4.4.0	Irrigated perennial horticulture	3
3.3.5	Sugar	3	4.4.1	Irrigated tree fruits	3
3.3.6	Cotton	3	4.4.2	Irrigated olives	3
3.3.7	Alkaloid poppies	3	4.4.3	Irrigated tree nuts	5
3.3.8	Pulses	3	4.4.4	Irrigated vine fruits	4
3.4.0	Perennial horticulture	3	4.4.5	Irrigated shrub berries and fruits	4
3.4.1	Tree fruits	2	4.4.6	Irrigated perennial flowers and bulbs	4
3.4.2	Olives	2	4.4.7	Irrigated perennial vegetables and herbs	4
3.4.3	Tree nuts	4	4.4.8	Irrigated citrus	4

Land-Use Code	Land use and management	NAAR Ranking	Land-Use Code	Land use and management	NAAR Ranking
3.4.4	Vine fruits	3	4.4.9	Irrigated grapes	4
3.4.5	Shrub berries and fruits	3	4.5.0	Irrigated seasonal horticulture	3
3.4.6	Perennial flowers and bulbs	3	4.5.1	Irrigated seasonal fruits	3
3.4.7	Perennial vegetables and herbs	3	4.5.2	Irrigated seasonal flowers and bulbs	3
3.4.8	Citrus	4	4.5.3	Irrigated seasonal vegetables and herbs	3
3.4.9	Grapes	3	4.5.4	Irrigated turf farming	3
3.5.0	Seasonal Horticulture	3	4.6.0	Irrigated land in transition	1
3.5.1	Seasonal fruits	3	4.6.1	Degraded irrigated land	1
3.5.2	Seasonal flowers and bulbs	3	4.6.2	Abandoned irrigated land	1
3.5.3	Seasonal vegetables and herbs	3	4.6.3	Irrigated land under rehabilitation	1
			4.6.4	No defined use – irrigation	1
			4.6.5	Abandoned irrigated perennial horticulture	1

The MLR is simply the NAAR divided by the neutralizing value of the liming product to ensure the whole of the NAAR is offset. The neutralizing value of applied lime is affected by the particle size, solubility and purity of the lime. As noted earlier, a conservative value of 85% was used (based on Upjohn et al. 2005).

$$MLR = NAAR \times \frac{100}{NV} \qquad [2.3]$$

The map of NAAR rankings is presented in Figure 2.5.

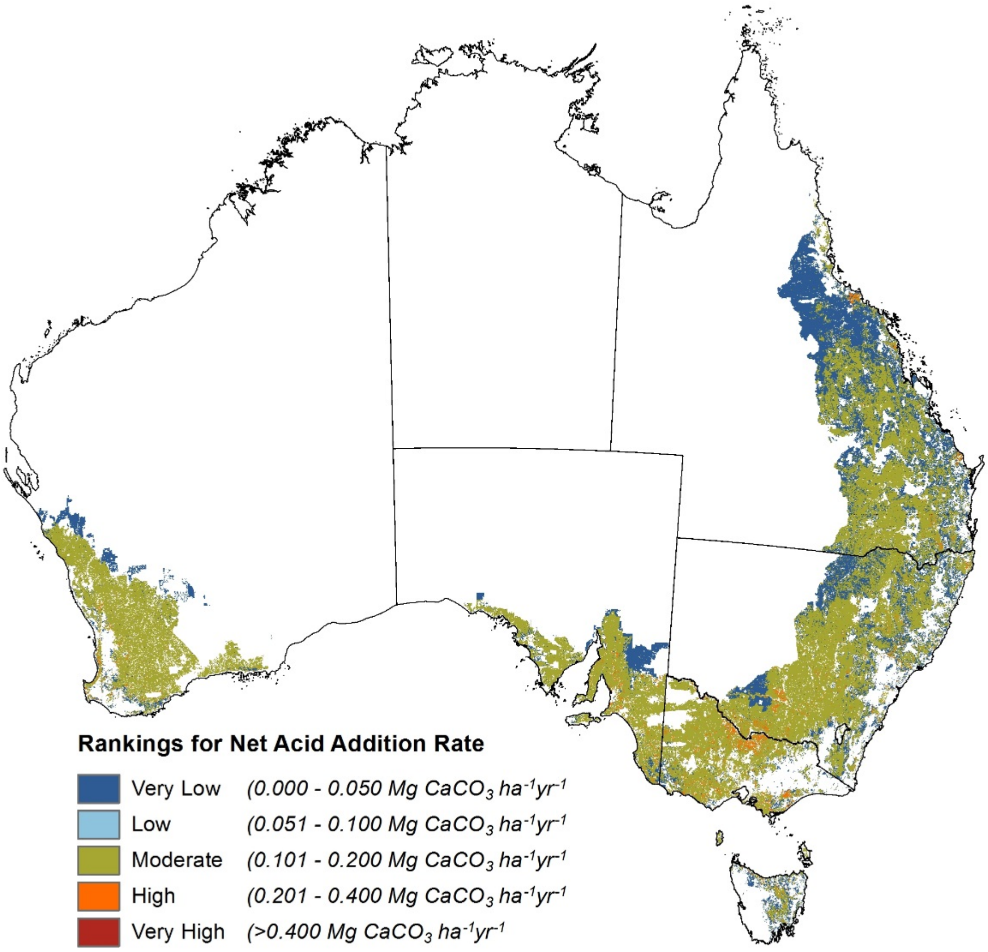

Figure 2.5: Map of rankings for the Net Acid Addition Rate using the classes presented in Table 2.2 and a provisional ranking of ALUM classes (see Table 2.3). These will be updated using Unkovich and Baldock (in press).

An index of the risk of soil acidification based only on soil characteristics and current land use has been calculated using the following indicators.

- Lime requirements (LR, scaled 0 to 1) – calculated using the current pH and buffering capacity (see Figure 2.4).
- The likely NAAR – estimated using the classes defined in Table 2.3 and mapped using the Australian Land Use and Management Classification (Table 2.4) (the five-level ranking has been scaled 0 to 1) (see Figure 2.5)

These two indices were classified according to Table 2.4 and the resulting map is shown in Figure 2.6.[8] Soil acidification is likely to be a problem in areas with a high risk ranking. This is useful for framing priorities for interventions but the map provides no information on the effectiveness of current land management. This important consideration is much harder to determine and a first approximation is attempted in the following sections.

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[8] This figure provides the basis for the map “A ranking of soil acidification risk for agricultural lands” for the Regional Partnerships App on the National Landcare Program website (http://www.nrm.gov.au/national-landcare-program).

Table 2.4: Risk ranking for acidification based on a cross-classification of the estimated lime requirements and the estimated Net Acid Addition Rate of current land use.

Lime Requirement (Mg/ha)	**Net Acid Addition Rate (Mg $CaCO_3$ /ha/yr)**				
	Very Low 0.00–0.05	Low >0.05–0.10	Moderate 0.00–0.05	High 0.20–0.40	Very High >0.40
>10–25	H	H	H	H	H
>5–10	M	H	H	H	H
>2–5	L	M	H	H	H
>1–2	L	L	M	H	H
>0–1	L	L	M	M	M

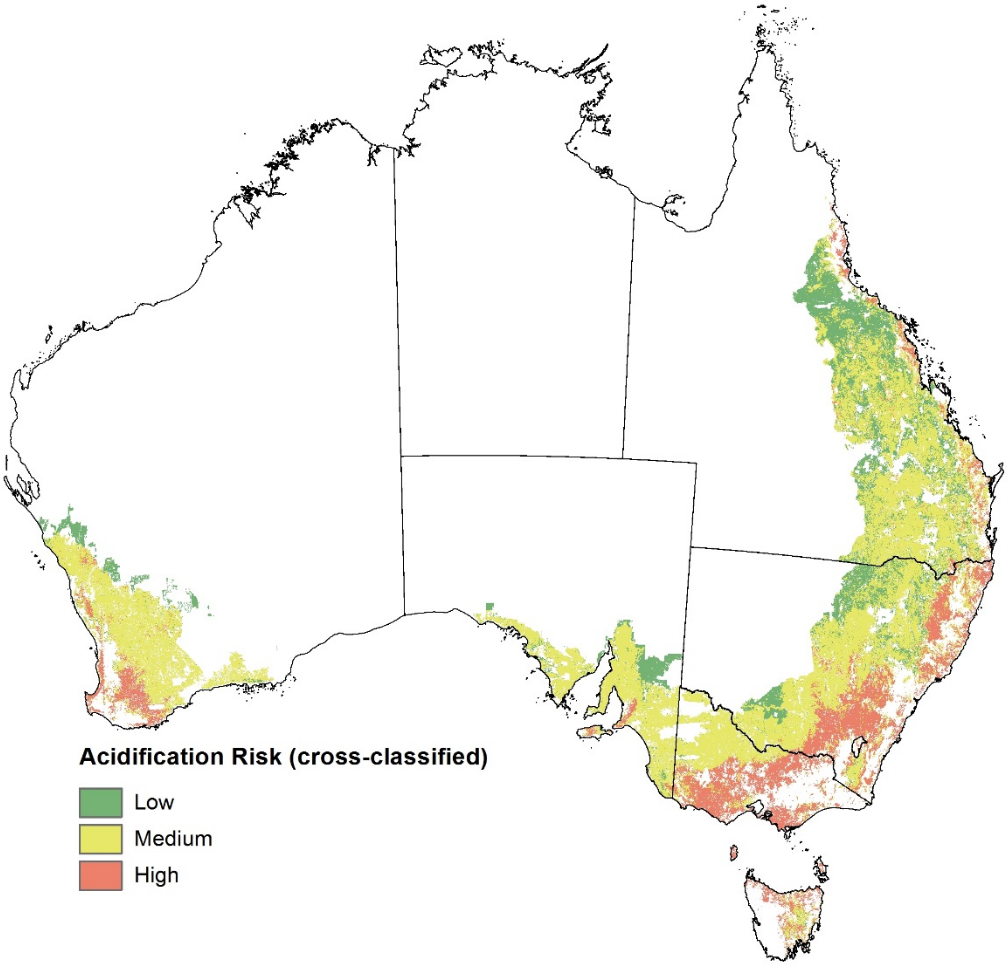


Figure 2.6: Areas where soil acidification is likely to be a problem based on the cross-classification in Table 2.4 of estimated lime requirements and net acid addition rates of current land uses.

2.5 Responses: the effectiveness of land management

Two simple albeit incomplete measures of the response to acidification and its effectiveness are the rates of soil testing and the actual rates of lime application. Both of these measures can be derived from ABS statistics but they need to be interpreted with caution. Some of the more important constraints on interpretation are caused by the following.

- The statistics on both indicators are from seven years ago and since then awareness of soil acidification has most likely increased because of active research and extension programs, especially in Western Australia, South Australia and more recently, New South Wales.
- The area of canola grown across southern Australia has increased substantially from 1.695Mha in 2009-2010 to 2.897Mha in 2014-2015 (ABARES 2016b). Lime application is a routine input in canola production in some but not all districts because of the crop's sensitivity to soil acidity. As a consequence, amelioration of soil acidity is effectively underway in these areas.
- Soil testing is an imperfect indicator of farmer awareness for a range of reasons. Farmers may have access to other sources of information on their farms or they may have information from soil testing undertaken outside the period for which there are reliable statistics. These issues and more are considered in detail by Lobry de Bruyn and Andrews (2016) in their review of farmer practices in Australia and the United States.

The rates of soil testing (ST) derived from ABS statistics are presented in Figure 2.7.

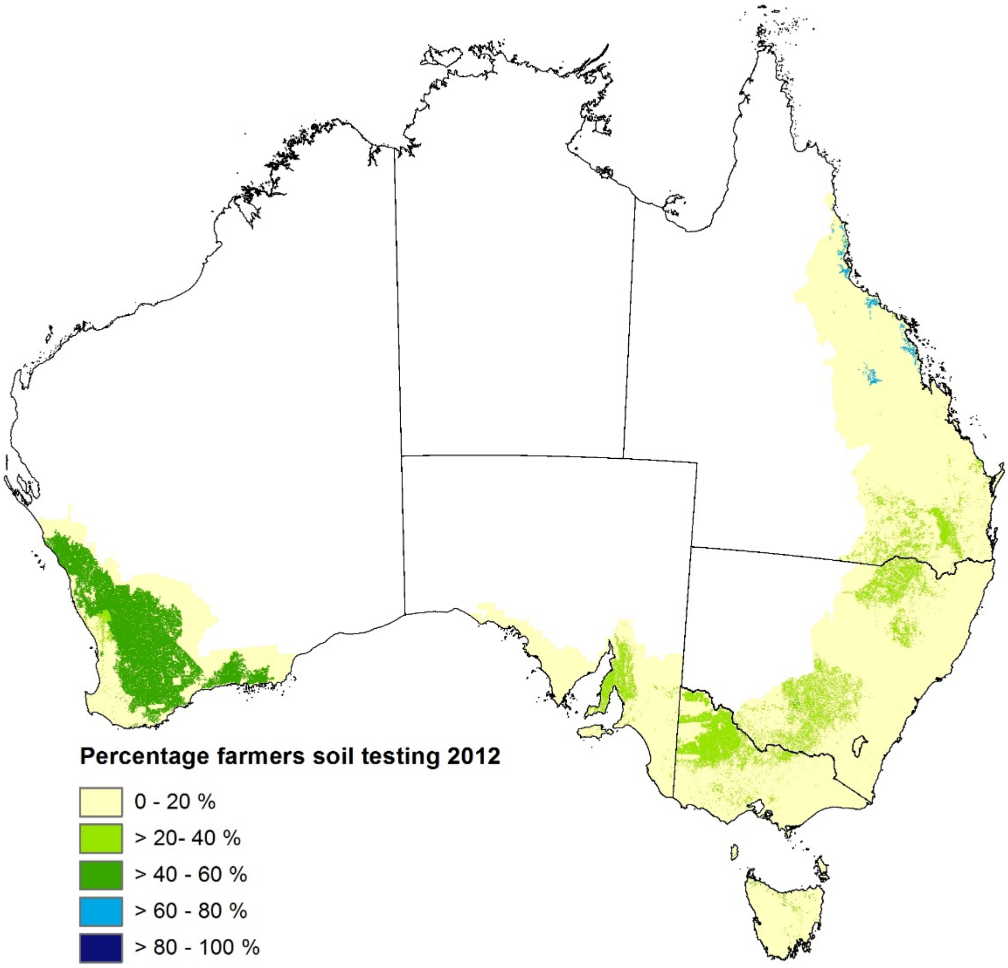


Figure 2.7: Rates of soil testing derived from the Agricultural Census.

The actual rates of lime application are difficult to determine for most parts of Australia. The most reliable data are for SW Western Australia (Gazey et al. 2013 and Gazey pers. comm.) and South Australia. Summaries are shown in Figures 2.8 and 2.9 and they have been compiled from several sources and multiple lines of evidence have been used to arrive at the final figures. Statistics on national rates of lime application have been produced by the ABS but the constraints on interpretation noted earlier made it difficult to generate a useful national map.

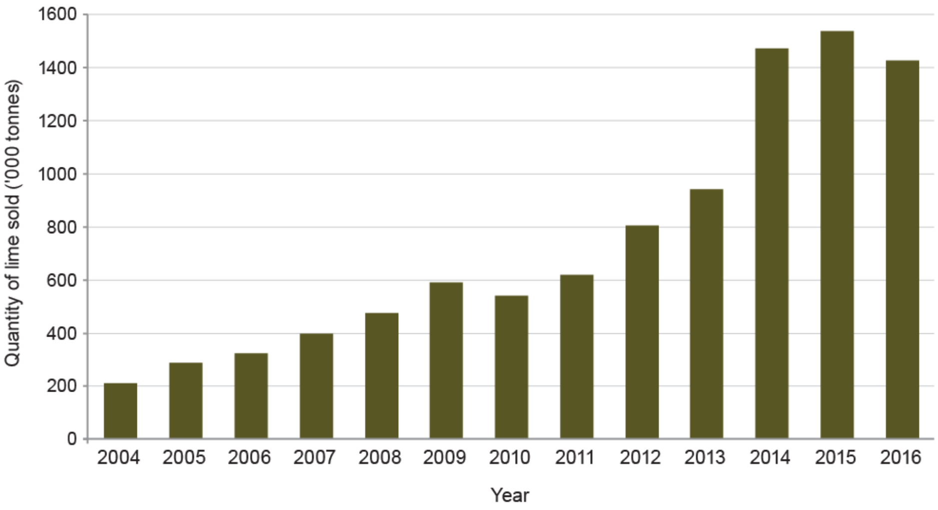


Figure 2.8: Estimated lime application in Western Australia to treat acidifying soils - rates from the last three years are still only 60% of the amount required to balance the estimated acidification rate (Lime WA Inc, SOE 2016, DAFWA (2013)).

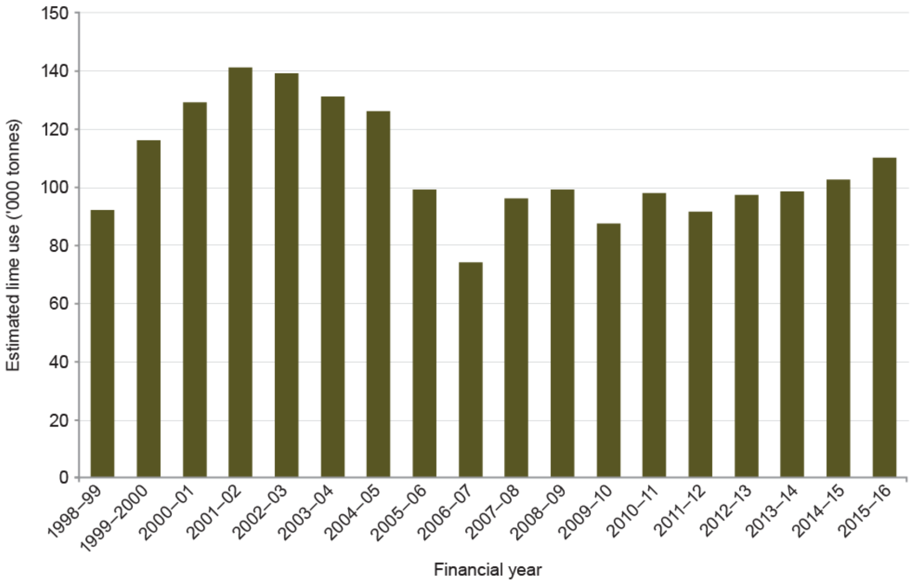


Figure 2.9: Estimated lime application on agricultural land in South Australia - the average rate over the last decade is just under 50% of the amount required to balance the estimated soil acidification rate (Government of South Australia 2015, SoE 2016). Note the large difference in magnitude compared to Figure 2.8.

2.6 Current and emerging risks

Risk involves an estimate of both likelihood and consequence of something happening. In this case, soil acidification that leads to a loss of agricultural productivity and environmental impact. The likelihood of acidification becoming a serious problem needs to take into account the adequacy of current rates of lime application, the level of farmer awareness and the net acid addition rate. As noted above, the rate of soil testing could be used as an indicator of farmer awareness acknowledging that it is an imperfect and incomplete measure. The gross value of agricultural production (GVAP, ABS 2011) could also be used as a proxy for the value of the asset and the consequence of acidification. Figure 2.10 shows the gross value of agricultural production for each NRM region on a per unit area basis. Most regions with a large GVAP also have a significant risk of acidification.

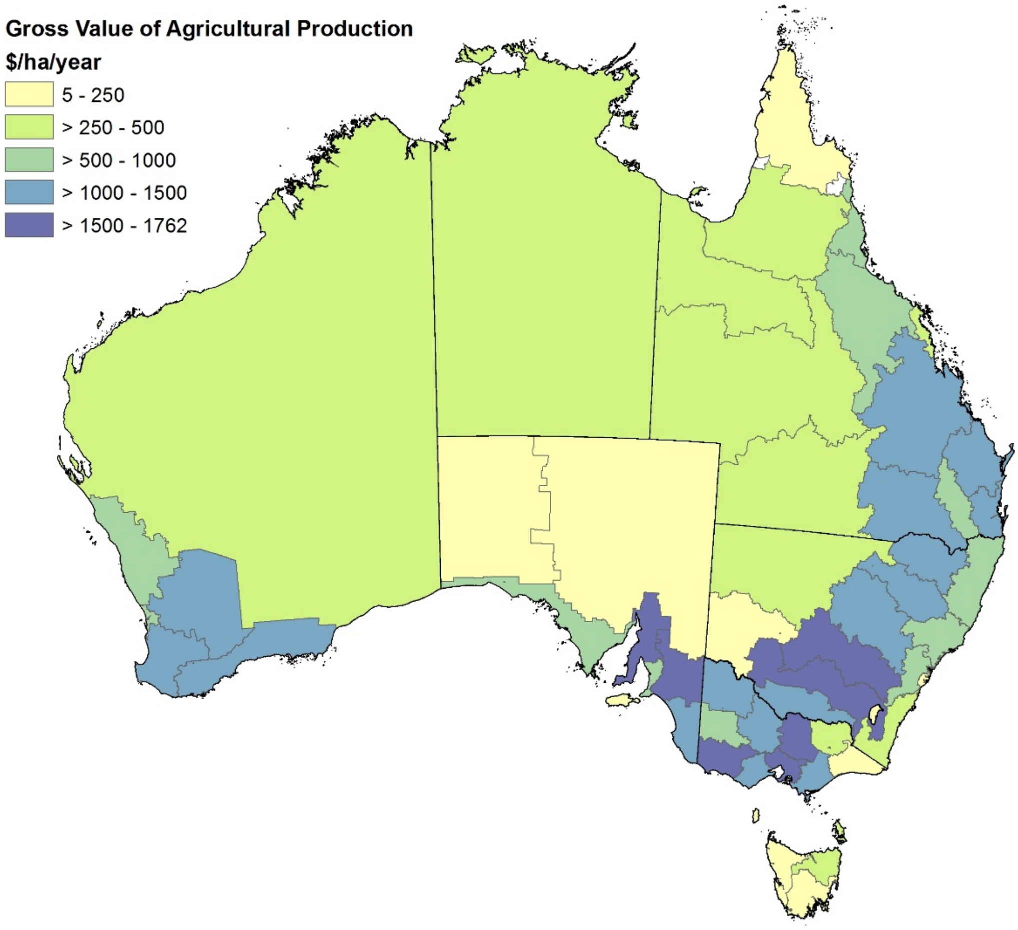


Figure 2.10: The gross value of agricultural production provides a proxy measure of the value of the overall asset potentially affected by soil acidification (ABS 2011).

We investigated whether risk could be estimated using the following indicators.

- Lime requirements (LR, scaled 0 to 1) – calculated using the current pH and buffering capacity (see Figure 2.4).
- Current lime application rates (LA, scaled 0 to 1) – derived from ABS data (SD2 by land use)
- Rates of soil testing (ST, scaled 0 to 1) – derived from ABS data (SD2 by land use)
- The likely NAAR - estimated using the classes defined in Table 2.3 and mapped using the Australian Land Use and Management Classification (Table 2.4 and Figure 2.5) (scaled 0 to 1)
- Gross value of agricultural production (GVA, scaled 0 to 1) – derived from ABS data (SD2 by land use) (Figure 2.10).

These five indices can be combined using the following equation to provide an overall index for the risk of acidification.

$$Overall\ risk\ ranking = \frac{1}{4}\left[(LR - LA) + (1 - ST) + NAAR + GVA\right] \qquad [2.4]$$

The overall risk index (scaled 0 to 1) would be highest when there is a large gap between the lime required and current application rates, soil testing is low, NAAR is high, and the value of production is large. However, the lack of reliable data on both soil testing (specifically for the amelioration of acidification) and district-level rates of lime application, meant that the analysis added little compared to the ranking shown in Figure 2.6. As an alternative, the results in Figure 2.6 were used in conjunction with published literature (particularly NLWRA 2001, SoE 2011, SoE 2016, DAFWA 2013) and advice from experts (see next section) to prepare the qualitative rankings for NRM regions shown in Figure 2.11.

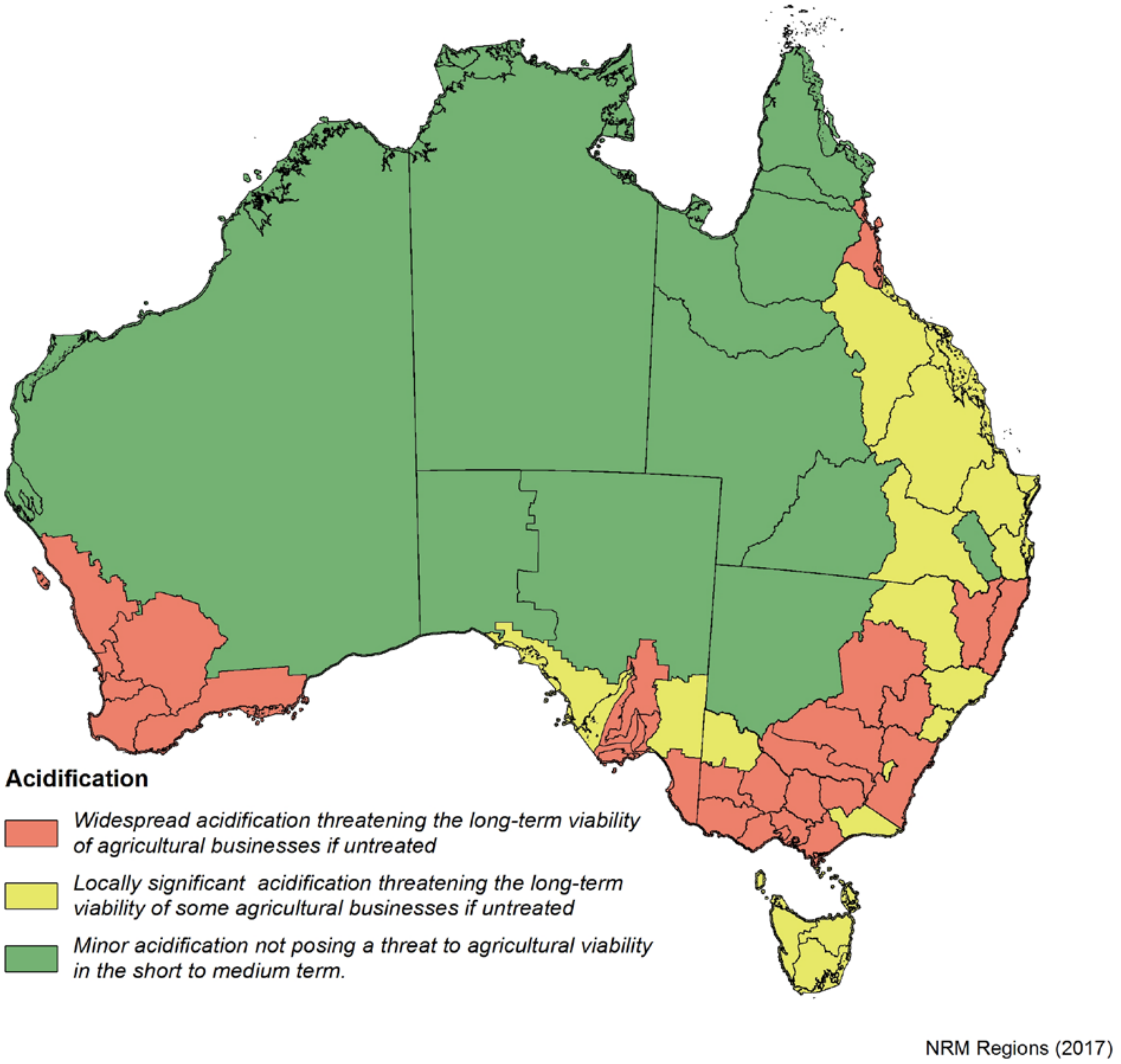


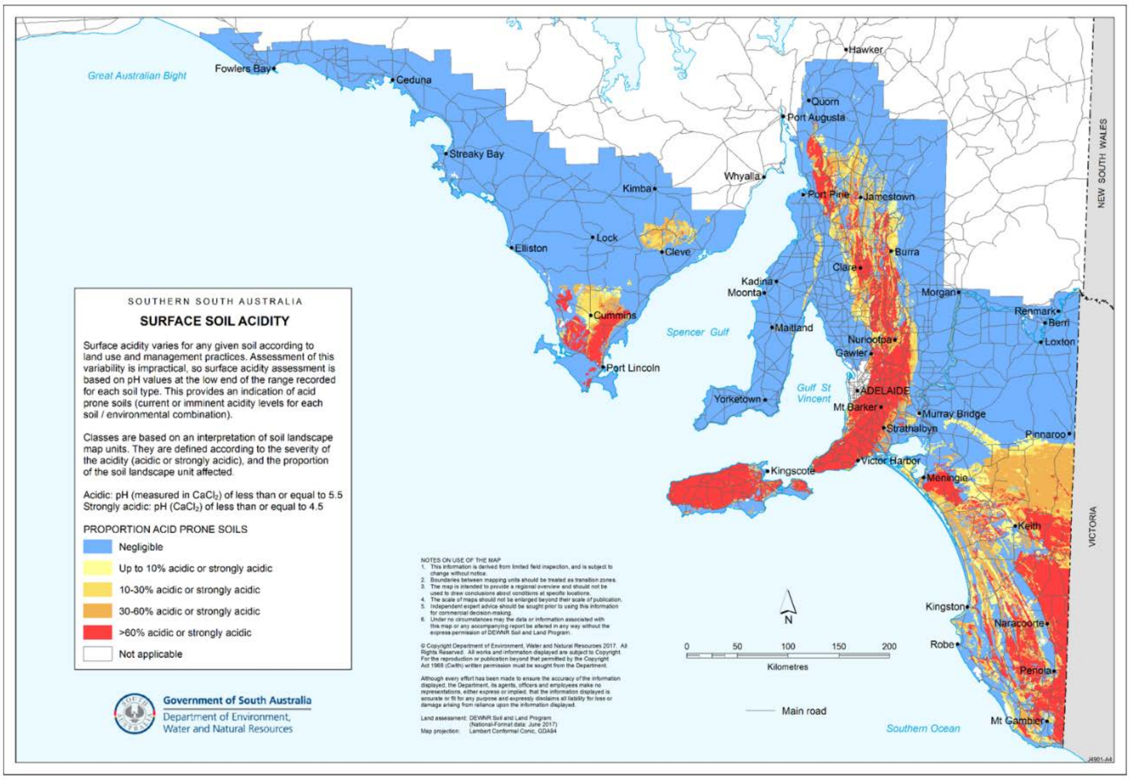
Figure 2.11: Ranking of acidification risk based on Figure 2.6 and published scientific literature.

2.7 Limitations of the analysis

The release of the Soil and Landscape Grid of Australia (Grundy et al. 2015) has enabled a more consistent continental-scale analysis of acidification (e.g. improved estimation of pH buffering capacity and lime requirements). The Grid was developed using the best publicly available data (over 300,000 point observations) although a significant proportion of these data had been collected more than a decade before. Unfortunately, there was no way of readily accessing the large quantities of data collected privately during the last decade (more than one hundred thousand soil tests are undertaken annually by commercial soil testing services in Australia (Dave Lyons, pers. comm.)). While there is a high degree of consensus that the Grid provides a much better understanding of soil properties across the continent, recent updates from several jurisdictions (primarily South Australia, Western Australia and the Northern Territory) bring into sharp relief the limitations of the analysis presented above. In particular, the lack of contemporary data on subsoil pH in agricultural lands (except in South Australia and Western Australia) are a major impediment to assessing acidification risks and trends.

2.7.1 South Australia

The South Australian Government updated its spatial analysis of soil acidification in mid-2017. Figures 2.12 and 2.13 show the current extent of acidic and strongly acidic soils across the agricultural lands of the state. Most notable is the much greater extent of acid soils in the northern and southern eastern agricultural areas than shown in Figure 2.2. More significant though is the future acidification potential shown in Figure 2.14 (the time frame being 10-50 years from 2015). These new results are based on recent experimental results, soil testing, updated estimates of the Net Acid Addition Rate and a thorough understanding of land management practices.



SOUTHERN SOUTH AUSTRALIA

SURFACE SOIL ACIDITY

Surface acidity varies for any given soil according to land use and management practices. Assessment of this variability is impractical, so surface acidity assessment is based on pH values at the low end of the range recorded for each soil type. This provides an indication of acid prone soils (current or imminent acidity levels for each soil / environmental combination).

Classes are based on an interpretation of soil landscape map units. They are defined according to the severity of the acidity (acidic or strongly acidic), and the proportion of the soil landscape unit affected.

Acidic: pH (measured in $CaCl_2$) of less than or equal to 5.5
Strongly acidic: pH ($CaCl_2$) of less than or equal to 4.5

PROPORTION ACID PRONE SOILS

- 🟦 Negligible
- 🟨 Up to 10% acidic or strongly acidic
- 🟨 10-30% acidic or strongly acidic
- 🟧 30-60% acidic or strongly acidic
- 🟥 >60% acidic or strongly acidic
- ☐ Not applicable

NOTES ON USE OF THE MAP
1. This information is derived from limited field inspection, and is subject to change without notice.
2. Boundaries between mapping units should be treated as transition zones.
3. The map is intended to provide a regional overview and should not be used to draw conclusions about conditions at specific locations.
4. The scale of maps should not be enlarged beyond their scale of publication.
5. Independent expert advice should be sought prior to using this information for commercial decision-making.
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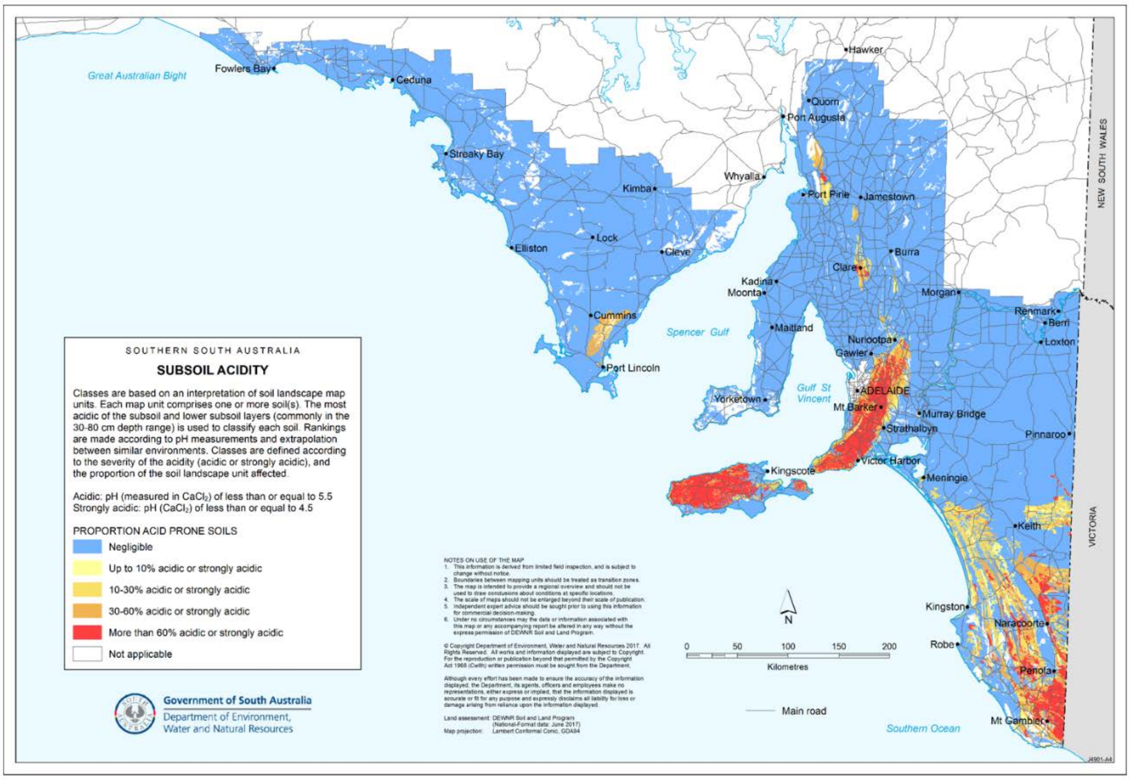
Land assessment: DEWNR Soil and Land Program
(National-Format data: June 2017)
Map projection: Lambert Conformal Conic, GDA94

Figure 2.12: Updated assessment of the extent of surface soil acidity across the agricultural lands of South Australia.



SOUTHERN SOUTH AUSTRALIA

SUBSOIL ACIDITY

Classes are based on an interpretation of soil landscape map units. Each map unit comprises one or more soil(s). The most acidic of the subsoil and lower subsoil layers (commonly in the 30-80 cm depth range) is used to classify each soil. Rankings are made according to pH measurements and extrapolation between similar environments. Classes are defined according to the severity of the acidity (acidic or strongly acidic), and the proportion of the soil landscape unit affected.

Acidic: pH (measured in $CaCl_2$) of less than or equal to 5.5
Strongly acidic: pH ($CaCl_2$) of less than or equal to 4.5

PROPORTION ACID PRONE SOILS

- 🟦 Negligible
- 🟨 Up to 10% acidic or strongly acidic
- 🟨 10-30% acidic or strongly acidic
- 🟧 30-60% acidic or strongly acidic
- 🟥 More than 60% acidic or strongly acidic
- ☐ Not applicable

NOTES ON USE OF THE MAP
1. This information is derived from limited field inspection, and is subject to change without notice.
2. Boundaries between mapping units should be treated as transition zones.
3. The map is intended to provide a regional overview and should not be used to draw conclusions about conditions at specific locations.
4. The scale of maps should not be enlarged beyond their scale of publication.
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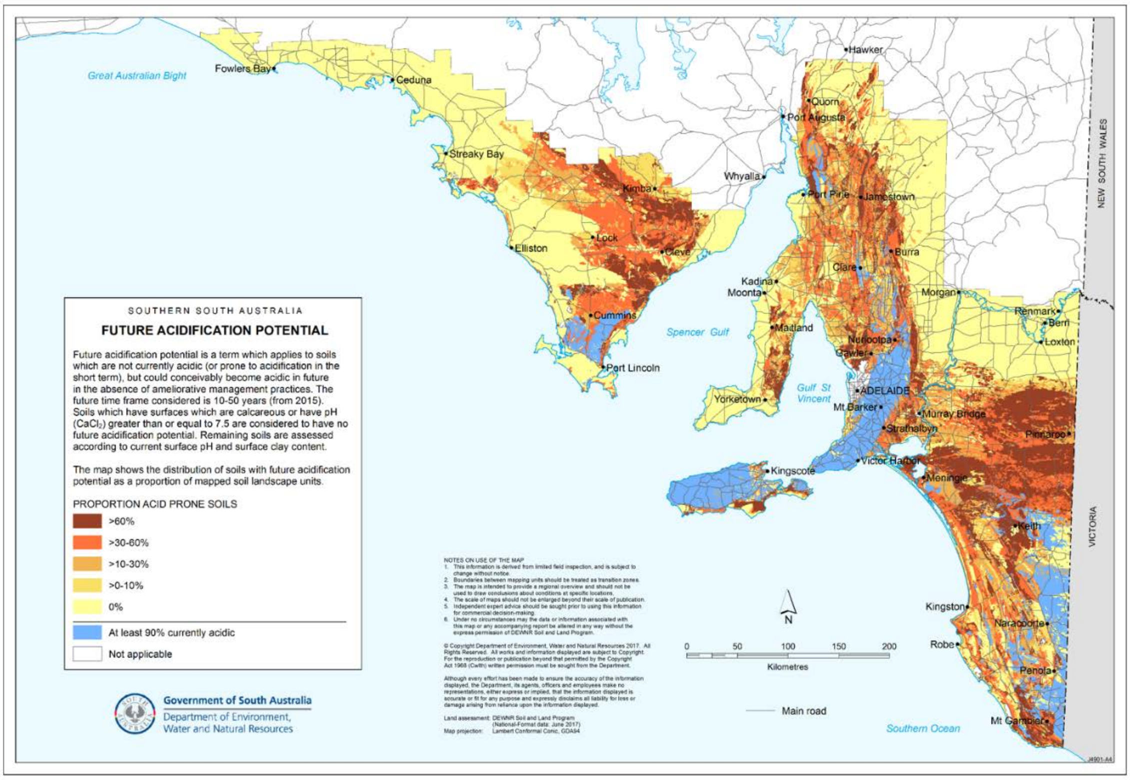
Land assessment: DEWNR Soil and Land Program
(National-Format data: June 2017)
Map projection: Lambert Conformal Conic, GDA94

Figure 2.13: Updated assessment of the extent of subsoil (0.3-0.8m) acidity across the agricultural lands of South Australia.



SOUTHERN SOUTH AUSTRALIA

FUTURE ACIDIFICATION POTENTIAL

Future acidification potential is a term which applies to soils which are not currently acidic (or prone to acidification in the short term), but could conceivably become acidic in future in the absence of ameliorative management practices. The future time frame considered is 10-50 years (from 2015). Soils which have surfaces which are calcareous or have pH ($CaCl_2$) greater than or equal to 7.5 are considered to have no future acidification potential. Remaining soils are assessed according to current surface pH and surface clay content.

The map shows the distribution of soils with future acidification potential as a proportion of mapped soil landscape units.

PROPORTION ACID PRONE SOILS

- 🟫 >60%
- 🟧 >30-60%
- 🟧 >10-30%
- 🟨 >0-10%
- 🟨 0%
- 🟦 At least 90% currently acidic
- ☐ Not applicable

NOTES ON USE OF THE MAP
1. This information is derived from limited field inspection, and is subject to change without notice.
2. Boundaries between mapping units should be treated as transition zones.
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Land assessment: DEWNR Soil and Land Program
(National-Format data: June 2017)
Map projection: Lambert Conformal Conic, GDA94

Figure 2.14: Estimated future acidification potential across the agricultural lands of South Australia.

2.7.2 Western Australia

Gazey et al. (2013), on the basis of extensive new data, demonstrated the extent of surface and subsoil acidification was much greater than previously thought. Between 2005 and 2012 a total of 161 000 samples were collected from over 93 000 sites to determine soil pH status and trend. More sampling has occurred since then but the results shown here are from the initial phase. Figure 2.15 shows the proportion of samples below the nominated targets for Western Australia for the surface layer (0–10 cm) of pH_{Ca} 5.5 (desired target) and pH_{Ca} 5.0 (critical threshold). Soil acidity is widespread and extreme in many areas of the southwest of Western Australia, particularly in sandy soils. Surface soil pH can be increased to above target (pH_{Ca} 5.5) over significant areas with the application of one to three tonnes per hectare of good quality lime.

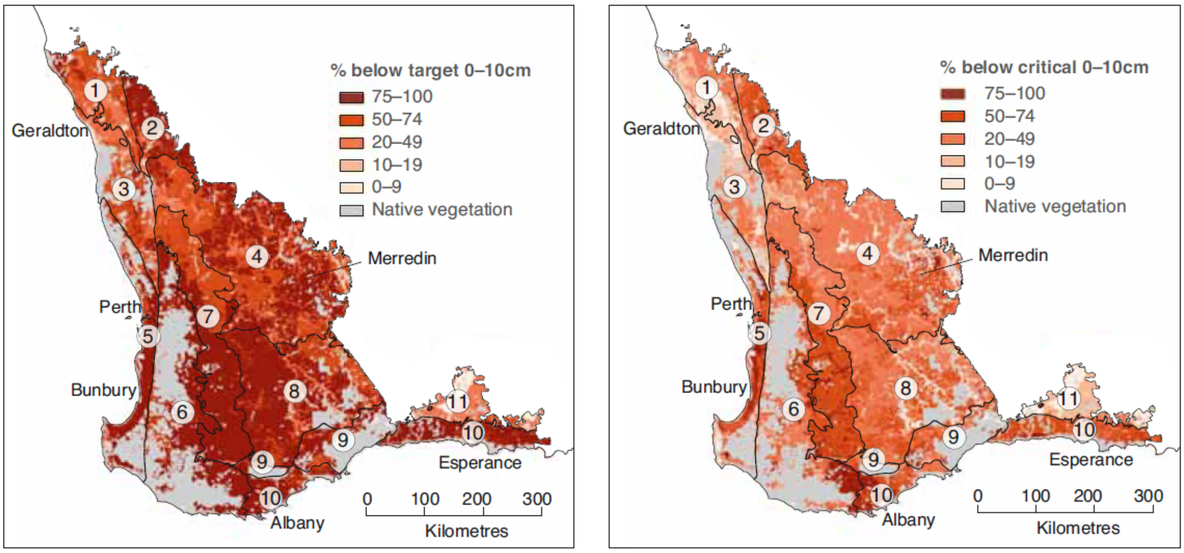


Figure 2.15: Percentage of sites sampled (2005–12) with soil pH at 0–10 cm depth below the established target of pH_{Ca} 5.5 (left) and the critical pH_{Ca} 5.0 (right). Grey indicates native vegetation and reserves (Gazey et al. 2013).

2.7.3 Conclusions

Several important conclusions can be drawn from Figures 2.12 to 2.15.

1. The extent and severity of soil acidification in South Australia is much greater than previous assessments have indicated (including that presented earlier in this section)
2. The Australian Soil and Landscape Grid is underestimating the extent and degree of soil acidification, particularly subsoil acidification, because of outdated data.
3. The intensification of cropping, and in particular the increase in nitrogen fertiliser usage and product removal, combined with inadequate liming, are causing significant acidification across large areas that were previously considered to be unaffected.
4. There is every reason to expect that a similar situation exists across the agricultural lands of Victoria, New South Wales and coastal Queensland, particularly with respect to subsoil acidification.

2.8 Possible interventions

2.8.1 Extension

While the scale and extent of soil acidification is large, Figures 2.8 and 2.9 contain an encouraging message. In both Western Australia and South Australia, the rates of lime usage have increased significantly during the periods when a concerted research, development and extension effort has been underway. Figure 2.16 provides further evidence that such efforts are worthwhile. These results are testimony to the quality of the advisors and the effectiveness of their work. Liming and the amelioration of soil acidity are often deferred by farmers because other and more immediate management activities need to be financed (e.g. herbicide, fertilisers, seed). Liming needs to be viewed as a regular servicing of the soil system to maintain soil health, productivity and ecosystem function. Conveying this message has been an important part of successful extension programs. Likewise, communicating the economic risks associated with subsoil acidification has also been critical. Finally, a feature of successful programs has been the establishment of convincing field experiments and liming trials.

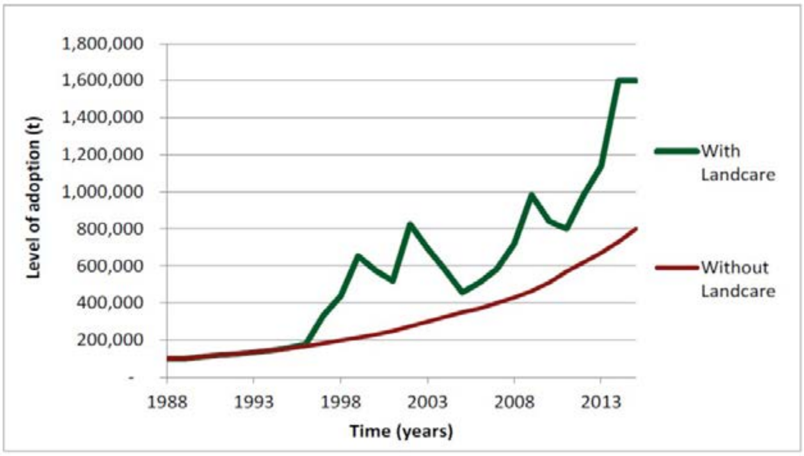


Figure 2.16: The level of adoption of liming has increased in Western Australia because of previous NLP investments into extension activities (Natural Decisions 2015).

A key intervention is therefore to ensure that high-quality and long-term extension activities are supported in all districts where soil acidification is likely to be a threat to soil function. Figure 2.11 provides the starting point for identifying these districts.

2.8.2 Lime-supply systems

Figures 2.8 and 2.9 also provide evidence on progress to date in dealing with the soil acidification in Western Australia and South Australia. The large shortfall in lime application against the target level for maintaining soil pH highlights the scale of the task ahead. The logistics and infrastructure required to supply sufficient lime are significant. Similar summaries are not available for other states but they should be developed as a matter of priority. Regular reporting on where and how much lime is being applied is an essential measure for tracking progress.

2.8.3 Monitoring

There have been repeated calls to establish a soil monitoring system for soil acidification in Australia (e.g. McKenzie et al. 2002, Baldock et al. 2010). While some jurisdictions have established partial networks, in most cases only the initial baseline measurements of soil properties have been completed. More significantly, most existing soil monitoring sites do not have an associated detailed monitoring of land management but this is crucial for understanding soil acidification (e.g. to enable calculation of the NAAR). The highest priority intervention should therefore be to establish a comprehensive network of monitoring sites across the agricultural lands at greatest risk, particularly with respect to subsoil acidification. The design of the network should build on the proposals that have been prepared by the National Committee on Soil and Terrain.

A second potential intervention is to create incentives for private-sector soil testing and advisory services to help them develop efficient field sampling and sensor systems for rapidly measuring soil pH. The collaborative public and private soil testing programs in Western Australia provide an excellent template for programs elsewhere. These monitoring systems should also feed data to update the Australian Soil and Landscape Grid so that it provides better contemporary information services for detection and response.

2.8.4 Research and development

As was noted earlier, a priority need is to improve the estimation of the pHBC and the Net Acid Addition Rate (NAAR) for common land management systems across Australia. This is a key input to improve the quality and local applicability of advisory services relating to soil acidification. These services also need to incorporate economic analyses of potential liming strategies.

Perhaps the most striking feature of research and development into soil acidification over the last 30 years has been its cycle of booms and busts. Most of the scientists involved in the peak of activity associated with the Soil Acidification Program managed by Land and Water Research and Development Corporation in the 1990s have retired or moved to different roles. The GRDC is investing in regional soil acidification activities at present but a broader program across industries and jurisdictions is required. The recurrent loss of expertise across industries and jurisdictions appears to be a significant factor that prevents Australia from dealing with a threat to soil function that should have been solved decades ago.

3 Soil carbon

3.1 Introduction

Arresting declines and increasing the stock of soil organic carbon content (SOC) in managed Australian soils has the potential to maintain or enhance their resilience, sustainability and productivity as well as provide opportunities to mitigate national greenhouse gas emissions. Soil organic carbon and the associated elements in soil organic matter (e.g. O, H, N, P and S) have a beneficial effect on a number of soil biological, chemical and physical properties (e.g. nutrient availability, genetic diversity, soil structure, plant-available water holding capacity).

The potential to increase soil organic carbon is a function of three variables:

1. the capacity for a soil to hold additional organic carbon
2. the ability to deliver more organic carbon to the soil, and
3. the rate of loss of organic carbon through decomposition.

A fourth overriding variable is the quality of land management. We will return to this topic at the end of this section because it needs to be a primary consideration in any interventions to increase the soil carbon stocks of Australian soils.

Returning to the initial three variables, a useful analogy is to consider a bucket with a tap at its base. The bucket is simultaneously filled with organic carbon as plants grow and deposit their residues on and in the soil, and drained as organic carbon is converted back to carbon dioxide during its decomposition. The capacity for a soil to hold additional organic carbon is defined by the size of the bucket and how full the bucket is.

- The size of the bucket is determined by soil properties that define the amount of soil present (depth and bulk density) and properties that provide mechanisms to stabilise carbon against decomposition (mineralogy).
- The magnitude of organic carbon input to a soil is defined by the net primary productivity (NPP) of the vegetation present (the ability of the vegetation to capture carbon via photosynthesis) and the proportion of the captured carbon that makes its way to the soil.
- Losses of carbon are controlled by the ability of the soil to retain and protect the organic carbon against decomposition and mineralisation.

These variables change across the Australian continent and so significant differences exist in both the current dynamics of soil organic carbon and the capacity to increase stocks.

3.2 Method

Our focus here is on the potential of Australian agricultural soils to capture and retain *additional* organic carbon. This is set against the current understanding of whether soil carbon stocks are increasing or decreasing under current land management (e.g. as summarized by SoE 2016). The assessment follows the same logic used by Baldock et al. (2009) and it incorporates improved environmental, soil, and land-use data that have become available over the last decade. Our purpose is to identify: regions where interventions are needed to arrest declines in soil carbon; and regions that have the greatest potential to increase stocks.

The analysis focuses on agricultural lands, rangelands and managed forests. Soils under native forests were excluded because it was assumed that soil carbon was in balance with environmental and edaphic properties, and there was limited potential to increase soil carbon through a change in management. While this may not be strictly correct in native forests and woodlands that are grazed (e.g. across Northern Australia), insufficient data were available to include such systems.

The compilation processes used for deriving indices are described below. Spatial data layers were typically divided into classes that were assigned a relative score. To derive the indices, the scores were either added (where layers provided independent evidence), cross-classified or multiplied (where layers provided a modification of a value). The three indices (capacity, gains and retention) were used to calculate an overall index of the potential for enhancing soil organic carbon content.

3.3 Capacity Index

The Capacity Index provides an indication of how full the soil organic carbon bucket currently is. An empty bucket (low carbon storage) is scored highly because there is plenty of capacity available for storage of additional carbon. A low score indicates that the bucket is already full (high carbon storage) and there is limited capacity to add additional carbon. The spatial layers used to derive this index included:

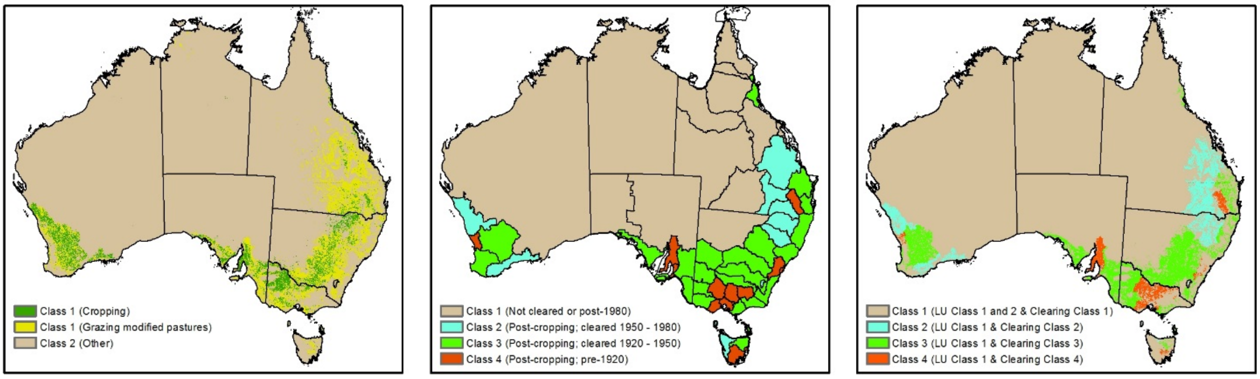
1. Clearing history – showing the approximate time when soils were cleared of native vegetation and brought into agricultural production.
2. Crop versus pasture – showing whether the cleared lands were brought into cropping or pasture production and whether they remained under this form of land management.
3. Clay content – the rate of decline in soil organic carbon after conversion to agriculture is reduced with increasing clay content due to the protection effect of clay.

3.3.1 Clearing history

Soil organic carbon content can decrease significantly after the clearing of native vegetation and initiation of agriculture (e.g. Guo and Gifford 2002; Sanderman et al. 2010; Luo et al 2010; Kopittke et al. 2017). The net decrease has been found to range from 0 to 70% with a mean value of approximately 40% (Luo et al. 2010). However, in some circumstances (e.g. low fertility sandy soils) an increase in net primary productivity and soil organic carbon may occur when agricultural production is implemented (Raupach et al. 2001, Griffin et al. 2003). Increases occur when a deficiency present under native condition (e.g. low availability of phosphorus) is overcome in the agricultural production system (e.g. by application of phosphorous fertiliser). Irrespective of whether the direction of change is positive or negative, an increasing length of time since clearing will allow the magnitude of the effect to be increased.

A four-class map summarizing the clearing history (Figure 3.1c) was created via a two-way table based on the time since clearing and the predominant form of agriculture implemented since clearing occurred. The latter (Figure 3.1a) used a simple binary classification of land use (Class 1:

either modified pastures, cropping or both; Class 2: all other land uses). The map of clearing period (Figure 3.1b) assigned each NRM region to a time period when most clearing occurred in that region.



National Land Use Cropping & Pastures

Clearing Date

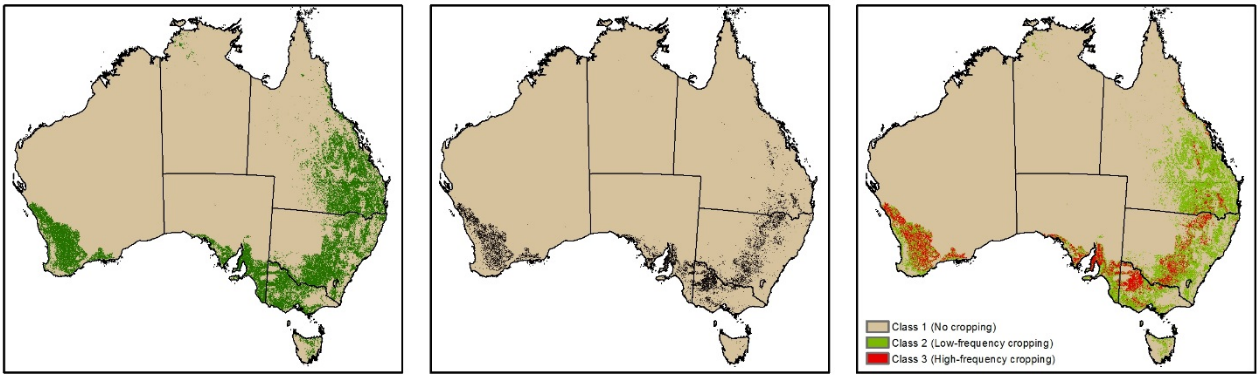
Clearing History

Figure 3.1: The (a) two-class map of land use and (b) four-class map of clearing period, were combined to produce the (c) four-class map of clearing history.

3.3.2 Vegetation: crop vs pasture

The decrease in soil organic carbon content after clearing depends on the subsequent land use. Decreases on land converted to pasture will be less than on land converted to cropping. A map of “crop vs pasture” aimed to capture this difference (Figure 3.2c). The map was derived by combining the following two maps:

1. Present Vegetation (Figure 3.2a) – created from the National Vegetation Information System (NVIS). Lands classified as “cleared, non-native vegetation” were differentiated from all other lands to produce a 2-class layer.
2. Cropping (Figure 3.2b) – created from ABARES (2016a), lands classified as cropped were differentiated to produce a 2-class layer.



NVIS 2016
Cleared, non-native vegetation

National Land Use
Cleared land currently with cropping

Vegetation
Crop vs Pasture

Figure 3.2: The (a) two-class map of present vegetation and (b) two-class mapping of cropping were combined to produce the (c) three-class map that depicts: 1. no cropping; 2. low-frequency cropping; and 3. high-frequency cropping.

3.3.3 Carbon with respect to clay

Although reductions in soil carbon after clearing are evident for most soils, it was recognised that the size of this reduction will vary with clay content. Soils that contain more clay are less likely to rapidly lose carbon after cultivation.

The Clay Decline Index was generated from the 0-5 cm clay layer of the Soil and Landscape Grid of Australia. Four classes (0-10% clay, >10-25% clay, >25-40% clay, and >40% clay) were assigned values from 1 to 4, respectively, to produce the Clay Decline Index (Figure 3.3). The observations supporting this were:

- soils with more clay would have a larger initial carbon content when agriculture was initiated than soils with less clay
- the magnitude of soil carbon loss when agriculture is established will be greater for clay soils than sands.

Using the bucket analogy, both the size of the bucket and the degree to which the bucket can be emptied once agriculture is established will increase with increasing clay content. As a consequence, soils with more clay should have a greater potential to capture additional soil carbon compared to the current soil carbon condition.

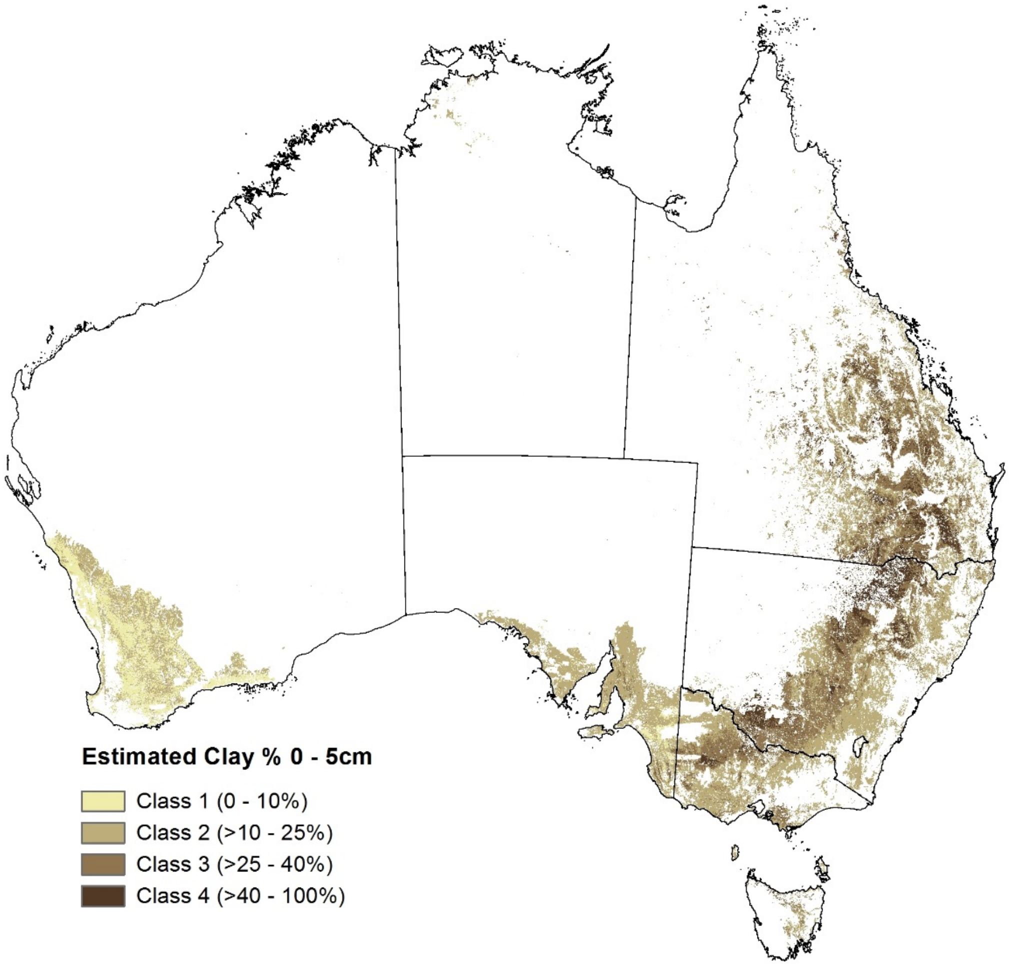


Figure 3.3: Clay Decline Index on lands used for cropping and pastures.

3.3.4 Capacity Index

The Capacity Index was created by multiplying the data layers for Clearing History (Figure 3.1c), Crop vs. Pasture (Figure 3.2c) and Clay Decline (Figure 3.3). This was then classified into five classes (Figure 3.4). Low values (blue) indicate minimal depletion and thus a low potential to capture additional organic carbon in the soil. Areas with a high potential to capture additional soil carbon are shown in red. The Capacity Index has been calculated for all areas across the continent that are used for cropping, pastures and grazing of native vegetation as defined by ABARES (2016).

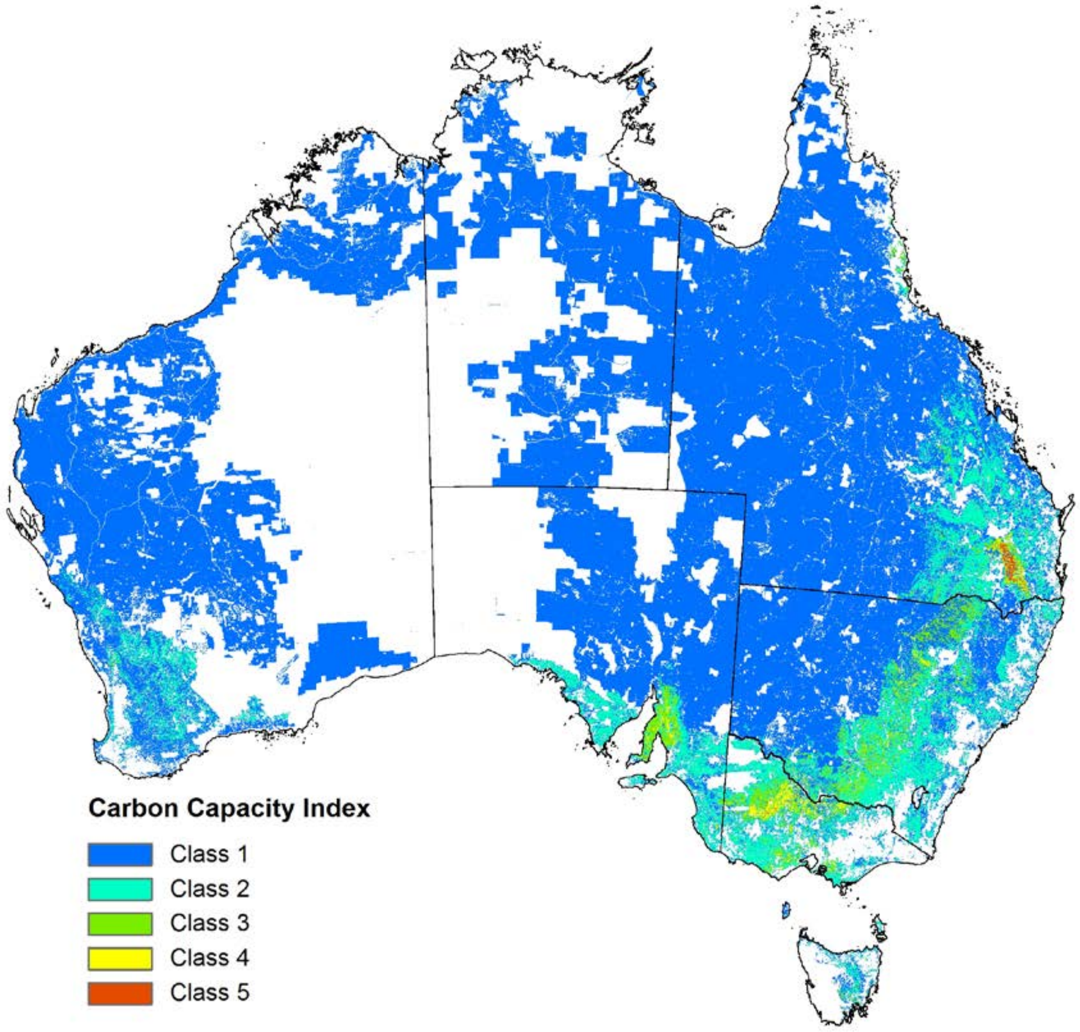


Figure 3.4: Carbon Capacity Index (Class 1 has the smallest capacity to store carbon and Class 5 the largest) for all areas across the continent that are used for cropping, pastures and grazing of native vegetation.

3.4 Carbon Gains Index

The Carbon Gains Index aims to summarize the potential to increase the inputs of organic carbon to the soil. Over the majority of Australia under dryland agriculture, the availability of water places a constraint on productivity which translates into a constraint on organic carbon addition to the soil. The greatest additions of organic carbon in the form of plant residues will occur where transpirational losses of water are maximised and direct evaporation, leaching and runoff losses of water are minimised. Potential increases in plant residue inputs under current cropping/pasture/agroforestry systems are possible if one or more of the following conditions exist:

1. Agricultural systems are not using water efficiently and the potential exists to utilise additional water to grow bigger crops (e.g. through choice of cultivars, rotations, nutrient management).
2. Existing constraints to efficient use of plant-available water can be overcome by management (e.g. deep ripping, and mitigating subsoil constraints).
3. Extension of the growing season by inclusion of perennials which will allow carbon to be captured by plants for a greater duration within a year.
4. Crops are grown when the soil contains enough water irrespective of time of year to maximise water use and reduce water lost via evaporation or leaching (e.g. opportunity cropping initiated when the soil profile fills in a manner typical of the northern cereal producing region).

The Carbon Gains Index has been calculated using updated continental estimates of Net Primary Productivity produced by Haverd et al. (2013) (Figure 3.5). The NPP provides an integrated summary of the capacity of the current systems of land use to assimilate and sequester carbon. However, this does not necessarily provide an estimate of the full potential because significant yield gaps are known to be present. At this stage, reliable estimates of the yield gap are only available in a consistent format for cropping lands[9] and Figure 3.6 shows the average yield gap for wheat over the 2000-2014 period.

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[9] See http://www.yieldgapaustralia.com.au

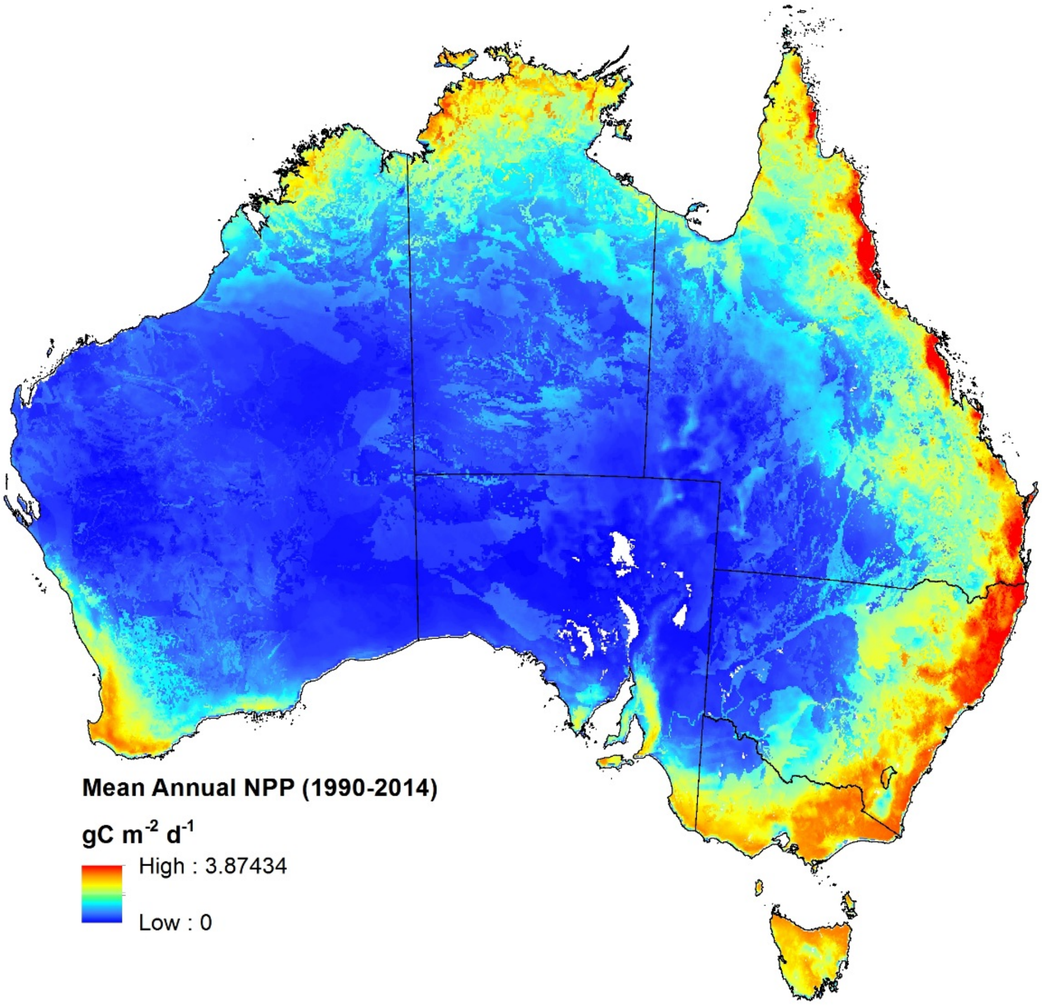

Figure 3.5: Average NPP for Australia (1990-2014) (update of Haverd et al. 2013).

It would be logical to add the estimate of NPP with the yield gap to provide an indication of the potential carbon gains. However, it would also be necessary to include an estimate of the 'yield gap' for pastures but such data were not readily available. At this stage, the Carbon Gains Index has been calculated by simply scaling the NPP noting that this will underestimate the potential in areas with a significant yield gap.

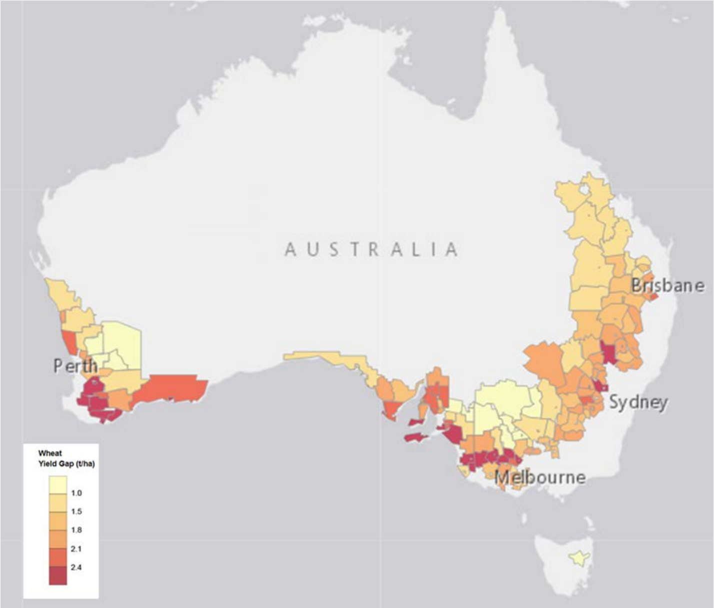

Figure 3.6: Average yield gap for wheat over 15 years (2000-2014) and mapped at Statistical Division Level Two (http://www.yieldgapaustralia.com.au).

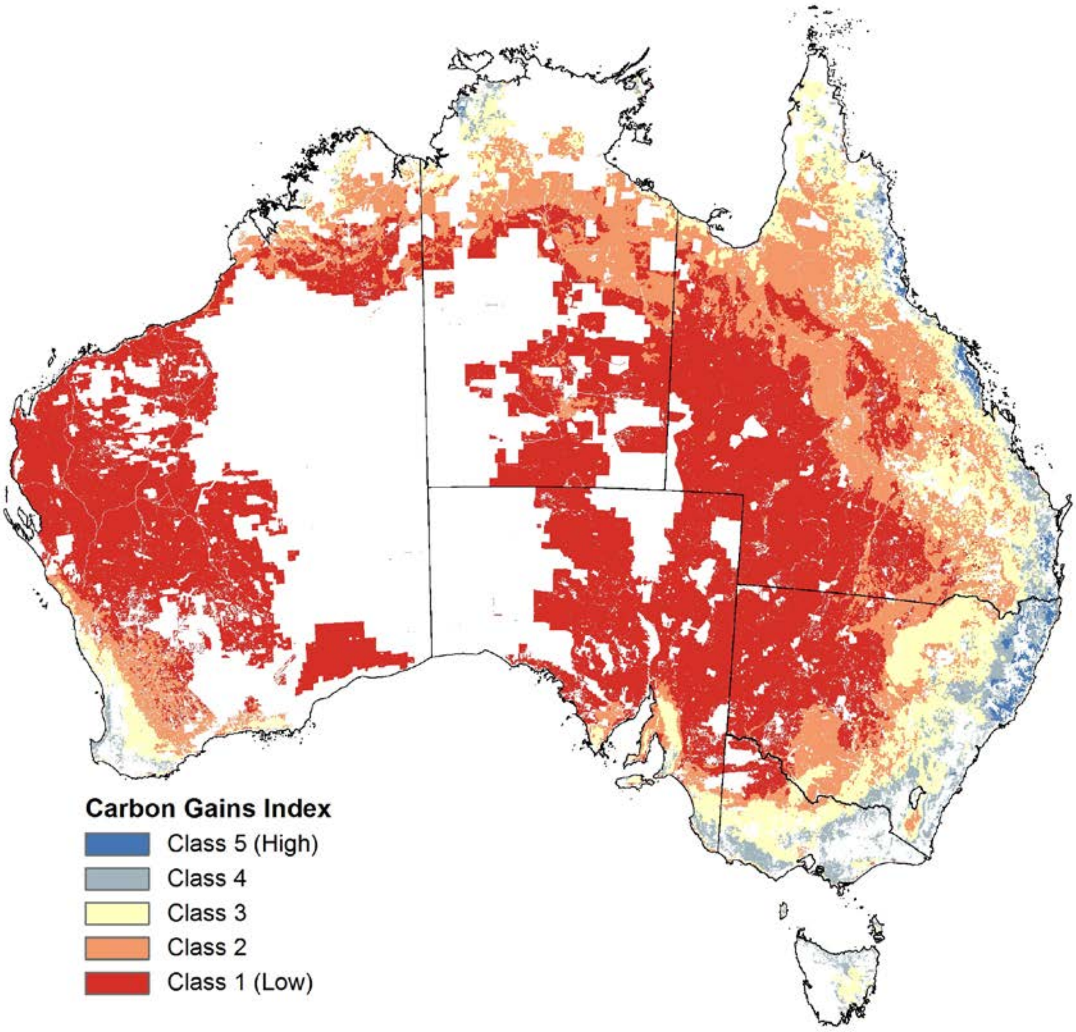

Figure 3.7: Carbon Gains Index based on estimated average NPP for all areas across the continent that are used for cropping, pastures and grazing of native vegetation.

3.5 Carbon Retention Index

The decomposition of organic materials represents the major loss mechanism for soil organic carbon. Erosion events may result in catastrophic losses of carbon from a particular location, but whether or not the eroded carbon is retained where deposited or more rapidly mineralised than it would have been in its original position remains a question to be addressed. Decomposition processes are facilitated by the combination of warm and moist soil conditions under which microbial activity is promoted (Baldock 2007). Some evidence exists to suggest tillage may have an influence on decomposition rates (Lal 2004), however, this is often confounded with the handling of stubbles in reduced or zero tillage systems. At present, conclusive evidence for an influence of passing a tillage implement (as opposed to the management of the stubbles *per se*) through soil on soil carbon content does not exist for Australian soils (Valzano et al. 2005). Additionally, a term to account for a tillage effect has not been required to be added to carbon cycling models in an effort to model carbon dynamics under different tillage regimes (Skjemstad et al. 2004). Accounting for the influence that the tillage system has on stubble retention has been sufficient to achieve successful modelling outcomes. Soil texture is also an important variable required in most modelling systems to assess the potential degree of protection that a soil may offer to organic carbon (Jenkinson et al. 1987). With increasing clay content, the ability of the soil to protect carbon against loss increases. Three parameters were developed to create the Carbon Retention Index:

1. the extent of cropping as defined through previous land use,
2. the ability of a soil to protect carbon from decomposition, and
3. the potential for soil microbial and faunal activity.

3.5.1 Previous land use

It is recognised that previous land use will have an influence on the magnitude of carbon losses. Many regions will have had a mixture of cropping and pasture with the exception of forestry or grazing in rangelands and other marginal cropping lands. Carbon in soils can be protected against biological attack and decomposition by a number of mechanisms involving some form of interaction with mineral particles (e.g. adsorption onto exposed surfaces and burial within aggregations of soil particles) (Baldock and Skjemstad 2000). As the amount of organic carbon present in a soil increases, the number of sites available for protecting any additional added carbon against microbial attack will decrease.

If a soil was previously under a cropping regime, it is likely that soil carbon will have been run down. Under conditions of low soil carbon, many of the potential sites that can protect organic carbon against biological decomposition will be available and unfilled. Under such circumstances the capability of protecting additional carbon will be high. If a soil was previously under pasture, due to the higher carbon contents typically achieved under pastures relative to grain crops, a greater proportion of the protection sites for the soil carbon will be occupied. Thus the ability of the soil to protect additional carbon will be lower. The national land use map was used to differentiate cropping areas from all other land uses. The two-class Previous Land Use map is shown in Figure 3.8.

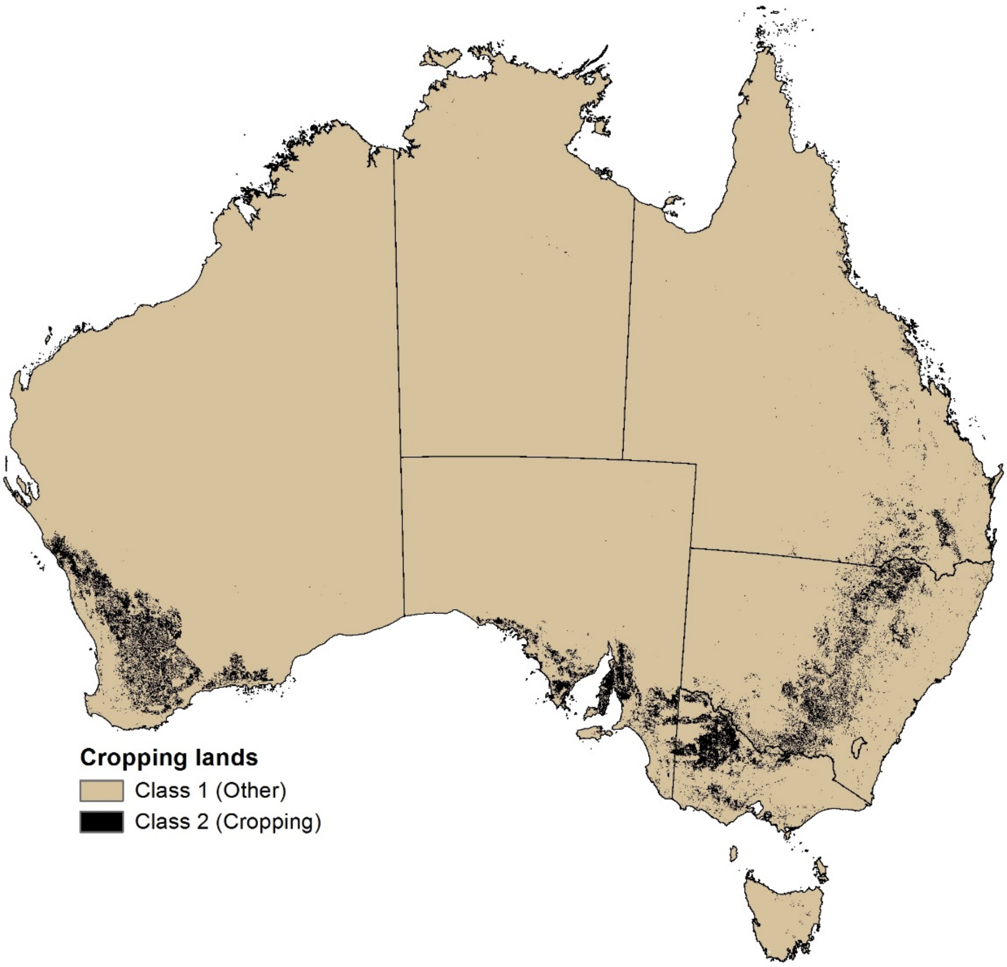

Figure 3.8: Previous land use derived from the national land-use map.

3.5.2 Clay and mineral protection

Soil texture and mineralogy are important parameters defining the ability of a soil to slow decomposition. Organic carbon can be protected against decomposition by interaction with the minerals present in a soil (Baldock and Skjemstad 2000). These interactions can result in a decreased solubility, adsorption onto mineral surfaces and/or burial within assemblages of mineral particles. Each of these protection mechanisms reduces the accessibility of organic materials to enzymatic attack and the extent of potential protection increases with increasing clay content. The presence of oxides or hydroxides of iron and aluminium offer an enhanced level of protection of soil organic matter against decomposition relative to other soil minerals. As a consequence, Ferrosols (Isbell et al. 2016) will tend to offer a greater protective effect than other Australian soil types.

Debate exists as to whether it is soil clay content itself, soil particle surface area or reactivity of soil surfaces as defined by mineralogy that is most critical. Here, we again use the estimates of clay content for the 0-5 cm layer from the Australian Soil and Landscape Grid (as described earlier for the Clay Decline Index) but with the following classes:

1. Class 1 – clay content <10%
2. Class 2 – clay content 10-25% and >45%
3. Class 3 – clay content >25-45%

Soils with a clay content >45% often exhibit vertic properties (i.e. significant shrinkage and swelling on exposure to drying and wetting cycles) that reduce the protective capability of clay. Therefore high clay content soils were placed into Class 2 along with the 10-25% clay soils.

Given the strong capacity of Ferrosols to protect soil organic carbon, a map of the distribution of Australian Ferrosols was created using the Australian Soil Classification map from the Australian Soil Resource Information System. This map was used to define a two-class Ferrosol data layer (Figure 3.9b). A Clay and mineral protection (Figure 3.9c) data layer was then constructed as a two-way table.

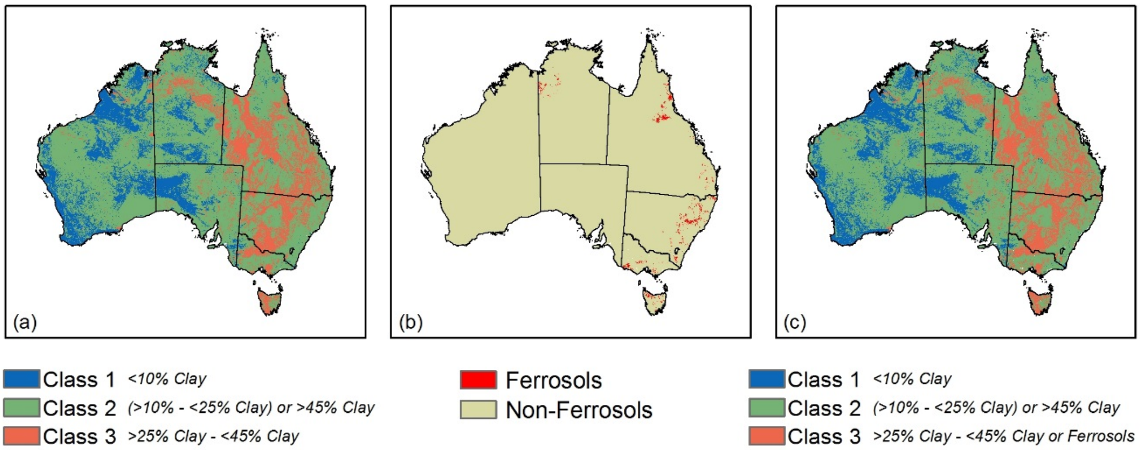

Figure 3.9: Clay and mineral protection is estimated by the (a) classification of clay content, and (b) distribution of Ferrosols, to produce (c) the final 3-class ranking.

3.5.3 Microbial activity

Losses of soil organic carbon due to decomposition are dependent on the activity of the microbial biomass present in the soil. Two key soil properties governing microbial activity are the availability of water and heat. These properties have been mapped using SMIPS data (Renzullo et al. 2014). The map was classified into five equal-interval classes. Class 1 corresponds with environments that have the most rapid decomposition rates and they tend to be hot and dry. Class 5 corresponds with environments that have the lowest decomposition rates (generally the coldest locations although areas that are also very wet may fall into Class 4).

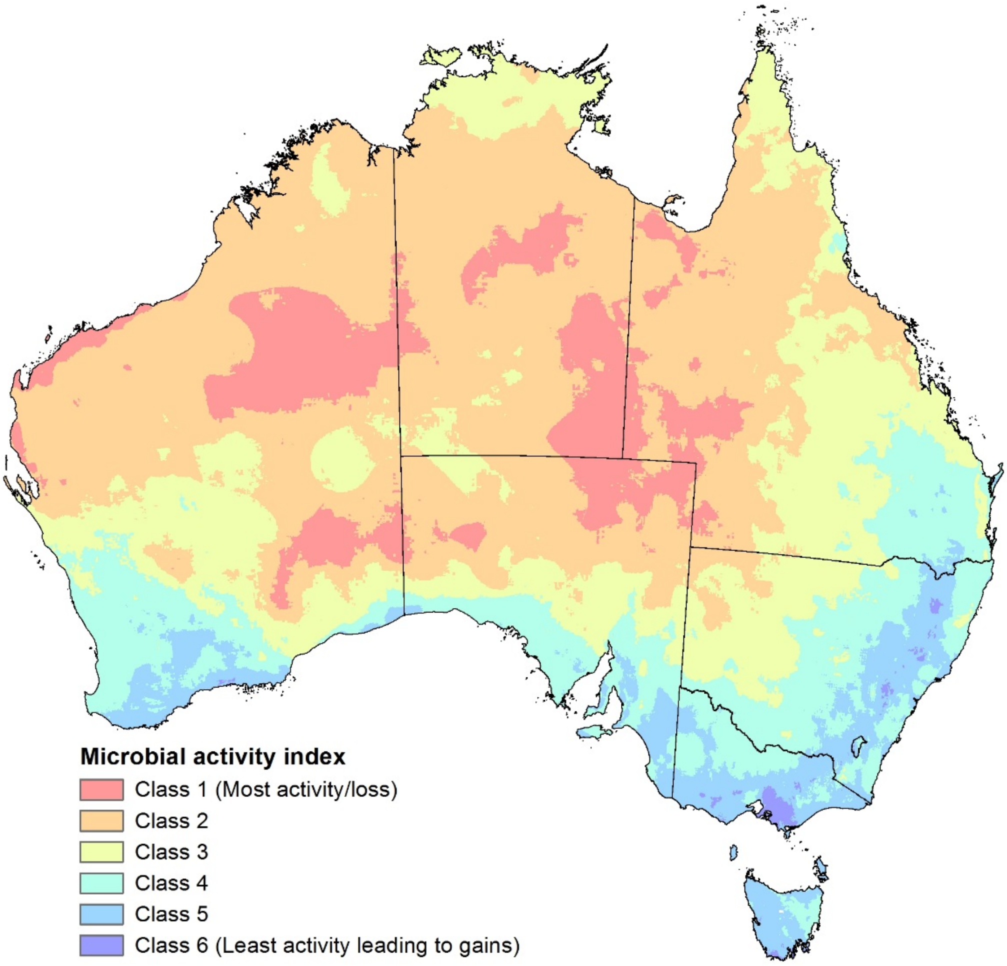

Figure 3.10: Microbial Activity Index.

3.5.4 Carbon Retention Index

The Carbon Retention Index (Figure 3.11) was calculated using Equation 3.1 and then classified into five classes separated by equal magnitudes. High values of the Carbon Retention Index indicate regions where added carbon is likely to be retained within the soil.

$$Carbon\ Retention\ Index = Microbial\ activity \times Clay\ and\ mineral\ protection \times Cropping\ lands \quad [3.1]$$

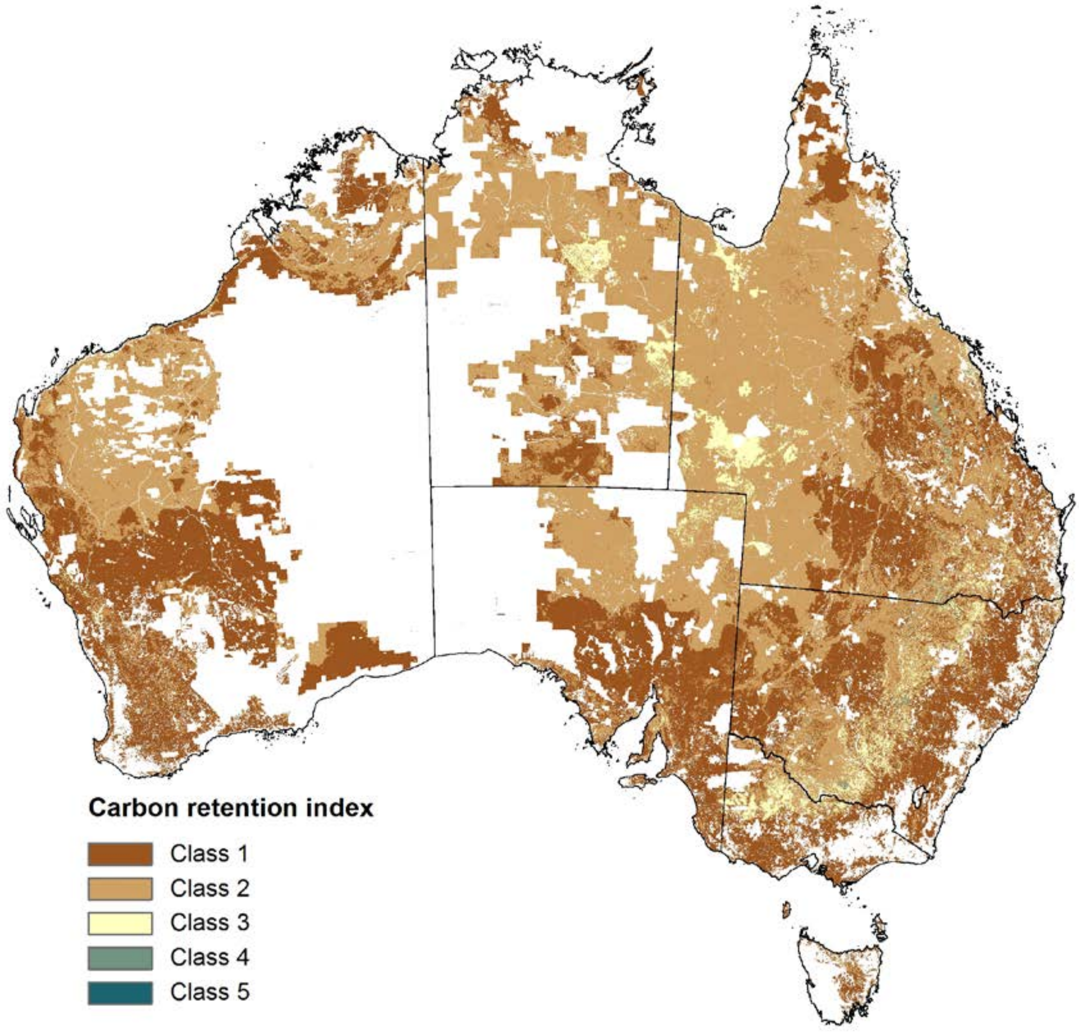

Figure 3.11: Carbon Retention Index describing the potential for added carbon to be retained within the soil. Class 1 areas have the lowest potential and Class 5 the highest.

3.6 Potential Capability Index

The Potential Capability Index (Figure 3.12) summarizes the potential for enhancing soil carbon. It was calculated according to Equation 3.2. Areas with a Carbon Capacity Index equal to one have a limited capacity to store additional carbon and they have a default allocation to Class 1 as a result.

$$If\ Carbon\ Capacity\ Index\ = 1, then\ Potential\ Capability\ Index = 1$$

$$else$$

$$Potential\ Capability\ Index\ =\ Capacity\ Index\ + Carbon\ Gains\ Index + Carbon\ Retention\ Index \quad [3.2]$$

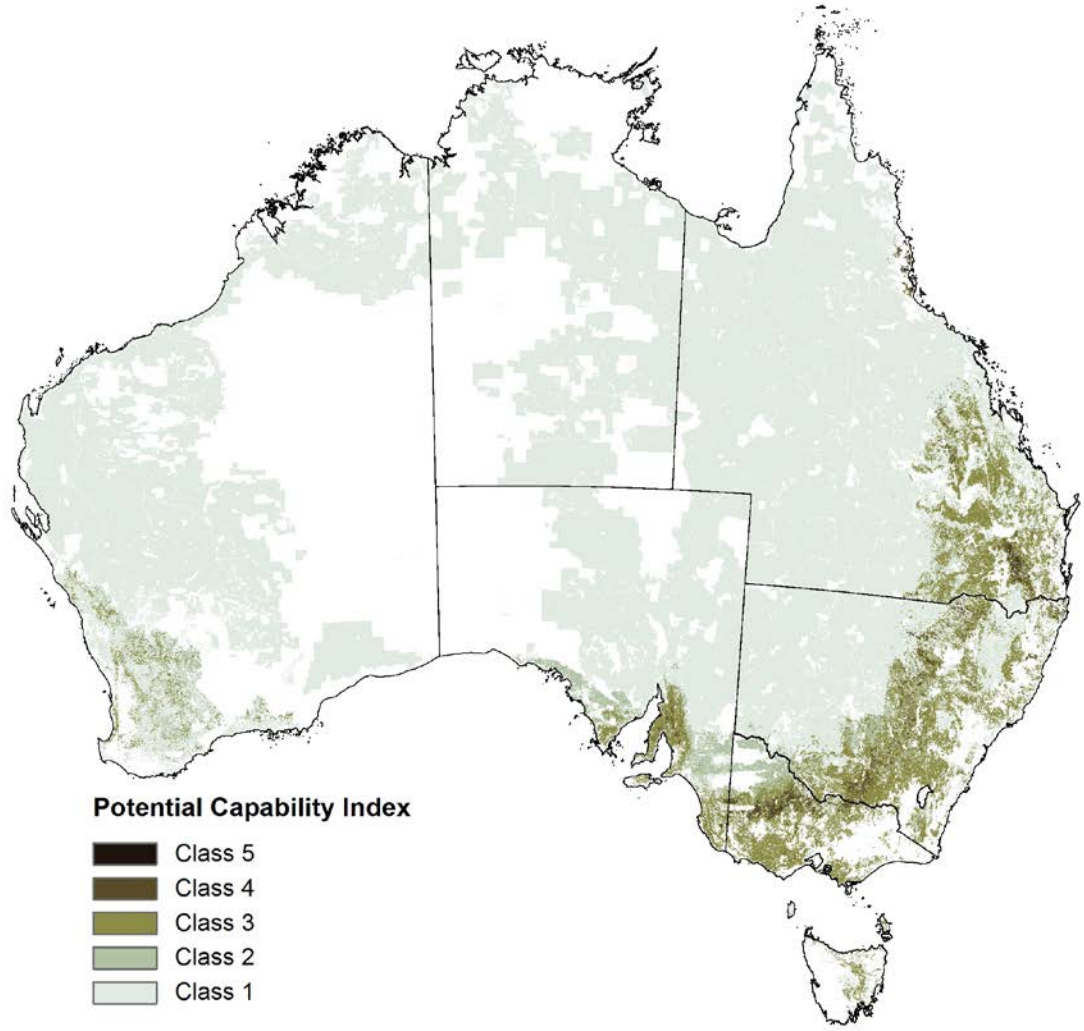

Figure 3.12: The Potential Capability Index for increasing soil carbon as calculated according to Equation 3.2 across lands used for cropping, pastures and grazing of native vegetation. Class 5 has the greatest potential and Class 1 the lowest.[10]

3.7 Opportunities for increasing soil organic carbon

At the beginning of this section it was highlighted that the quality of land management has a large influence on the capacity to sequester carbon. The SCARP Study (see Baldock et al. 2013 for an overview) was a comprehensive investigation into soil carbon stocks across a wide range of climates, soils and management systems in Australia. It confirmed that broad patterns of soil carbon variation correlate with first order drivers such as climate and soil type. It also demonstrated that increasing soil stocks in some environments is difficult. For example, results from both trial and commercial grower sites throughout Queensland indicated that no-till systems

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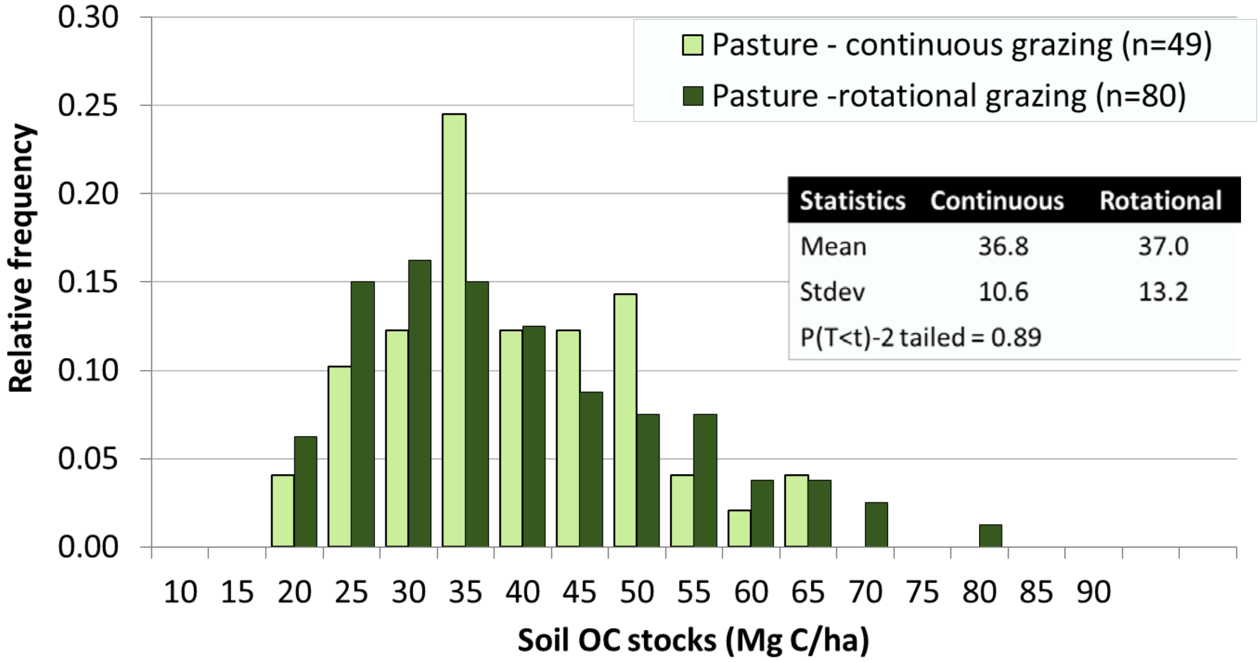
[10] This figure provided the basis for the map "An index of potential for the capture and retention of additional soil organic carbon" for the Regional Partnerships App on the National Landcare Program website (http://www.nrm.gov.au/national-landcare-program). In the map, Figure 3.13 was reclassified into three equal intervals depicted as *High*, *Medium* and *Low*.

are not capable of increasing soil organic carbon in either Queensland grain or sugarcane systems. However, no-till may be capable of slowing carbon loss following a period of carbon input from, for example, a pasture ley (Page et al., 2013).

The SCARP Study also revealed that no individual management practice has the same influence on 0-0.3 m soil carbon stocks across all agricultural regions. Statistically significant differences in carbon stocks were often not detected despite strong variations in the management practices assessed (e.g. continuous pasture versus continuous cropping). Figure 3.13 provides an example from the SCARP study from the Central Tablelands of New South Wales. The soil carbon stocks under the presumably more exploitative continuous grazing management system showed no statistical difference compared to the more conservative rotational grazing system. However, there are large differences in carbon stocks across the region (i.e. a four-fold difference).



Statistics	Continuous	Rotational
Mean	36.8	37.0
Stdev	10.6	13.2
P(T<t)-2 tailed = 0.89		

Figure 3.13: Variations in soil carbon stocks (0-0.30 m) comparing continuous grazing and rotational grazing on the Central Tablelands of New South Wales.

The SCARP Study concluded amongst other things that:

- Poor application of a particular management practice which on average has the capability to increase soil carbon may result in a loss of soil carbon.
- Equally, a very good application of a practice that is found to decrease soil carbon on average may result in increased soil carbon stocks if levels of carbon capture and return to the soil are high enough (Cowie et al., 2013; Page et al., 2013; Cotching et al., 2013; Badgery et al., 2013; Davy and Koen, 2013; Wilson and Lonergan, 2013).

The results from the SCARP study were initially surprising. They challenged the conventional wisdom that conservative land management practices would result in larger carbon stocks. They also challenged the straightforward extension messages that prevailed at the time. However, the results point to a more fundamental set of factors that determine whether soil carbon stocks can be increased.

- Net Primary Productivity needs to be maintained at a high level relative to the potential at the location of interest to ensure that carbon capture by the plant flows through to the soil. In grazing systems this means that overgrazing has to be avoided. In cropping systems, varietal selection, the timing of key operations (e.g. sowing) and application of the right fertiliser at the right time all need to be optimizing to maximize the production of dry matter.
- Water-use has to be efficient and this entails overcoming soil constraints that may be chemical, physical or biological in nature.

These findings have major implications for the design of programs that aim to increase soil carbon stocks and soil quality more generally. Such outcomes cannot be achieved by relying only on compliance with a general set of management practices (note that these practices may generate a range of other benefits). To achieve a good result in terms of soil carbon, close attention must also be given to the implementation of the practice. In short, this means maximising net primary productivity as outlined above. Current extension programs need to be updated to include this guidance.

Tracking progress will also require a modification to existing monitoring systems. A logical first step would be to combine farm management surveys that record relevant practices (e.g. tillage frequency, stubble management, soil testing) with time-series remote sensing of net primary productivity at the farm scale. The capability to do this already exists (e.g. Figure 3.5) but it needs to be tailored to the specific task of tracking soil carbon stocks.

Bearing in mind the above caveats, the potential to increase soil organic carbon for each NRM region has been ranked according to the simple schema shown in Figure 3.14. The risk rankings are based on the Potential Capability Index (Figure 3.12) and the assessments presented in SoE (2011, 2016).

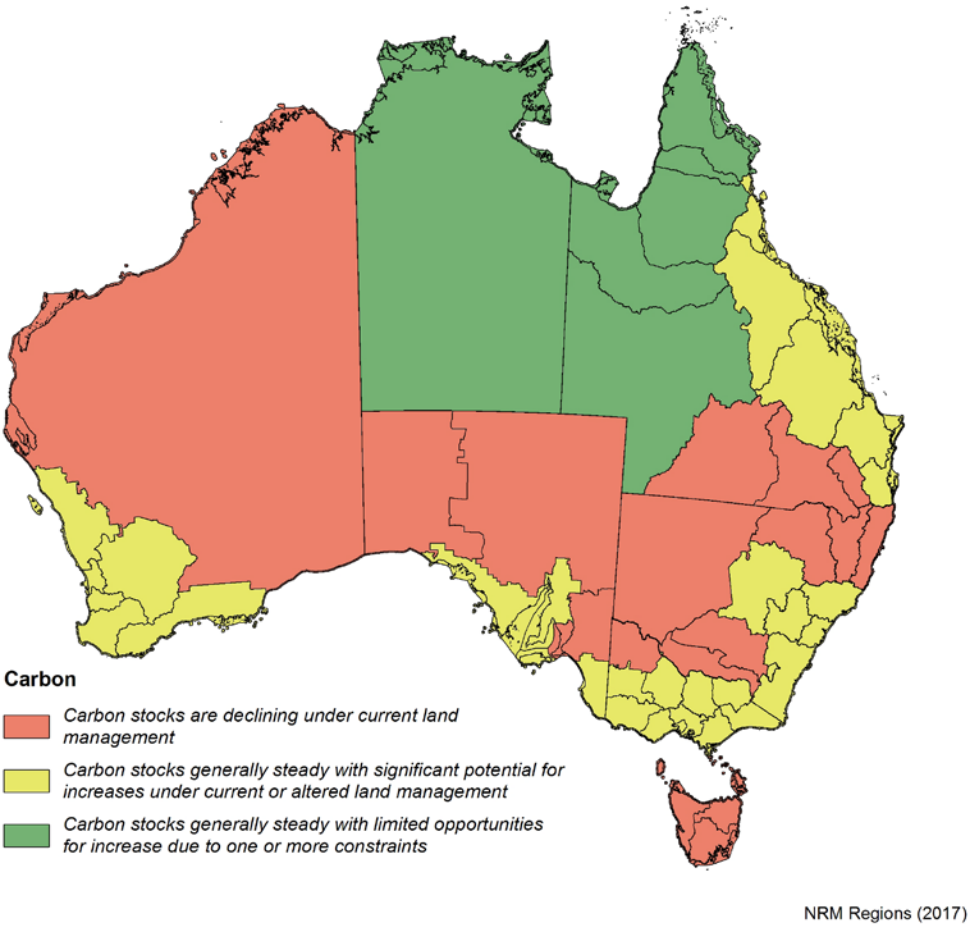


Figure 3.14: Generalized trends in carbon-stock change and regions with potential for increases under current or altered land management.

4 Hillslope erosion

4.1 Significance, causes and consequences

The control of soil erosion by water has the potential to preserve the soil resource and have a major influence on other soil attributes including soil organic matter, nutrient status and rates of acidification. Soil erosion is tightly linked with downstream water quality both within the rural enterprise (e.g. stock watering points and farm dams) and off-site (e.g. in rivers, reservoirs, estuaries and the ocean). The erosion of surface soils is a long-standing problem that was observed within the first few years of European land development in almost all districts across Australia. Though there are regional success stories in reducing the rates of soil erosion by water, the national picture is still one of steady degradation and associated decline of the soil resource on sloping lands.

Soil erosion is primarily triggered by the reduction of vegetative cover of soils. Locally, the level of vegetative cover (both living and dead) is controlled by the combined impacts of climate variability and human management of the vegetation. In grazing lands the primary human-controlled driver on vegetation is animal stocking rate. In cropping lands the primary human-controlled drivers are tillage and other forms of management of plant residues. Gullies form where the accumulated effect of hillslope erosion leads to the local exposure of unstable subsoils to the erosive power of overland flow and raindrop impact. Gully erosion is a persistent and pervasive form of erosion in Australian landscapes and it degrades the values of rural land and contributes the largest portion of downstream sediment.

The consequences of soil erosion by water are a gradual reduction of the soil resource available in most locations in the Australian rural landscape, an increase in the soil resource in zones of sediment deposition (including footslopes, alluvial plains and floodplains) and chronically elevated concentration of sediment and nutrients in downstream water (typically three to five times that of pre-European levels). The loss of soil, and the associated loss of nutrients and potential land productivity, are at a rate that may be perceptible only in units of decades, or generations of land managers. The rates of hillslope erosion across Australia's rural landscapes are, however, much greater than the rates of soil formation, so a net run-down of the soil resource is occurring (details are provided in the sections below).

The focus in this section is primarily on hillslope erosion (sheet and rill erosion). Gully and streambank erosion are other major forms of soil erosion for Australian landscapes. In the catchments that drain to the lagoon of the Great Barrier Reef, gullies and streambanks are a specific focus of remediation. Elsewhere, data on the location and activity of gully and streambank erosion is relatively poor. However, the evidence suggests that if the purpose of remediation is solely on downstream impacts then the control of gully and stream bank erosion should be emphasised.

4.2 New insights into soil erosion by water across Australia

The previous assessment of priorities for hillslope erosion (Hairsine et al. 2009) identified priority areas where soil loss could be reduced. Since that time, several studies have provided improved insights for the nation and for particular regions. Later in this section these more recent studies are used to support regional interpretations and recommended strategies for reducing soil erosion by water.

Nationally, there has been a re-examination of the comparison of rates of soil erosion by water and the rates of soil formation (Bui et al., 2010 and Bui et al., 2011). Bui et al. (2010) suggested "a tolerable soil loss of 0.2 t ha^{-1} yr^{-1}. " This compares to the estimated national average current hillslope erosion rate of 1.86 t ha^{-1} yr^{-1} (Teng et al., 2016) and soil formation rates of the order of 0.01 t ha^{-1} yr^{-1} (e.g. Pillans, 1997).

Bui et al. (2010) state:

> *"Estimates of the time to critical soil loss (Tc), defined here as the time for complete erosion of the soil A horizon, are in the range 100-500 years for the most highly eroding areas. However, some studies [see review in Stocking, 2003] have noted an exponential reduction in agricultural productivity with loss of topsoil. Thus loss of just a small fraction of the A-horizon (a few cm of soil) may in some regions lead to a significant decline (>25%) in soil agricultural productivity over time frames of less than 100 years."*

Thus, a simple comparison of current erosion rates and available topsoil stocks or soil formation rates may underestimate the significance of the soil erosion problem for land productivity. The new analysis of nutrient loss due to erosion by water presented below addresses this issue.

Recent advances in sediment tracing and modelling have also provided an improved understanding of erosion and sediment transport, particularly for the coastal catchments of Queensland. This work has contributed to a broader reappraisal of the relative importance of hillslope erosion versus gully and streambank erosion (e.g. Brooks et al. 2014, Hancock et al. 2014). These studies and the related modelling (e.g. Bartley et al. 2014) also point to erosion sources close to the coast (or other receiving water) as priorities for remediation for the purposes marine water quality improvement.

The general picture of priorities that has emerged from the accumulated studies is: where the focus is on maintaining land productivity then reducing hillslope erosion is the primary focus; where the focus is on improving downstream water quality then reducing gully, streambank and hillslope erosion in areas proximate to the receiving waters is the focus.

There have been some significant changes to the spatial extent and forms of land disturbance since previous assessments. Of particular significance is the renewed interest by government in agricultural development across northern Australia (e.g. Stone et al., 2016). More specifically, the changes include:

1. The expansion of grazing and cropping areas in northern Australia. Driven by land clearing and the removal of regrowth (SoE 2016), new areas of land are exposed to cycles of varying cover levels associated with grazing and in smaller areas, cropping. For instance there has been extensive development of grazing land and new banana enterprises in the southern Cape York NRM region in the last decade.

2. There has been an incremental increase in grazing intensity across large parts of northern Australia (e.g. O'Reagain et al., 2014). The primary driver is an increase in the density of watering points. An example of this is provided in Waddell et al. (2012) who reported on extensive soil erosion and downstream water pollution in the Gascoyne River catchment of Western Australia.
3. In south eastern Australia gully erosion has been recognised as a major source of in-stream sediment (Wasson et al., 1998). In this region the rate of gully erosion is decreasing but it still dominates other sources of sediment including hillslope erosion in current river sediment budgets. In northern Australia gullies have been observed to be triggered by European land development from 1860 onwards. Bartley et al. (2014) identify native vegetation clearance and the arrival of drought tolerant African cattle breeds in the 1980s as causal factors. This effect continues to this day in the north of Australia with new gullies being observed to form in the 2010s (McCloskey et al., 2016 and Shellburg et al. 2016). Once formed, gullies will be a major source of excess sediment in streams and estuaries for many decades to come.
4. The emergence of Coal Seam Gas (CSG) and other forms of non-conventional mining presents an additional extensive form of land-surface disturbance. Disturbance of the soil is primarily as a result of the extensive network of tracks and roads associated with this industry. Vacher et al. (2014) provides the first Australian study of this effect and identifies erosion from the tracks as being locally significant. The tracks were found to frequently intersect the natural drainage network so the erosion has consequences both on-farm and downstream.
5. The recent analysis of soil erosion by wind in Australia (Leys et al., 2017) and hillslope soil erosion by water (Teng et al., 2016 - critiqued in detail below) allows a comparison of spatial priorities for addressing these two forms of erosion. Leys et al. (2017) identify areas in the arid zone as having the most significant wind erosion. Teng et al. (2016) identify the grazing and cropping zones of the eastern uplands and some parts of northern Australia as the areas of high erosion by water. Consequently there is very little spatial overlap and regional priorities are almost universally separate (either wind or water erosion control). The small area of overlap is in the Flinders Ranges region of South Australia.
6. There has been a steady uptake of the machinery necessary for reduced tillage in cropping systems (SoE, 2016). The use of this new machinery is reducing erosion rates around the time of planting. In the sugarcane industry, reduced tillage and the maintenance of vegetative cover around the time of planting (as opposed to the ratoon phases) remains a research topic. Significant reductions in soil erosion rates for this industry are possible through the uptake of the recent findings by Rohde et al. (2013) (see below in "Opportunities for reducing hillslope erosion").

4.3 Analysis

This section outlines the state and trend of soil erosion by water across Australia. The analysis and interpretation builds on Hairsine et al. (2009) and SoE (2011) and it uses the most recent estimate of the annual average rate hillslope erosion for erosion for Australia (Teng et al. 2016). The analysis and interpretation seeks to:

1. critique and interpret the hillslope erosion map of Teng et al. (2016)
2. provide national maps of estimated mean annual nutrient loss for total Nitrogen (TN), total Phosphorus (TP) and soil organic carbon (SOC) caused by hillslope water erosion
3. update the regional interpretation provided by Hairsine et al. (2009) using more recent analyses including that described at Point 1
4. provide a national map and interpretation of the temporal trends in cover-related risks associated with soil erosion by water over recent decades.

4.3.1 Hillslope erosion by water - interpreting Teng et al. (2016)

This component of the report benefits from the publication by Teng et al. (2016). This peer-reviewed journal paper provides the most recent assessment of the rate of hillslope erosion (sheet and rill erosion) for Australia. It replaces Lu et al. (2003) and the related National Land and Water Audit (2002) assessments of hillslope erosion. Figure 4.1 provides a graphical summary of the Teng et al. (2016) analysis showing the estimates of the soil erodibility (K), rainfall erosivity (R), cover (C), topography (LS) and management (P) factors used in the Revised Universal Soil Loss Equations calculations. Teng et al. (2016) provides a comparison of their estimates with those of previous analyses. No direct comparison with local field studies is attempted.

The spatial patterns of hillslope erosion by water presented in Figure 4.1 show the higher erosion rates are in steeper and more intensively used landscapes of eastern and northern Australia. There is also some influence of rainfall intensity with more erosive rainfall in the northern parts of the country. Cropping zones and grazing regions where vegetative cover has been low due to the combined effects of climate and human management lead to estimated hillslope erosion rates greater than 5 tonnes per hectare per annum (yellow, orange and red areas in the main panel Figure 4.1).

Some anomalies are present in Figure 4.1. Most notably, steep forested areas along the Great Dividing Range and in Western and Central Tasmania (some of which are in parks and reserves) are estimated as having high hillslope erosion rates. These forested areas have much lower actual erosion rates and this error in the maps of Teng et al. (2016) is due to the poor suitability of the Universal Soil Loss Equation for these environments. These forested landscapes are masked out where Teng et al.'s RUSLE output is used in the analysis and interpretation presented in this report.

Yang (2014) identified a significant problem in the cover estimates used by Lu et al. (2003). This problem involved the misclassification of some dead vegetation as bare soil in the image analysis of satellite-based vegetation maps used by Lu et al. (2003). Lu et al. (2003) estimated the cover factor using a classification of remote sensing for the period 1981 to 1994. By contrast, Teng et al. (2016) estimated the cover factor by reclassifying the Dynamic Land Cover Dataset (DLCD; Lymburner et al., 2010) which is based on interpretation of remote sensing for the period 2000 to 2008, and allocating an RUSLE cover factor to each land cover type. Note that the period of the DLCD remotely sensed input data coincides with the Millennium Drought in eastern Australia (van Dijk et al., 2013). Furthermore, the direct estimation of the cover factor from fractional cover data (as demonstrated by Yang, 2014 for New South Wales) is more direct and defensible than the Dynamic Land Cover product, as the latter is untested against field data suited to this application.

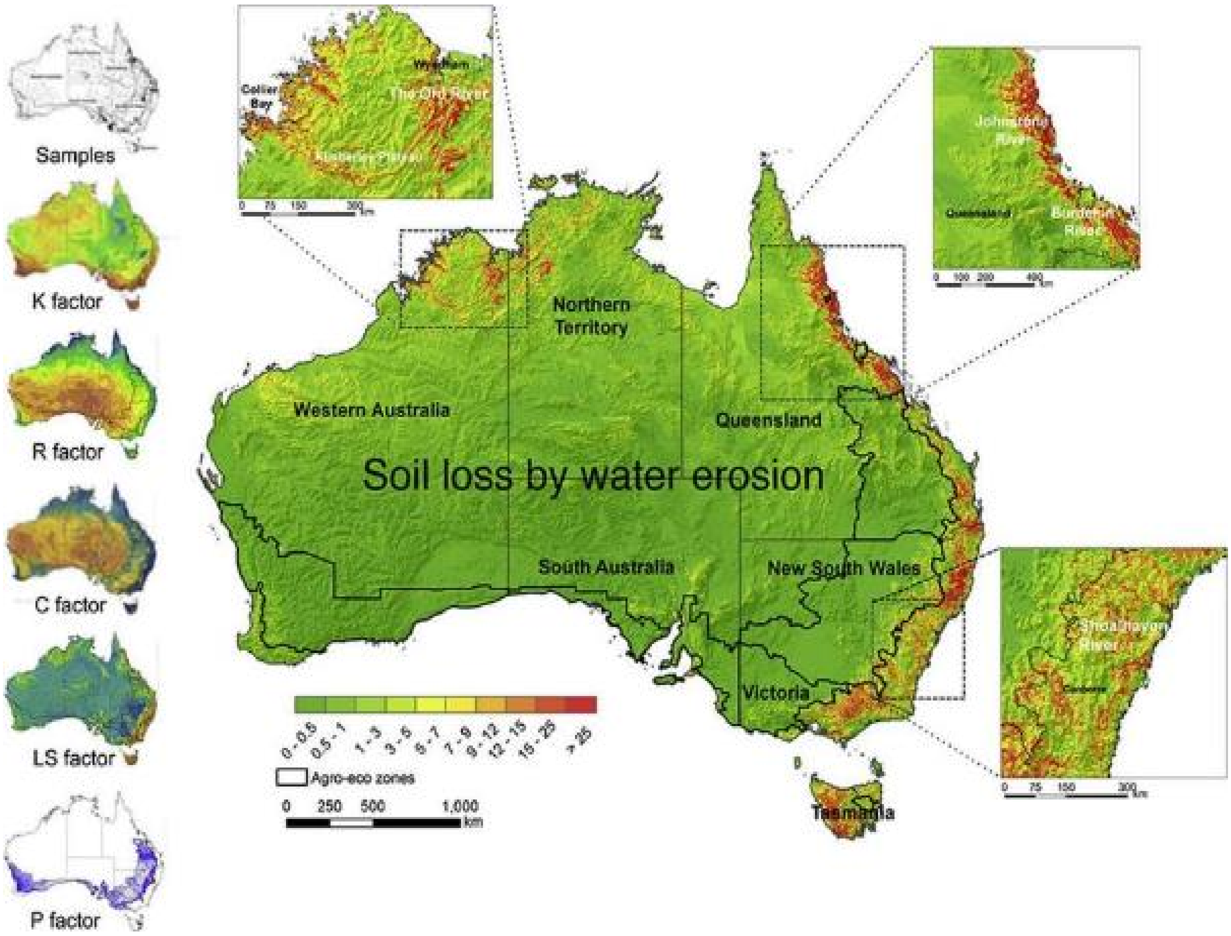


Figure 4.1: The estimates of annual average hillslope erosion (sheet and rill) for Australia, showing spatial layers of the factors used in the Revised Universal Soil Loss Equation (reproduced from Teng et al. 2016).

Teng et al. (2016) estimated hillslope erosion rates for extensive grazing lands that are considerably less than those of Lu et al. (2003). Although Teng et al. (2016) address some limitations in Lu et al. (2003), problems remain in the interpretation of soil erosion across the agricultural landscapes where cover varies within land use types. Inclusion of a long-term fractional-cover analysis in a future assessment is a priority. To partly address this issue an analysis of 16 years of MODIS-derived fractional cover is presented in section 4.3.3.

Despite these issues, Teng et al. (2016) have provided notable improvements on the analysis of Lu et al. (2003). Estimates of the soil erodibility factor are considerably enhanced through the use of improved soil data from the Soil and Landscape Grid of Australia and the algorithms used to provide the spatial distribution of these attributes.

4.3.2 National maps of the rate of nutrient loss by water erosion

The mean annual rate per unit area of nutrient loss by water has been calculated by:

$$Annual\ rate\ nutrient\ loss = Annual\ rate\ hillslope\ erosion \times Soil\ surface\ nutrient\ concentration \quad [4.1]$$

The most recent estimate of the mean annual rate of water erosion is provided by Teng et al. (2016) as shown in Figure 4.1.

The surface soil nutrient concentration in Equation 4.1 is for the upper five centimetres of the soil as this is the only available national estimate of surface nutrient concentration (Soil and Landscape Grid of Australia). This approximation is likely to lead to an underestimate of the nutrient loss rate as the concentration at the very surface of the soil is likely to be higher than the average for the upper five centimetres.

The quantity calculated in Equation 4.1 is difficult to interpret without a reference point or benchmark. Here we compare the rate of erosion of a nutrient to its total stock. The relative rate of nutrient loss by water is defined by:

$$Relative\ rate\ of\ nutrient\ loss\ (\%\ per\ year)\ =\ \frac{100 \times Mean\ annual\ rate\ of\ nutrient\ loss\ per\ unit\ area}{Total\ soil\ nutrient\ stock\ per\ unit\ area} \quad [4.2]$$

where

$$Total\ soil\ nutrient\ stock\ per\ unit\ area = \sum_{i=1}^{I}(nutrient\ conc.layer\ i\ \times\ thickness\ of\ layer\ i) \quad [4.3]$$

where *I* is the number of soil layers. Equation 4.2 can be implemented for different nutrients.

The units of the relative rate of nutrient loss are T^{-1}, so the value gives an indication of the rate at which the soil nutrient stock is being exhausted. The inverse of the relative rate of the nutrient loss/100 is the time taken to taken to exhaust the soil's nutrient (though this interpretation assumes no other net inputs or outputs of nutrient (e.g. through leaching or fertilisers)).

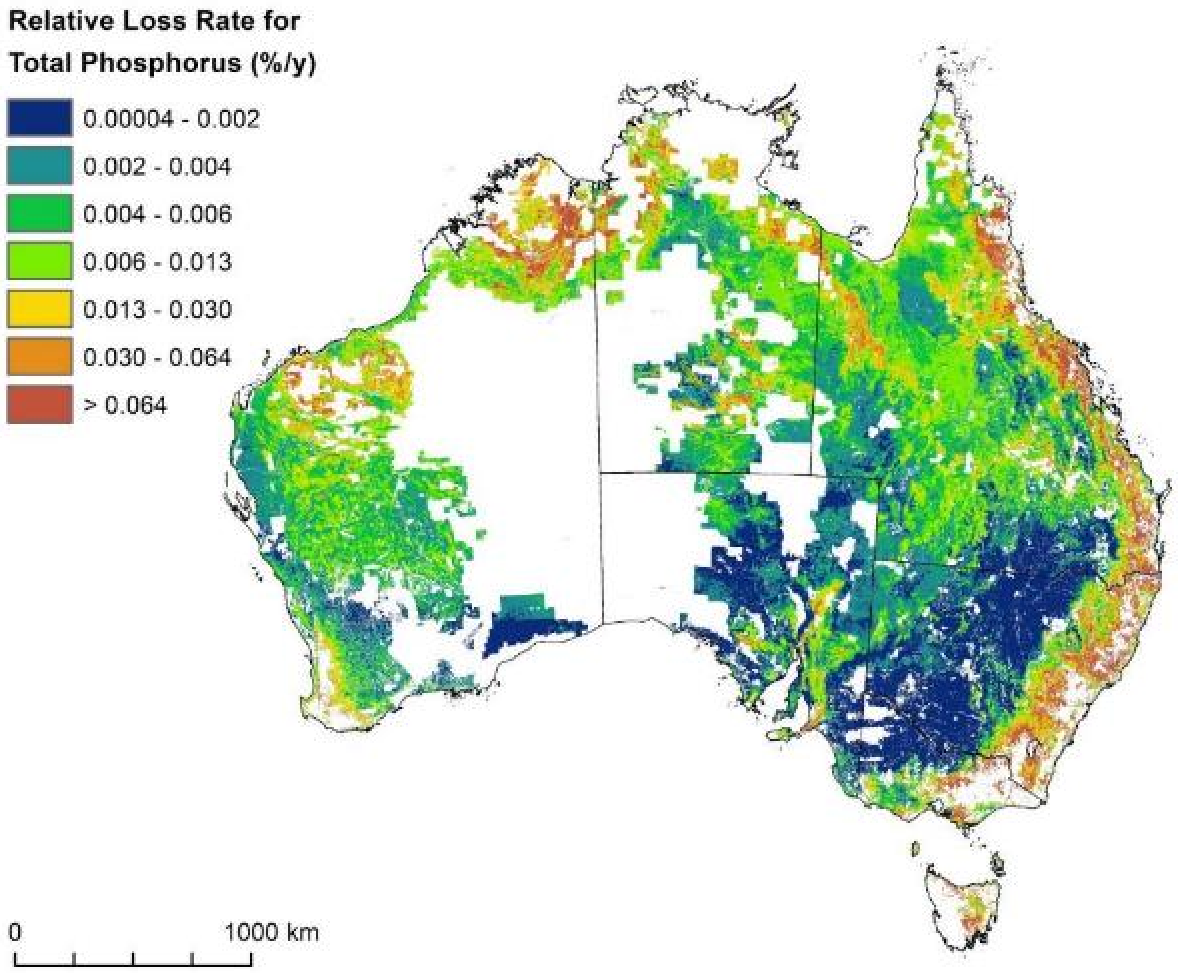


Figure 4.2: The relative nutrient loss index for Total Phosphorus (TP) as calculated using Equation 4.2. The colours used are defined by the 0 to 20, 20 to 40, 40 to 60, 60 to 80, 80 to 90, 90 to 95 and 95 to 100 percentiles of the coloured area. One way of interpreting this figure is to take, for example, a value of 1% Total-P loss per year. It then takes on average 100 years to exhaust the Total-P stock – with all other inputs and losses being neutral. Note the extensive areas of nutrient loss by water erosion in the more intensively used areas of Australia. The calculations are only made for non-reserve, non-forested parts of Australia.

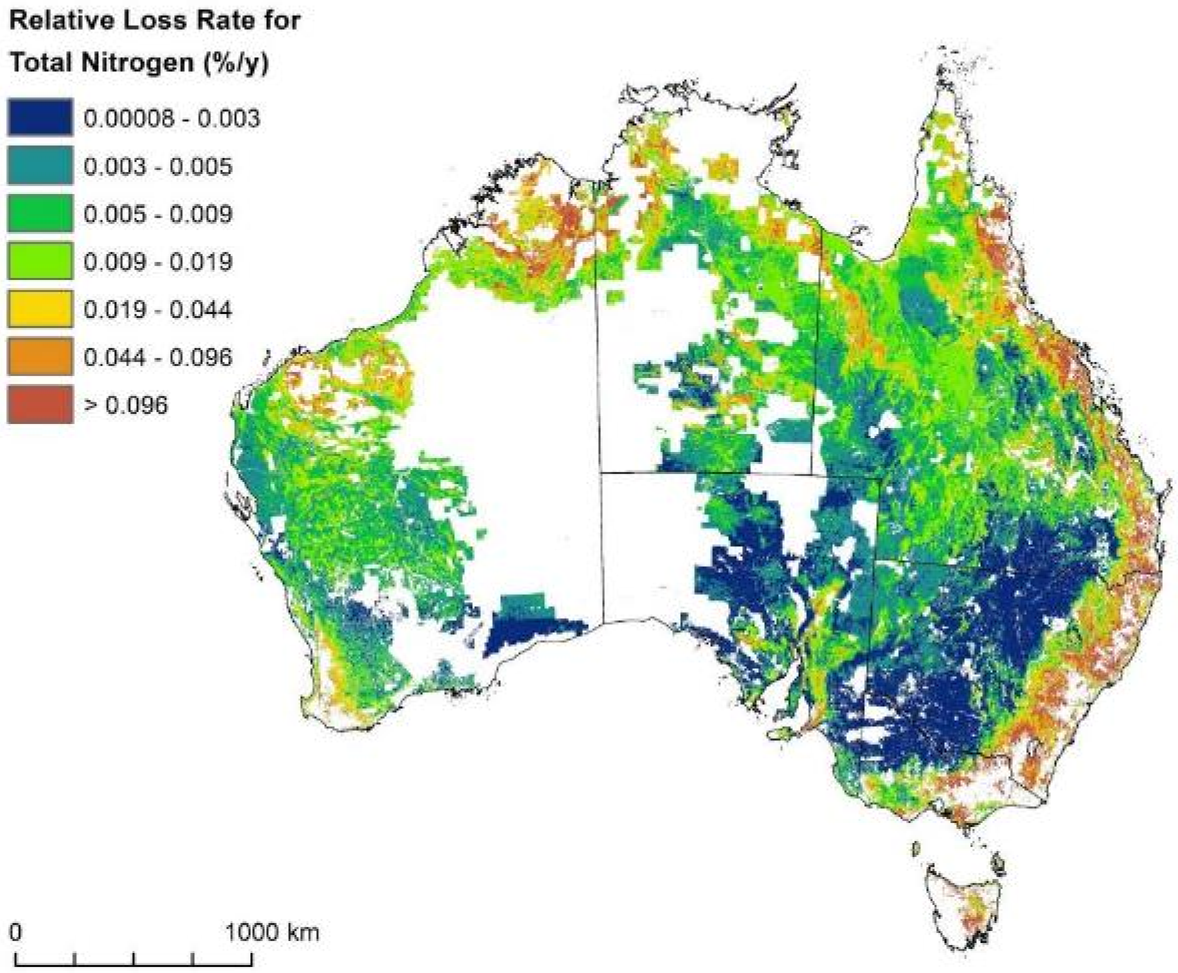


Figure 4.3: The relative nutrient loss index for Total Nitrogen (TN) as calculated using Equation 4.2. The colours used are defined by the 0 to 20, 20 to 40, 40 to 60, 60 to 80, 80 to 90, 90 to 95 and 95 to 100 percentiles of the coloured area. One way of interpreting this figure: if the value was for example 1% Total-N loss per year then on average it would take 100 years to exhaust the Total-N stock – with all other inputs and losses being neutral. Note the extensive areas of nutrient loss by water erosion in the more intensively used areas. The calculations are only made for non-reserve, non-forested parts of Australia.

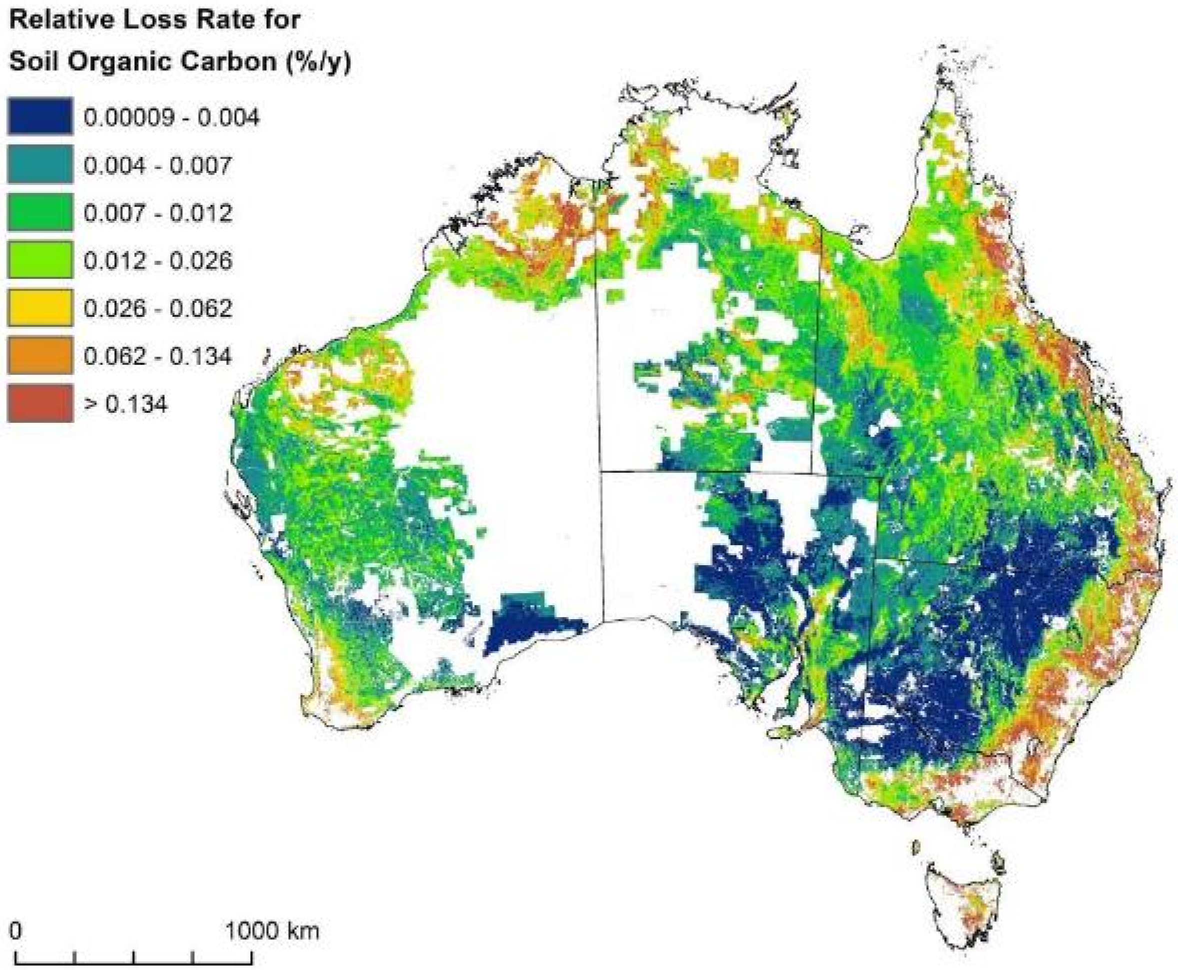


Figure 4.4: The relative nutrient loss index for Soil Organic Carbon (SOC) as calculated using Equation 4.2. The colours used are defined by the 0 to 20, 20 to 40, 40 to 60, 60 to 80, 80 to 90, 90 to 95 and 95 to 100 percentiles of the coloured area. One way of interpreting this figure: if the value was for example 1% Total-C loss per year then on average it would take 100 years to exhaust the stock of Soil Organic Carbon – with all other inputs and losses being neutral. Note the extensive areas of nutrient loss by water erosion in the more intensively used areas. The calculations are only made for non-reserve, non-forested parts of Australia.

An overall index of nutrient loss for water erosion can then be produced by combining the value of the relative rate of nutrient loss for each nutrient. The simplest approach is to average the values, so:

$$Nutrient\ loss\ index\ = \frac{1}{J}\sum_{j=1}^{J} Relative\ nutrient\ loss\ rate\ of\ nutrient\ j \quad [4.4]$$

where J is the number of types of nutrient considered. Here total N, total P and Soil Organic Carbon are being assessed so J=3.

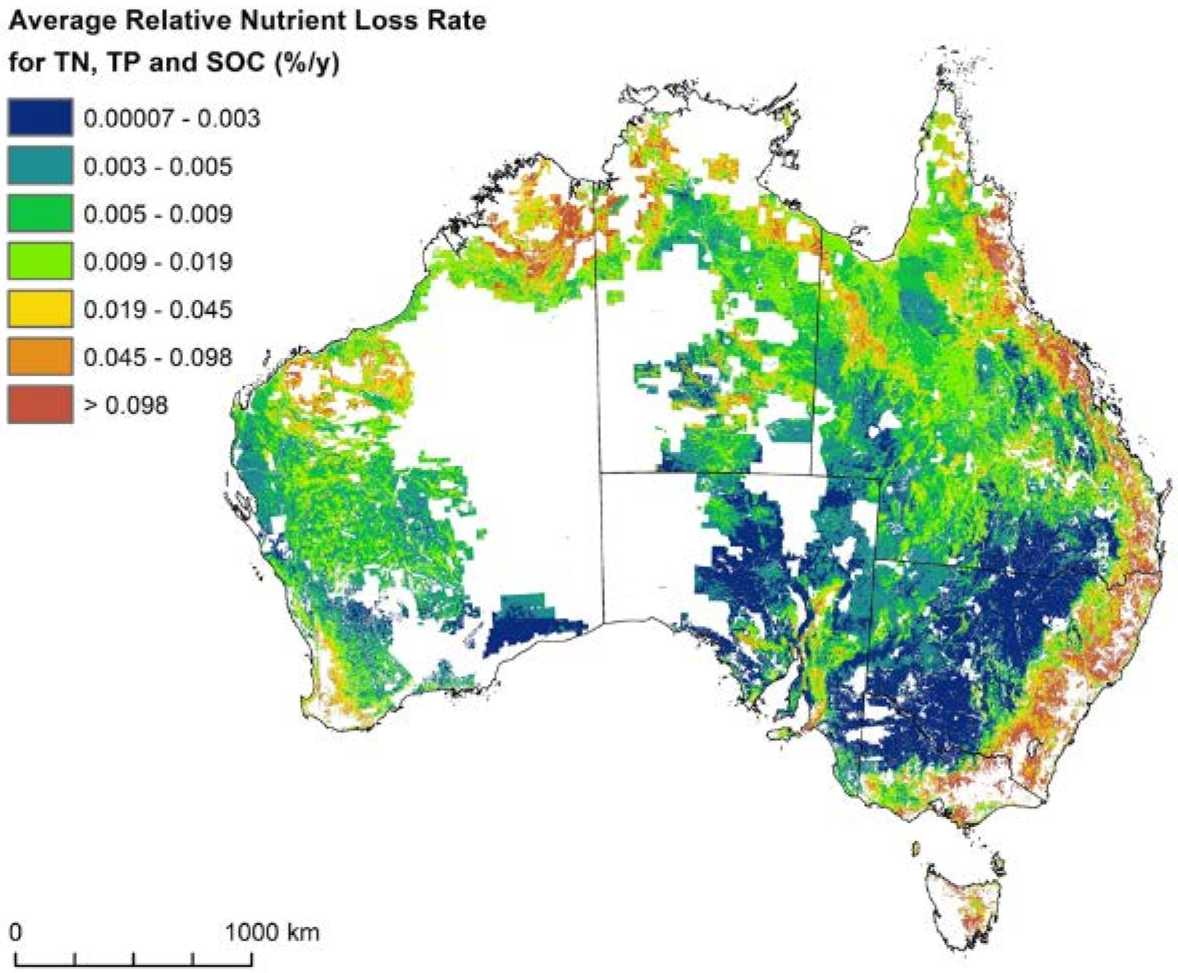


Figure 4.5: Nutrient loss index as calculated using Equation 4.4. The colours used are defined by the 0 to 20, 20 to 40, 40 to 60, 60 to 80, 80 to 90, 90 to 95 and 95 to 100 percentiles of the coloured area. One way of interpreting this figure: if the value was for example 1% nutrient loss per year then on average it would take 100 years to exhaust the nutrient stock – with all other inputs and losses being neutral. Note the extensive areas of nutrient loss by water erosion in the more intensively used areas. The calculations are only made for non-reserve, non-forested parts of Australia.[11]

The approach specified at Equation 4.2 and the index provided at Equation 4.4 provide a simple measure of hillslope erosion and it can be compared to similar estimates for erosion by wind.

4.3.3 A time trend measure of the bare soil and vegetative cover as influencing water erosion

In this section we provide an analysis of fractional cover (2000 to 2016) to address the limitations of Teng et al. (2016) discussed in Section 4.3.1 and, consequently, included in Figures 4.1, 4.2, 4.3, 4.4 and 4.5. For any given plot of land, the extent of vegetative cover indicates the erosion risk from its maximum (bare soil) to its minimum (fully covered) at any given time. Vegetation cover is

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[11] This figure provides the basis for the map "An index of average relative nutrient loss rate from hillslope soil erosion" for the Regional Partnerships App on the National Landcare Program website (http://www.nrm.gov.au/national-landcare-program). In the three-class map, *High* corresponds to the >95 to 100 percentile in Figure 4.5, *Medium* corresponds to the >80 to 95 percentile, and *Low* corresponds to the 0 to 80 percentile.

highly variable through time, both in its forms (including growing vegetation, mulch and litter) and its extent. An analysis of cover over a long period of time provides a useful estimate of the average risk of erosion.

Yang (2014) provides a method for combining remotely sensed estimates of bare soil, photosynthetic vegetation and non-photosynthetic vegetation (from Guerschman et al., 2009) with monthly rainfall erosivity estimates. This is the best available method of remotely assessing cover for erosion predictions and is well suited to environments where climate is highly variable and non-green vegetation is a significant component of the overall cover. Implementing the method of Yang (2014) to determine the cover factor and thereby providing an updated estimate of the rate of soil erosion across Australia is recommended. However the resources to do this were beyond the scale of this study.

Instead, a more tractable time trend analysis of the bare soil component has been undertaken and it gives a local relative assessment of the rates of soil erosion for the MODIS sensor period (2000 to 2016). This remotely sensed product permits the assessment of the vegetation cover for every satellite overpass (approximately every 16 days for Australia) when an area is cloud free. Guerschman et al. (2009) provide details of how images are processed to calculate the percentages of photosynthetically active cover (green), non-photosynthetically active cover (brown) and bare soil.

In Appendix 3 a brief review of recommended minimum cover levels is provided. This review shows Australian experts recommend that total cover levels (combined green and brown cover) in the range 20 to 70 percent are required to keep erosion to a minimum. Here we select 50 percent cover as an indicator level of cover, below which significant acceleration of erosion by water will occur in both cropping and grazing lands. This indicator level is identical to cases where the level of bare soil is greater than 50 percent.

We have used the threshold of 50 percent total cover to screen the fractional cover for the 17 year period 2000-2016 and report the findings as maps for each aggregated year. The aggregated measure for each year is given by:

$$Bare\ soil\ erosion\ index\ for\ year\ Y = \frac{number\ of\ images\ in\ year\ Y\ where\ the\ percent\ of\ bare\ soil\ is > 50\%}{total\ number\ of\ images\ interpretable\ for\ \ year\ Y} \quad [4.5]$$

These data can then be presented as tiling of seventeen annual maps of the bare soil index of erosion (Figure 4.6).

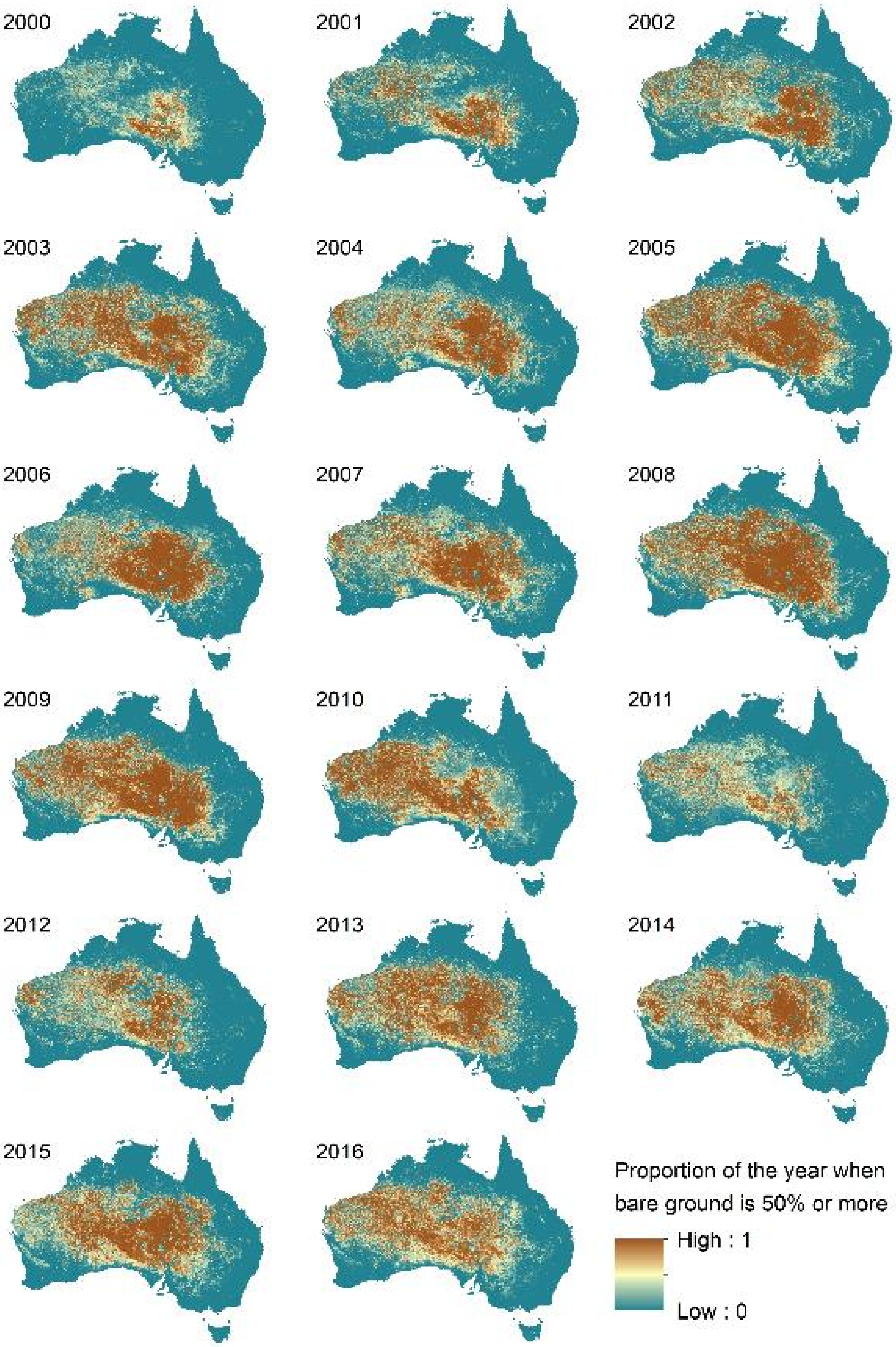

Figure 4.6: Annual maps of the bare soil index of erosion as defined in Equation 4.5. The bare soil index is the proportion of each year when bare ground is equal to or greater than 50% of each grid cell (fractional cover is less than 50%), derived from MODIS fractional cover time series (Guerschman et al., 2009). 0 values (blue) represent greater than 50% fractional cover for the whole year, while values of 1 (brown) indicate fractional cover less than 50% for the whole year.

To interpret the cover index between NRM regions a further measure is introduced:

$$Regional\ bare\ ground\ indicator = \frac{\sum Bare\ soil\ erosion\ index\ for\ each\ pixel\ in\ the\ region}{Number\ of\ pixels\ in\ the\ region} \quad [4.6]$$

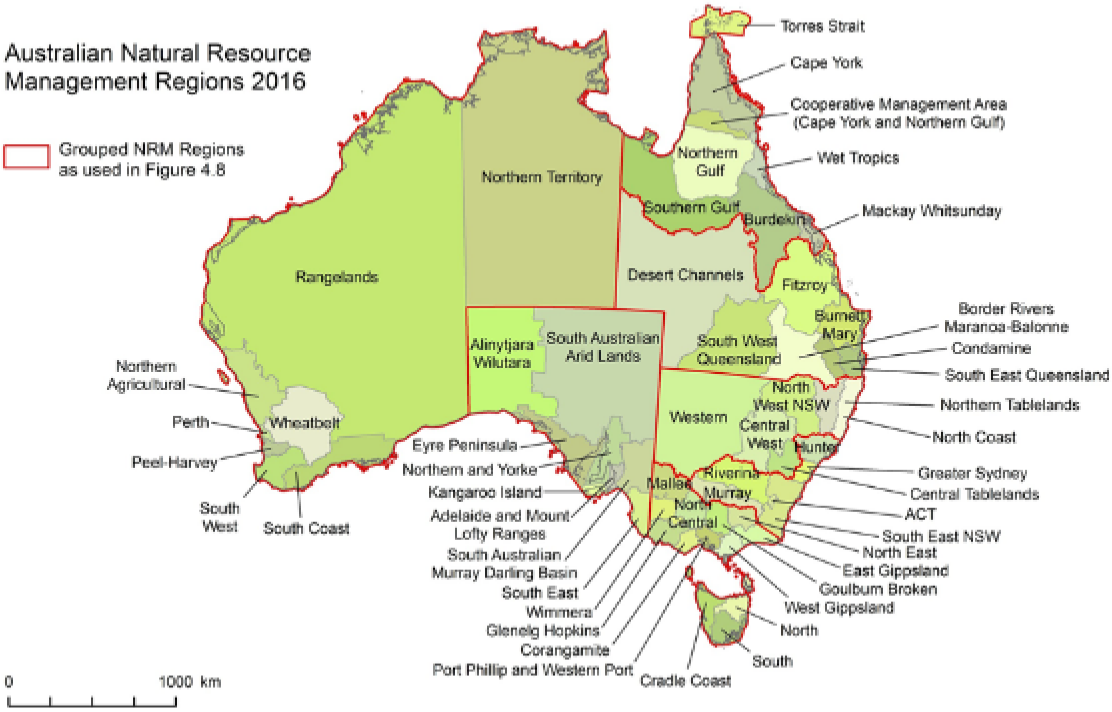

Figure 4.7: Map of the 2016 Australian Natural Resource Management Regions 2016 (dataset from the Australian Government Department of the Environment). The red outlines show how the Regions are grouped in the graphs in Figure 4.8.

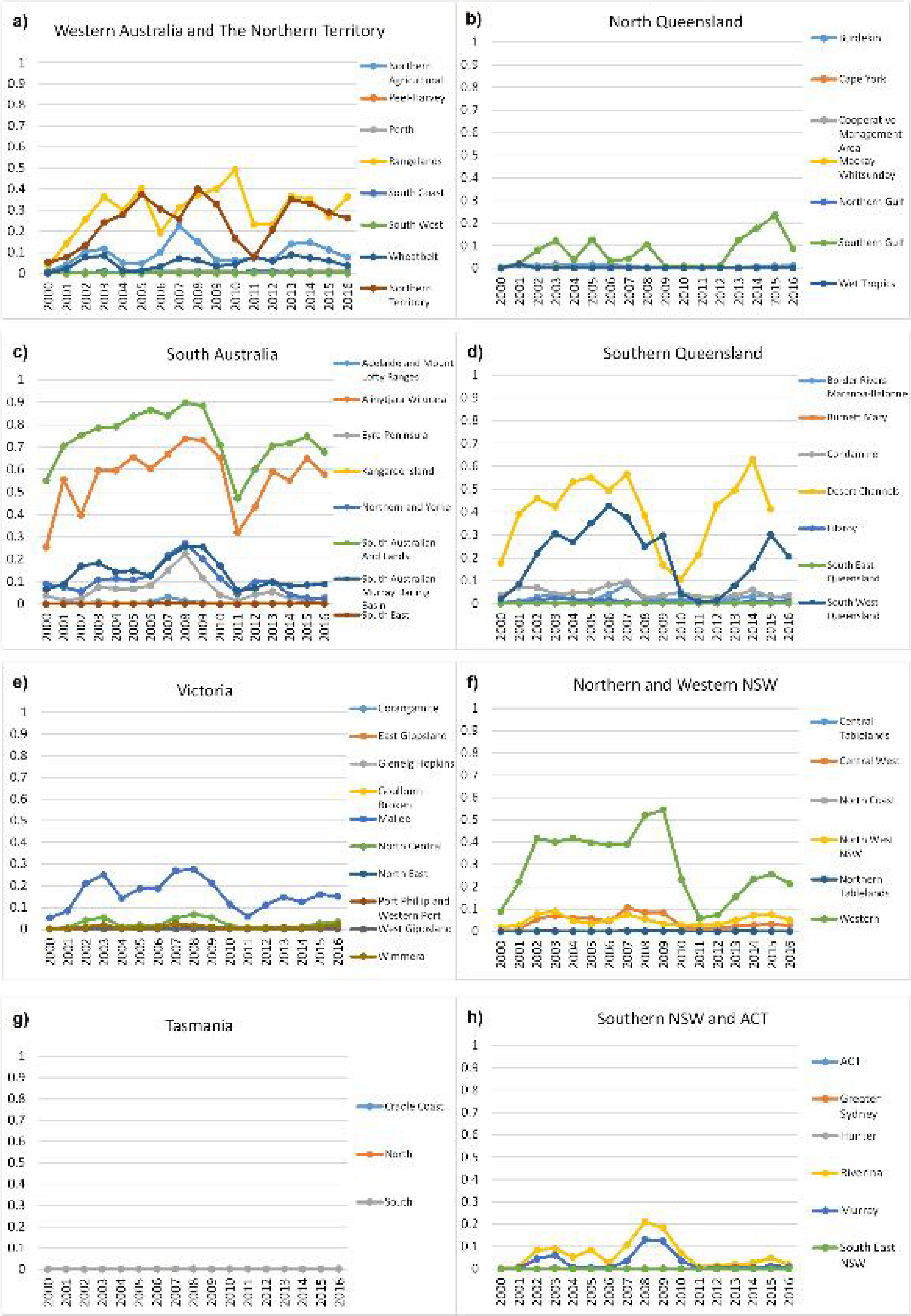

Figure 4.8: Time series of the regional bare ground indicator when bare ground is greater than 50% (fractional cover is less than 50%), spatially averaged for each NRM Region for the years 2000 to 2016. Generally, a higher value of the y-axis value results in a higher long term risk of erosion by water and wind. Other factors such as the influence of topography, soil erodibility and rainfall erosivity are not included here but are reflected in the time averaged maps presented in Figure 4.1. Some regions show a gradual rundown of cover levels when drought persists over several years. See Table 4.1 for further interpretation.

The influence of drought on vegetation is coupled to the influence of human management. Specifically, in grazing systems stocking rates may change in response to the available vegetative biomass. For vegetation-cover to fall below thresholds for soil erosion (typically 50% ground cover) reducing stock numbers as dry weather persists is a key point in the coupling of a meteorological drought to later soil erosion. In cropping systems, decisions on whether to plant crops are often determined by the available soil moisture.

4.3.4 Opportunities for reducing soil erosion by water

The map of hillslope erosion rate by water provided by Teng et al. (2016) and reproduced in Figure 4.1 is the best available guide to spatial priorities as guided by historic erosion rates. Limitations to this map have been described above. The data for this map are publicly available in GIS format from http://doi.org/10.4225/08/582cef2dd5966.

Most states have guidelines for soil conserving practices. Web-published resources are available for Queensland, New South Wales, Victoria, Tasmania, South Australia, Western Australia and the Northern Territory. While they are of varying detail and currency, they provide techniques based on accumulated experience. The uptake of available techniques is likely to be the single largest limitation on controlling soil erosion by water. There are opportunities for learning exchanges between states. For instance, the recent edition of the Queensland guidelines is relevant to several other jurisdictions.

A package of improved grazing management practices for semi-arid tropical grazing has been developed by McIvor (2012) and is being promoted by government and industry bodies. This package includes guides to stocking rates, pasture spelling and prescribed burning with the dual objectives of profitability and sustainability. Further uptake of this package is a vital part of addressing the soil erosion problem across the grazed landscapes of Northern Australia.

Seasonal forecasting of rainfall (see Bureau of Meteorology, 2017) can be especially useful for land managers' decision making concerning both animal stocking numbers and whether to plant a crop. Increased and better use of seasonal climate forecasts have the potential to reduce the instances of a combination of high stocking rates, low available grass feed and low animal sale prices (e.g. McKeon et al. 2000). In marginal cropping landscapes, seasonal climate forecasts have the potential to reduce the occurrence of failed crops and the resulting bare soil (e.g. Nelson et al., 2002). The Bureau of Meteorology provides seasonal maps of the past accuracy of these maps that further inform these decisions.[12] However, Marshall et al. (2011) found a reluctance by decision makers in grazing lands to use these tools.

In cropping areas it is widely accepted that zero or reduced tillage with the retention of crop residues are appropriate to conserve soil moisture, maintain soil structure and reduce soil erosion by water and wind (e.g. Carrol et al., 1997 and Malinda, 1995).

Even in well-managed grasslands of southern Australia soil erosion rates remain well above soil formation rates (e.g. Hancock et al., 2015). Therefore the application of soil conservation techniques across most managed landscapes remains essential to sustain soil and nutrient stocks.

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[12] See http://www.bom.gov.au/climate/ahead/about/#tabs=Past-accuracy

Hillslope erosion due to unsealed roads and tracks associated with CSG operations is an emerging form of erosion. Vacher et al. (2014) documented an example of soil disturbance associated with CSG operations. In another context, Motha et al. (2004) found around 40 percent of the sediment carried by a stream in a predominantly agricultural catchment in West Gippsland (Victoria) was sourced from unsealed roads and tracks.

The study of Lal et al. (2013) shows that cropping in the wet-dry tropics of northern Australia results in sustained high to extreme erosion by water – even on modest slopes. This study investigated an experimental farm in the Northern Territory where cropping had been conducted on slopes of 1.5 degrees for several decades. There have also been observations of new gully networks associated with the recent intensification of land use in northern Australia (McCloskey et al., 2016, Olley et al., 2013 and Shellburg et al., 2016). These studies suggest soil erosion will be a major constraint on cropping development in northern Australia and that best management practices developed elsewhere may need to be revised for these landscapes.

4.3.5 Interpretation and recommended erosion mitigation strategies for NRM regions

Table 4.1 provides a synopsis of the interpretation and recommended erosion mitigation strategies for each of Australia's NRM regions.

Table 4.1: A synopsis interpretation of each NRM region's bare soil time trends, recent erosion-related knowledge and recommended area-specific strategies. Note that the Australia-wide recommended strategies presented in the previous section apply to many or all the NRM regions.

Jurisdiction & NRM region	**Comments on vegetation cover and erosion risk based on the NRM fractional cover plots (see Figures 4.6 and 4.8).**	**Comments on rates of hillslope erosion by water and associated nutrient loss (see Figures 4.1 to 4.5)**	**Comments on appropriate erosion mitigation strategies specific to this region (see text for strategies common to many regions)**
ACT	The ACT's risk of hillslope erosion is generally low with the exception of small areas of tillage for improved pastures and new urban development.	Some forested parts of the ACT are mapped as having a high soil erosion rate by Teng et al. (2016). This is an artefact of steep slopes and long slope lengths in forested lands. This result should be ignored.	Focus on erosion control should primarily be on existing gully networks which continue to yield significant sediment.
NSW Central Tablelands	The majority of this region maintained ground cover during the Millennium Drought to reduce hillslope erosion during drought-breaking rains.	Predicted erosion and nutrient loss rates are very patchy. Soil conservation practices for highly erodible soils and rehabilitation of existing gully networks are a priority.	The identification of active gully networks should guide rehabilitation of these major sediment sources.
NSW Central West	Some parts of this region have a perennial problem with maintaining ground cover to mitigate against hillslope erosion.	Predicted erosion and nutrient loss rates are very patchy. Soil conservation practices for highly erodible soils and rehabilitation of existing gully networks are a priority.	The uptake of existing soil conservation guidelines remains a priority.
Greater Sydney	Risk of hillslope erosion during the Millennium Drought was confined to very small sub-areas.	Some forested parts of the Greater Sydney basin are mapped as having a high soil erosion rate by Teng et al. (2016). This is an artefact of steep slopes and long slope lengths in forested lands. This result should be ignored.	

Jurisdiction & NRM region	Comments on vegetation cover and erosion risk based on the NRM fractional cover plots (see Figures 4.6 and 4.8).	Comments on rates of hillslope erosion by water and associated nutrient loss (see Figures 4.1 to 4.5)	Comments on appropriate erosion mitigation strategies specific to this region (see text for strategies common to many regions)
NSW Hunter	The risk of hillslope erosion during the Millennium Drought was confined to very small sub-areas.		The control of active gully networks remains a priority.
NSW Murray	There was a rundown of cover in some areas during 2007-2010. This effect increased the susceptibility of the region to wind and water erosion.	Gentle slopes and moderate rainfall erosivity combine to make this a region of low to moderate erosion rates in the analysis of Teng et al. (2016).	Stocking rates during drought periods appear to be contributing to elevated hillslope erosion rates.
NSW North Coast	Though this region has historically low levels of soil exposure, high rainfall erosivity and steep topography combine to make for a moderate to high erosion risk.	Some parts of the North Coast NRM region are mapped as having a high soil erosion rate by Teng et al. (2016). This is an artefact of steep slopes and long slope lengths in forested lands. This result should be ignored.	Rohde et al. (2013) provide details of sugarcane management practices to reduce erosion hazard in key phases of the cropping cycle.
North West NSW	The arid portion of this NRM region is likely to have naturally low cover. The perennially low cover of the region cannot be attributed to natural or human influences by this analysis.	Low slopes make the risk of soil erosion by water mostly low.	Some of the principles of McIvor (2012) are likely to be relevant to the grazing industries in this region.
NSW Northern Tablelands	This is generally an area of low hillslope erosion risk with a few exceptions where overgrazing and topography combine to increase the risk.	This region appears to have maintained good cover levels throughout the Millennium Drought.	
NSW Riverina	There was a significant rundown of cover during the Millennium Drought (2000-2009).	Gentle slopes and moderate rainfall erosivity combine to make this a region of low to moderate erosion in the analysis of Teng et al. (2016).	Some re-examination of the factors leading to the high stocking rates during droughts seems warranted.
South East NSW	The risk of hillslope erosion during the Millennium Drought was confined to small sub-areas.	Some parts of SE NSW are mapped as having a high soil erosion rate by Teng et al. (2016). This is an artefact of steep slopes and long slope lengths in forested lands. This result should be ignored.	
NSW Western	Soils are continuously exposed to water and wind erosion. This analysis cannot separate the natural and human-driven effects. There was a sustained rundown of cover levels in the period 2000-2009.		Some re-examination of the factors leading to the high stocking rates during droughts seems warranted.
Northern Territory	Sustained low cover levels were measured across the semi-arid parts of the Northern Territory in the period 2000-2016.	Where low cover levels and moderate topography combine, hillslope erosion is high. Nutrient losses in these low fertility environments appear significant. In northern Australia new networks of gullies have recently developed as a result of land-use intensification (e.g. McCloskey et al., 2016)	In the grazing lands the guidelines of McIvor (2012) provide a comprehensive and practical approach to reducing erosion while maintaining or enhancing productivity.

Jurisdiction & NRM region	Comments on vegetation cover and erosion risk based on the NRM fractional cover plots (see Figures 4.6 and 4.8).	Comments on rates of hillslope erosion by water and associated nutrient loss (see Figures 4.1 to 4.5)	Comments on appropriate erosion mitigation strategies specific to this region (see text for strategies common to many regions)
QLD Border Rivers Maranoa-Balonne	During the Millennium Drought this region had small areas of low cover.	Gentle slopes in the cropping lands make the risk of erosion by water low to medium.	
QLD Burnett Mary	This area of relatively low hillslope erosion risk had a few local areas emerge during the period 2000-2016.	Some horticultural areas require industry-specific soil conservation measures (e.g. the maintenance of litter or grass cover beneath tree crops). Streambank erosion and gully erosion are known to be major forms of erosion that contribute to downstream water quality problems.	Rohde et al. (2013) provide details of sugarcane management practices to reduce erosion hazard. In the grazing lands the management of gully and streambank erosion should be the focus.
Burdekin	The evidence provided by the fractional cover of 2000-2016 analysis in Figures 4.6 and 4.8 conflict with other analyses and observations for this region. This region has persistent soil exposure. The largely grazing landscapes have slopes, rainfall erosivity and soil exposure that combine to make it one of the highest erosion regions in Australia.	Teng et al. (2016) and Lu et al. (2003) both identified this region as having the highest hillslope erosion rates in Australia.	In the grazing lands the guidelines of McIvor (2012) provide a comprehensive and practical approach to reducing erosion while maintaining or enhancing productivity. Rohde et al. (2013) provide details of sugarcane management practices to reduce erosion hazard. In the grazing lands the current focus on rehabilitating existing gullies is justified.
Cape York	This region has relatively low erosion risk due to most areas having perennial cover. However, parts of this region have been cleared in recent years and there is an emerging risk of erosion including gullying.	In contrast to the analysis presented in Figure 4.8, there is some recent evidence of land development and associated emerging erosion problems (e.g. Olley et al., 2013)	The further development of highly dispersive sodic soils should be avoided due to the risk of new gully networks. In the remaining grazing lands the guidelines of McIvor (2012) provide a comprehensive and practical approach to reducing erosion while maintaining or enhancing productivity.
QLD Condamine	Figure 4.8 areas shows there have been persistent areas of low cover in this region for the last 17 years.	The Eastern Darling Downs has a history of medium to high erosion rates and also a history of the early implementation of soil conservation measures.	Strip cropping on floodplains was pioneered in this region. Opportunities remain to expand the uptake of this measure. In the grazing lands the guidelines of McIvor (2012) provide a comprehensive and practical approach to reducing erosion while maintaining or enhancing productivity.
QLD Cooperative Management Area	This region has perennially low cover areas associated with high exposure to water and wind erosion.		In the grazing lands the guidelines of McIvor (2012) provide a comprehensive and practical approach to reducing erosion while maintaining or enhancing productivity.
QLD Desert Channels	Figure 4.8 shows this area had persistent areas of low cover for almost all of the period 2000-2016.	Soils are continuously exposed to wind and water erosion. This analysis cannot separate the natural and human-driven effects.	

Jurisdiction & NRM region	**Comments on vegetation cover and erosion risk based on the NRM fractional cover plots (see Figures 4.6 and 4.8).**	**Comments on rates of hillslope erosion by water and associated nutrient loss (see Figures 4.1 to 4.5)**	**Comments on appropriate erosion mitigation strategies specific to this region (see text for strategies common to many regions)**
QLD Fitzroy	The evidence provided by the fractional cover of 2000-2016 analysis in Figures 4.6 and 4.8 conflicts other analyses and observations for this region. Teng et al. (2016) and local studies conclude there is a nationally high rate of hillslope erosion and associated nutrient loss in this NRM region.	There is a legacy of long-term field experiments on the effectiveness of land-use change and soil conservation measures in the central Fitzroy basin (e.g. Carrol et al. 1997 and Cowie et al. 2007). The practical outcomes of these trials are well represented in the state guidelines (Queensland Government, 2015).	In the grazing lands the guidelines of McIvor (2012) provide a comprehensive and practical approach to reducing erosion while maintaining or enhancing productivity. The current focus on rehabilitating existing gullies is justified and recent gully mapping will assist in target this work. Where floodplains are cropped, strip-cropping techniques used on the Darling Downs may be adapted for this region.
QLD Mackay Whitsunday	The fractional cover analysis presented in Figures 4.6 and 4.8 shows this region maintained good cover levels 2000-2016.	The forested part of the region is mapped as having a high soil erosion rate by Teng et al. (2016). This is an artefact of steep slopes and long slope lengths in forested lands. This result should be ignored. This region has high rainfall and good cover. Some localities have occasional bare soils, likely associated with cropping for sugarcane or overgrazing.	The high rainfall erosivity and relatively steep slopes of much of this region justify a continued focus on erosion control. Rohde et al. (2013) provide details of sugarcane management practices to reduce erosion hazard.
QLD Northern Gulf	The fractional cover analysis presented in Figures 4.6 and 4.8 shows this region maintained good cover levels 2000-2016.		In the grazing lands the guidelines of McIvor (2012) provide a comprehensive and practical approach to reducing erosion while maintaining or enhancing productivity.
South East Queensland	This region has a history of relatively high vegetative cover and consequent low hillslope erosion risk.	The forested part of South East Queensland is mapped as having a high soil erosion rate by Teng et al. (2016). This is an artefact of steep slopes and long slope lengths in forested lands. This result should be ignored.	The current focus on remediating gully and streambank erosion is strongly supported by the peer reviewed evidence.
South West Queensland	The fractional cover analysis presented in Figures 4.6 and 4.8 shows this region had large areas of bare soils during the Millennium Drought and in the period 2013-2016. This trend leaves these areas highly vulnerable to wind and water erosion.	Some soils are continuously exposed to water and wind erosion. In areas of moderate topography and consistently low cover hillslope erosion is continuing at moderate to high rates.	In the grazing lands the guidelines of McIvor (2012) provide a comprehensive and practical approach to reducing erosion while maintaining or enhancing productivity.
QLD Southern Gulf	Parts of this region have perennially high soil exposure. This analysis cannot separate the natural and human-driven effects. Dry season burning has a specific influence here.	In northern Australia new networks of gullies have recently developed as a result of land use intensification (Shellburg et al., 2016)	In the grazing lands the guidelines of McIvor (2012) provide a comprehensive and practical approach to reducing erosion while maintaining or enhancing productivity.
QLD Wet Tropics	This high rainfall region generally has high cover. Some localities have occasional bare soils, likely associated with sugarcane plant crops or overgrazing.	The forested part of the Wet Tropics NRM region is mapped as having a high soil erosion rate by Teng et al. (2016). This is an artefact of steep slopes and long slope lengths in forested lands. This result should be ignored.	This is a high energy environment where high rainfall intensities and steep slopes combine to make erosion rate very high. Maintenance of high levels vegetation cover at all times is

Jurisdiction & NRM region	Comments on vegetation cover and erosion risk based on the NRM fractional cover plots (see Figures 4.6 and 4.8).	Comments on rates of hillslope erosion by water and associated nutrient loss (see Figures 4.1 to 4.5)	Comments on appropriate erosion mitigation strategies specific to this region (see text for strategies common to many regions)
			recommended. Rohde et al. (2013) provide details of sugarcane management practices to reduce erosion hazard in this key phase of the cropping cycle.
SA Adelaide and Mount Lofty Ranges	The fractional cover analysis presented in Figures 4.6 and 4.8 shows this region maintained good cover levels for almost all of its areas in the period 2000-2016.		The Adelaide and Mount Lofty Ranges Board NRM Board Region (2011) developed a set of best management practice guidelines for small grazing properties that included erosion management.
SA Alinytjara Wilurara	The fractional cover analysis presented in Figures 4.6 and 4.8 shows this region has very high levels of bare soil when compared nationally. This analysis cannot separate the natural and human-driven effects.		
SA Eyre Peninsula	Soils are often exposed to water and wind erosion. Vegetation cover was observed to partly recover in 2011.	Large areas of bare soil did appear during the Millennium Drought making these soils susceptible to wind and water erosion. Widespread of adoption of no-till farming has reduced erosion risk in recent years.	Moderate rainfall intensities and gentle slopes combine to give this area a low to medium risk of erosion by water.
SA Kangaroo Island	The fractional cover analysis presented in Figures 4.6 and 4.8 shows this region maintained good cover levels for almost all of its areas in the period 2000-2016.		Moderate rainfall intensities and low topographic slopes combine to make this area have a low to medium risk of erosion by water.
SA Northern and Yorke	Soils are often exposed to water and wind erosion. Vegetation cover was observed to partly recover in 2011.	Large areas of bare soil did appear during the Millennium Drought making these areas susceptible to wind and water erosion. Adoption of no-till farming is widespread and this has reduced erosion risk substantially.	Moderate rainfall intensities and low topographic slopes produce a low to medium risk of erosion by water.
South Australian Arid Lands	The fractional cover analysis presented in figures 4.6 and 4.8 shows this region has very high levels of bare soil when compared nationally.	Soils are continuously exposed to water and wind erosion. This analysis cannot separate the natural and human-driven effects.	
SA Murray Darling Basin	Significant areas are often exposed to wind and water erosion. Vegetation cover was observed to partly recover in 2011.		Moderate rainfall intensities and low topographic slopes produce a low to medium risk of erosion by water.
SA South East	The fractional cover analysis presented in Figures 4.6 and 4.8 shows this region maintained good cover levels for almost all areas in the period 2000-2016.	Intensive land use for horticulture results in small areas with a significant risk of hillslope erosion. No-till farming has been widely adopted and this has reduced erosion risk across the region.	For the majority of this NRM region, moderate rainfall intensities and low topographic slopes produce a low to medium risk of erosion by water.

Jurisdiction & NRM region	Comments on vegetation cover and erosion risk based on the NRM fractional cover plots (see Figures 4.6 and 4.8).	Comments on rates of hillslope erosion by water and associated nutrient loss (see Figures 4.1 to 4.5)	Comments on appropriate erosion mitigation strategies specific to this region (see text for strategies common to many regions)
TAS Cradle Coast	The fractional cover analysis presented in Figures 4.6 and 4.8 shows that all regions of Tasmania maintained relatively good vegetative cover in the period 2000-2016.	Some parts of the Cradle Coast are mapped as having a high soil erosion rate by Teng et al. (2016). This is an artefact of steep slopes and long slope lengths in forested lands. However, moderate erosion is present on Ferrosol slopes under intensive cropping, and skeletal soils where peats have been damaged by wildfires in the South West.	This is an area of generally low risk of hillslope erosion by water. There are a few local exceptions where steep slopes are cropped and plant residues are not retained.
TAS North	The fractional cover analysis presented in Figures 4.6 and 4.8 shows that all regions of Tasmania maintained relatively good vegetative cover in the period 2000-2016.	Central Tasmania is mapped as having a high soil erosion rate by Teng et al. (2016). This is an artefact of steep slopes and long slope lengths in forested lands. This result should be ignored.	This is a region of generally low risk of hillslope erosion by water. There are a few local exceptions where steep slopes are cropped for horticulture and plant residues are rarely retained.
TAS South	The fractional cover analysis presented in Figures 4.6 and 4.8 shows that all regions of Tasmania maintained relatively good vegetative cover in the period 2000-2016.	Some parts of southern Tasmania are mapped as having a high soil erosion rate by Teng et al. (2016). This is an artefact of steep slopes and long slope lengths in forested lands. This result should be ignored.	This NRM region has a generally low water erosion risk and soils are rarely exposure to erosive forces.
VIC Corangamite	This region maintained a high level of cover throughout the period 2000-2016. The risk of hillslope erosion is generally low with the exception of a few steeper, highly disturbed hillslopes (including farm tracks), where it is moderate.		Moderate rainfall intensities and gentle slopes combine to make this area produce a low to medium risk of hillslope erosion by water.
VIC East Gippsland	This region has a perennially high level of vegetative cover and therefore a low hillslope erosion risk.	Some forested parts of this region are mapped as having a high soil erosion rate by Teng et al. (2016). This is an artefact of steep slopes and long slope lengths in forested lands. This result should be ignored.	The continued focus on reducing streambank and gully erosion is appropriate.
VIC Glenelg Hopkins	This region has a perennially high level of vegetative cover and therefore a low hillslope erosion risk.	Moderate rainfall intensities and low topographic slopes produce a low to medium risk of erosion by water.	The risk of hillslope erosion is generally low with the exception of a few steep, highly disturbed hillslopes, where it is moderate. The continued focus on reducing streambank and gully erosion is appropriate.
VIC Goulburn Broken	The fractional cover analysis presented in Figures 4.6 and 4.8 shows this region maintained good levels of cover throughout the period 2000-2016.	The risk of hillslope erosion is generally low with the exception of a few steeper, highly disturbed hillslopes.	The continued focus on reducing streambank and gully erosion is appropriate.
VIC Mallee	The Mallee has a perennial problem with maintaining vegetative cover. It's susceptible to wind and, to a lesser extent, water erosion. The fractional cover analysis presented in Figure 4.8 shows up to ~30 percent of this region had a significant erosion risk in 2008.		Moderate rainfall intensities and low topographic slopes produce a low to medium risk of erosion by water.

Jurisdiction & NRM region	Comments on vegetation cover and erosion risk based on the NRM fractional cover plots (see Figures 4.6 and 4.8).	Comments on rates of hillslope erosion by water and associated nutrient loss (see Figures 4.1 to 4.5)	Comments on appropriate erosion mitigation strategies specific to this region (see text for strategies common to many regions)
VIC North Central	Small parts of this region have a perennial problem with maintaining vegetative cover making it susceptible to wind erosion.	Much of the forested uplands of this region are mapped as having a high soil erosion rate by Teng et al. (2016). This is an artefact of steep slopes and long slope lengths in forested lands. This result should be ignored.	Relatively low rainfall erosivities and low topography in the non-forested landscapes combine to make this a low risk of hillslope soil erosion by water. The continued focus on reducing streambank and gully erosion is appropriate.
VIC North East	This region maintained good cover levels through the 2000-2016.	Much of the forested uplands of this region are mapped as having a high soil erosion rate by Teng et al. (2016). This is an artefact of steep slopes and long slope lengths in forested lands. This result should be ignored.	The continued focus on reducing streambank and gully erosion is appropriate.
VIC Port Phillip and Western Port	This region maintained good cover throughout the period 2000-2016.		Locally, gully and streambank erosion control should be maintained as the focus.
VIC West Gippsland	This region has a perennially high level of vegetative cover and therefore a low erosion risk.	Some horticultural areas have steep slopes and use bare fallow practices making the erosion risk moderate for these areas.	Where specific problems are observed, gully and streambank erosion control should be maintained as the focus for remediation resources.
VIC Wimmera	The fractional cover analysis presented in Figure 4.8 shows there were only very small areas (~2 percent) experiencing low cover levels in 2000-2016.		Moderate rainfall intensities and gentle slopes combine to produce a low to medium risk of erosion by water.
WA Northern Agricultural	This region had significant areas of low cover during the period 2000-2016. This results in soil being exposed to wind and, to a lesser extent, water erosion		Rainfall erosivity and topography are moderate, resulting in a moderate hillslope erosion risk
WA Peel-Harvey	The Peel-Harvey region maintained good cover levels throughout the period 2000-2016.		Rainfall erosivity and topography are low to moderate, resulting in a low to moderate hillslope erosion risk
Perth	The Perth region generally has a highly perennial vegetative cover. Some local exceptions exist where horticulture or overgrazing results in periodically low cover levels.		Rainfall erosivity and most topography are moderate, resulting in a moderate hillslope erosion risk.
WA Rangelands	The rangeland soils of Western Australia have a perennially high exposure to water and wind erosion. The attribution of this low cover to natural or human influences was not part of this analysis.	Teng et al. (2016) identified the grazed areas in the Kimberley sub-region having potentially high erosion rates due to the combination of high rainfall erosivity and steep slopes.	In the grazing lands the guidelines of McIvor (2012) provide a comprehensive and practical approach to reducing erosion while maintaining or enhancing productivity.

Jurisdiction & NRM region	Comments on vegetation cover and erosion risk based on the NRM fractional cover plots (see Figures 4.6 and 4.8).	Comments on rates of hillslope erosion by water and associated nutrient loss (see Figures 4.1 to 4.5)	Comments on appropriate erosion mitigation strategies specific to this region (see text for strategies common to many regions)
WA South Coast	The South Coast region had a high cover level throughout the period 2000-2016		Low rainfall erosivity and seasonal patterns of vegetation mean this region has a low to moderate risk of hillslope erosion. Locally, streambank and gully erosion should continue to be the focus.
WA South West	This region maintained good cover levels for the period 2000-2016.		Low rainfall erosivity and seasonal patterns of vegetation mean this region has a low to moderate risk of hillslope erosion
WA Wheatbelt	The analysis presented in Figures 4.6 and 4.8 shows that this region had up to 10 percent of the area highly exposed to erosion during the period 2000-2016.		Further uptake of conservation tillage practices to maintain higher cover levels after the cropping season is a key step to addressing erosion by water in this region.

A summary of the significance of hillslope erosion is provided in Figure 4.9. Note that while having low rankings, the risk of erosion by water is accelerating due to land use intensification in the Southern Gulf (QLD) and Cape York (QLD) NRM regions.

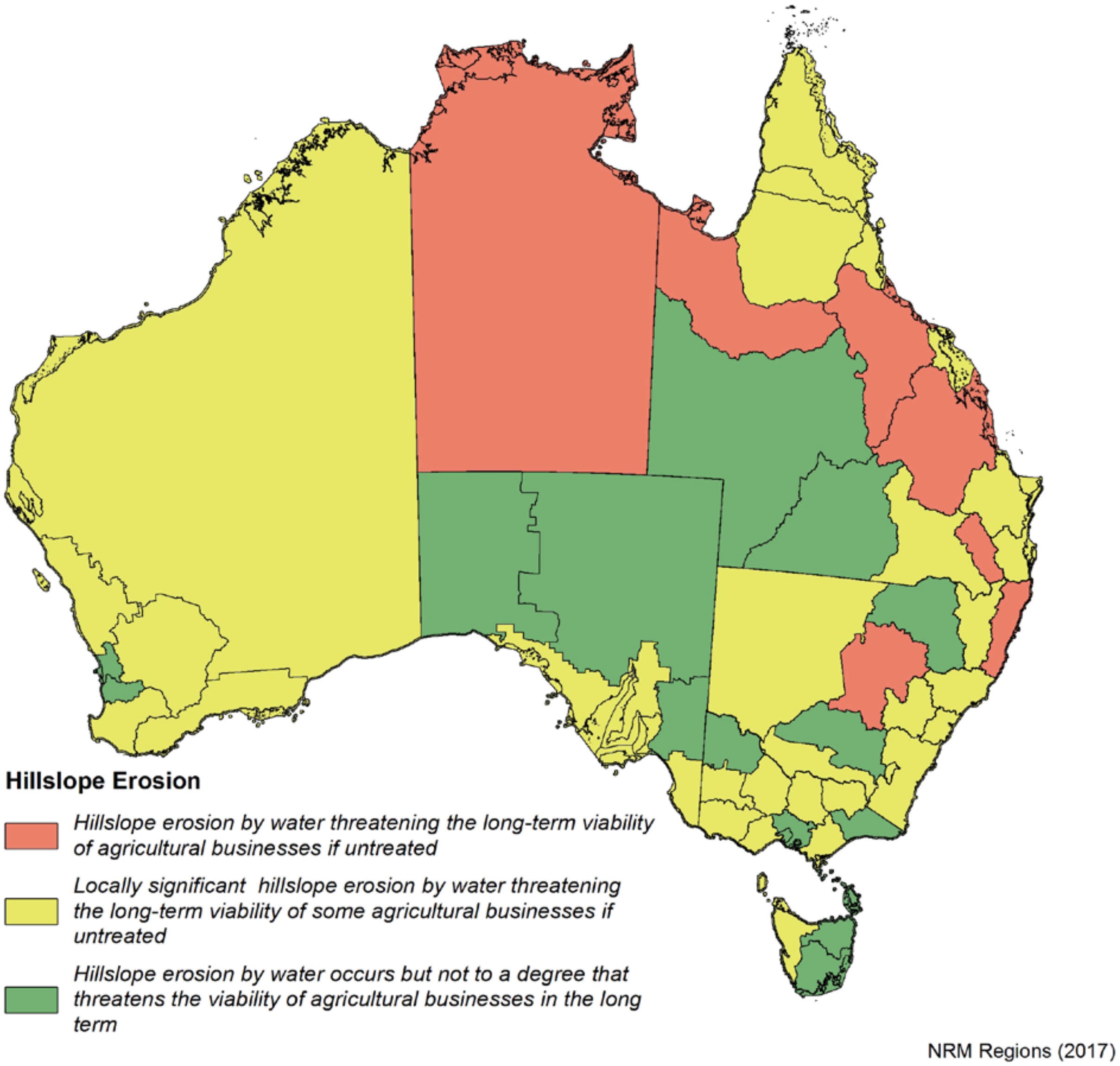


Figure 4.9: The significance of hillslope erosion for Australia's NRM regions. Note that while having low rankings, the risk of erosion by water is accelerating due to land use intensification in the Southern Gulf (QLD) and Cape York (QLD) regions.

4.4 Priorities for intervention and future analysis

We conclude the analysis of soil erosion by water with a list of suggested priorities for intervention. They reflect both an emphasis on prevention of erosion and reduction of existing erosion.

4.4.1 Priorities for intervention

1. Soil erosion by water continues to occur at unsustainable rates for most of the managed landscapes of Australia and increased awareness is required across all agricultural industries. Practical presentations to the grazing and cropping industries and relevant government decision-makers are a priority.
2. The ongoing quest for agricultural development in Northern Australia has clear risks associated with soil erosion. The introduction of a quantitative sustainability agenda into

decision making is essential and has started through the Northern Territory Government's mitigation schemes that aim to ensure the sustainable conversion of pasture and woodland into cropland. The danger is to repeat historical mistakes which compromise local soil productivity and create off-site impacts. A specific example of this is the emergence of new gully networks in northern Australia. The cost of mapping dispersive soils and precluding land-use intensification on these vulnerable soils is dwarfed by the costs of impacts and remediation after gullies have formed.

3. The uptake of new reduced tillage and residue retention practices in the sugarcane industry is a clear priority with multiple benefits for the land resource, on- and off-site impacts.

4.4.2 Recommended future analyses:

1. A revision of the national estimate of hillslope erosion by Teng et al. (2016) should be performed to include:
   - the current estimate of time varying fractional cover (as presented in Figure 4.6)
   - recalculation of the cover factor using the fractional-cover approach as described by Yang (2014) (significantly, this should include the influence of seasonal patterns of rainfall and cover as identified by Lu et al. (2003))
   - use of the most recent high-resolution topographic data
   - masking to exclude land uses where the methodology is not appropriate
   - checking new estimates against long-term field data and appropriate sediment tracer methodologies. Only with this final step can a full peer-review process be implemented and the output of Teng et al. (2016) superseded.
2. A causal analysis of the record of fractional cover (i.e. bare soil and vegetative cover) as presented in Figure 4.6 is required. It should aim to differentiate the drivers of cover and in particular, the impacts of climate and land management.
3. A quantitative social science investigation into the factors that limit the uptake of soil conservation practices.

5 Nutrient imbalances

5.1 Significance, causes and consequences

The productivity and sustainability of Australian agriculture depends fundamentally on effective nutrient management. The main nutrients of interest are nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg) and sulfur (S). Of the 17 elements known to be essential for plant and microorganism growth, eight are required in minute quantities. These so-called micronutrients or trace elements are boron, chlorine, cobalt, copper, iron, manganese, molybdenum and zinc. Micronutrients can be harmful if there are large amounts in available forms. Deficiencies, on the other hand, are more common in highly leached sands, organic soils and soils with very high pH. They can also develop on intensively cropped soil that has been fertilised only with macronutrients such as N and P.

The need to improve nutrient management in agriculture is a national challenge and global imperative. The four global actions of highest priority identified by the ITPS (2015a) all have a connection to nutrient management and their third action is unequivocal:

> *'Compelling evidence exists that humanity is close to the global limits for total fixation of nitrogen and regional limits for phosphorous fertilizer use. Therefore we should act to stabilize or reduce global nitrogen and phosphorous fertilizer use while simultaneously increasing fertilizer use in regions of nutrient deficiency. Increasing the efficiency of N and P use by plants is a key requirement to achieve this goal.'*

Nutrient imbalances are widespread. The ITPS (2015a) define these imbalances as occurring when inputs of nutrients (through additions of chemical or organic fertilisers or other sources) are either:

- insufficient to allow crops to achieve their development and yields, or
- in excess of nutrients exported during the harvest of the crops.

Nutrient insufficiency affects profitability and it can contribute to land degradation. In many parts of the world, nutrient insufficiency is a root cause of food insecurity (ITPS 2015c). Nutrient excess can negatively affect water quality and it is a major contributor to greenhouse gas emissions primarily through the release to the atmosphere of nitrous oxides.

The history of agricultural production in Australia highlights the importance of nutrient management. Figure 5.1 shows the major negative impact on wheat yields caused by the mining of soil nutrients in the early phases of dryland agriculture. Improved cultivars and superphosphate halted the initial phase of nutrient exhaustion around 1900 in many farming systems. Significant yield improvements then occurred after the 1940s due to increased N-inputs via legumes and improved rotations. In some districts, the detection and remedying of micronutrient deficiencies also had a major impact on crop and pasture production.

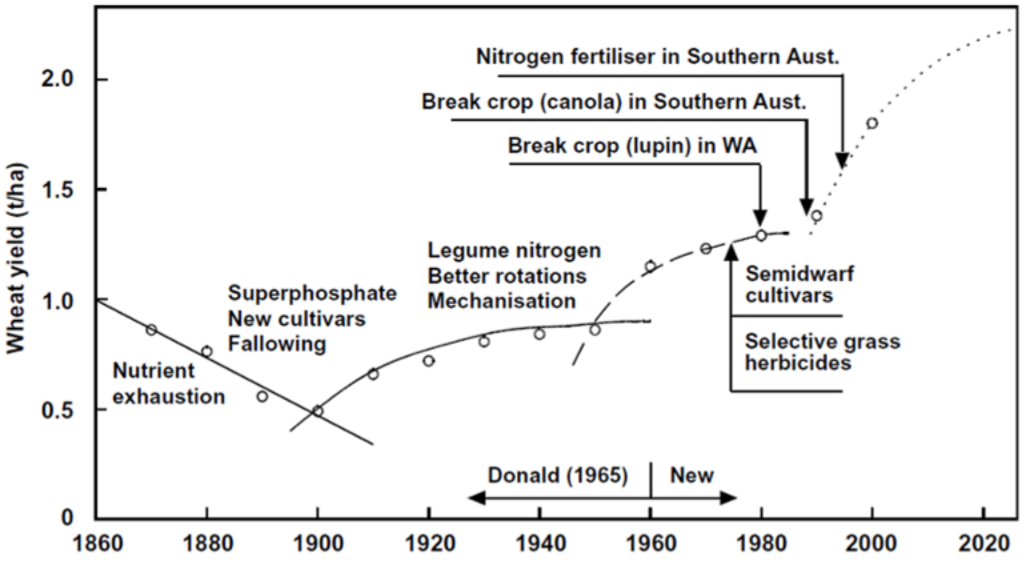


Figure 5.1: Wheat yields in Australia from 1870 to 2000 (after Donald (1965) and Angus et al. (2010)).

Fertiliser use has grown steadily since the 1950s, transforming agriculture and food production in most parts of the world including Australia (Aarons et al. 2017). Ongoing intensification of agricultural land has ecological consequences, including negative impacts on carbon sequestration, biodiversity and water and air quality. Of particular concern are low efficiencies of use for N and P and subsequent nutrient losses through soil water drainage and surface runoff and volatilization of ammonia. Intensive animal production is a major source of N and P loss to the environment because of large nutrient fluxes from fertiliser, imported feed and biological N-fixation, encouraged by the high profitability of producing animal protein. As demand for animal protein continues to rise, a growing global issue is managing excreted N and P and land application of animal manure.

In Australia the increase in N-fertiliser usage was delayed to some extent for several reasons including unpredictable responses to N fertilisers (Figure 5.2). However, the introduction of break crops (e.g. canola), management of other constraints (e.g. acidity), premiums for higher protein wheat and improved seasonal climate forecasting reduced the risks associated with N fertilisers (Angus and Grace 2017). As a consequence, N fertiliser usage in Australia increased dramatically. The Millennium Drought (van Djik et al. 2013) slowed this trend but it soon re-established and current rates of N-fertiliser use are now at an historic high while rates for P fertiliser have been relatively stable (especially after the removal of subsidies for superphosphate in the early 1970s) with slight declines in recent years. K usage has steadily increased, particularly in Western Australia during the 1990s (NLWRA 2001) (Figure 5.3).

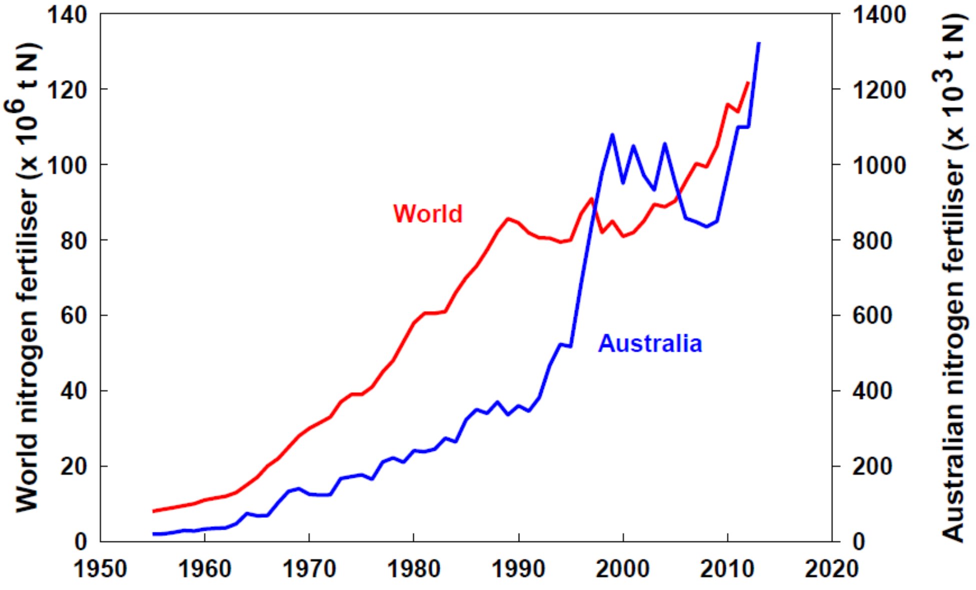


Figure 5.2: Changes in N-fertiliser use in Australia and the world (Angus and Grace 2017).

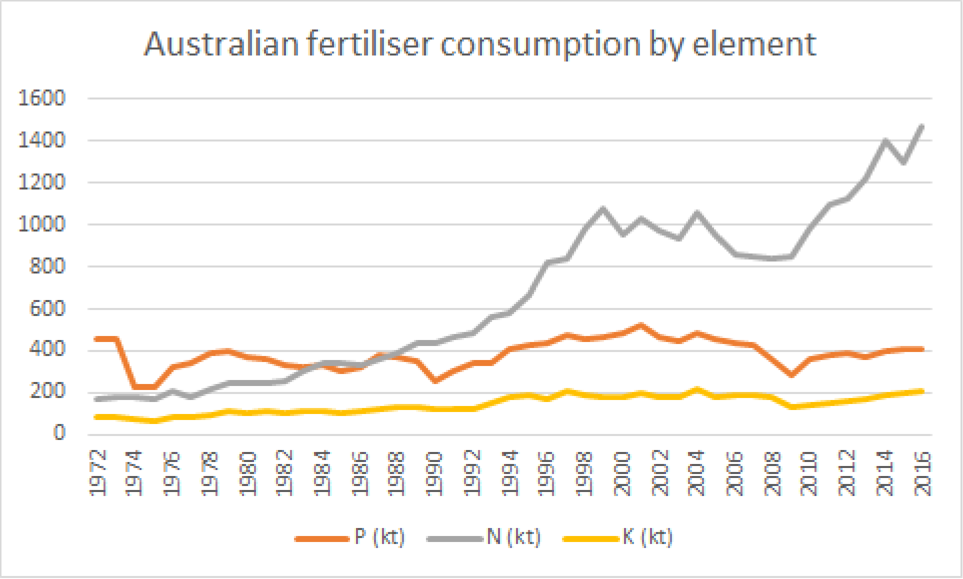


Figure 5.3: Consumption of N, P and K (kt yr^{-1}) in Australia (ABARES 2016b).

This history would suggest that nutrient excesses, particularly for nitrogen, might be expected in farming systems across Australia. However, the patterns of imbalance are more subtle and vary by nutrient, district and industry. The increase in N and P fertiliser use on crops and pastures also presents economic challenges for primary producers because the low crop and pasture utilisation of applied fertiliser nitrogen and phosphorus results in poorer economic returns than might otherwise be expected.

In this report we focus primarily on nitrogen because of the significant increase in application rates relative to other nutrients. This is not to downplay the significance of other nutrients in Australian agriculture.

5.2 Nitrogen

The estimated average N-fertiliser use by different industries is presented in Table 5.1. The key features are the large differences in rates and total quantities of N-fertiliser use across different industries. A summary of the nitrogen balance for the extensive non-agricultural, pastoral, dryland-farming and intensively used lands of Australia is presented in Table 5.2. The key features are the contrasts in importance of different pathways for inputs, removal in products, losses, transfers and final balances across the major agricultural zones. The implications of these different patterns are considered in the following sections on cotton, dairy, sugar and dryland farming.

5.2.1 Cotton

Average N-application rates in cotton production in Australia are high. This does not necessarily provide guidance on nitrogen use efficiency. For example, Macdonald et al. (2015) document that it is possible to grow high-yielding cotton crops using large inputs of N and with low emissions of nitrous oxides (i.e. indistinguishable from background emissions). However, this is often not the case and the nutrient use efficiency varies substantially. Growers cannot afford to allow their cotton crop yields to be limited by N deficiency (or other nutrients) and as a result they tend to manage this risk by using excessive N fertiliser (Rochester and Bange 2016). However, there is significant scope to reduce inputs of N fertiliser without reducing yields (Rochester 2011).

5.2.2 Dairy

Gourley et al. (2016) report that: '*on-going intensification of Australian dairy systems has led to fewer and larger dairy farms with increased stocking rates, greater reliance on imported feed, and higher nitrogen fertiliser use and milk production per cow and per ha.*' Over the period of their study, N inputs always exceeded outputs, with inputs growing at a faster rate. Intensification of milk production is inevitably associated with greater nutrient surpluses at the farm scale.

In a long-term trend analysis of N recovery on Australian dairy farms between 1990 – 2012, Stott and Gourley (2016) found that on-going intensification at both the national and state level led to fewer and larger dairy farms, with increased stocking rates, reliance on imported feed, nitrogen fertiliser use and milk production per cow and per hectare. All N recovery measures deteriorated markedly over the 22 year period, with N surplus for the average industry dairy farm increasing from 54 to 158 kg N ha^{-1} and N-use efficiency declining from 40 to 26%.

In a separate study, Gourley et al. (2012) documented the whole-farm nutrient balances for 41 Australian dairy farms. They reported N-balances ranging from 47 to 601 kg N/ha.yr. N-use efficiency ranged from 14 to 50%, with a median value of 26%. For the purposes of this report and taking into account the significant improvements in nutrient management within the dairy industry, it is still reasonable to assume that wherever dairy farms operate in Australia, relatively large nutrient inputs are occurring and nutrient-use efficiency is low. This implies that off-site impacts are likely to occur due to nutrient imbalances.

Table 5.1: N-fertiliser use for Australia based on data from 2010-2014 (Angus and Grace 2017).

		Area (m Ha)	Average fertiliser use (kg N ha^{-1})	Total fertiliser use (Mt N)
Dryland crops		24	45	1.08
Intensive farming				
	Cotton	0.44	300	0.09
	Dairy pastures	2.00	100	0.20
	Irrigated cereals	0.31	100	0.03
	Sugar cane	0.36	150	0.06
	Viticulture and horticulture	0.50	100	0.05
Other				
	Sports-fields, parks and gardens	0.1	200	0.02
	Licks and stockfeed			0.03
Total				1.59

Table 5.2: Summary of the nitrogen balance (Mty^{-1}) for major zones in Australia for 2014 prepared by Angus and Grace (2017) (see original publication for methods, sources and assumptions).

Zone	Non agricultural (309 M ha)	Pastoral (355 M ha)	Dryland farming (97 M ha)	Intensive (4 M ha)
Input				
N in rain	0.6	1.2	0.3	
Biological N fixation	0.8	1.1	3.2	0.02
Fertiliser N			1.08	0.36
N removal in products				
Crop products			-0.9	-0.26
Animal products*		-0.02	-0.1	-0.1
Losses				
Ammonia**	-1.7	-2.1	-0.6	-0.2
Denitrification			-0.3	-0.6
Nitrate leaching and runoff			-0.1	
Biomass burning (net NO_x)	-0.3	-0.2	-0.1	
Transfers* **				
N in dust storms	±0.3	±0.3		
Soil organic to mineral N			±0.7	±0.1
BALANCE	-0.6	-0.1	2.5	-0.6

* Empty live-weight of slaughter animals, milk and clean wool

** Loss from plant communities, soil, urine, and urea fertiliser

*** Not included in balance

5.2.3 Sugarcane

Patterns of N-fertiliser use in the Australian sugarcane industry differ from most other primary industries. Bell et al. (2014) observe that application rates of nitrogen fertiliser in the industry rose steadily from very low levels in the early 1900s to around 60 kg N/ha in the 1940s. It increased further to 160-180 kg N/ha in the 1970s and by the 1990s was approximately 200 kg N/ha (Keating et al, 1997, Johnson 1997). However, from the mid-1990s onwards, application rates declined to around 160 kg N/ha by 2013. The reductions were caused by factors including falling sugar prices, increasing costs of N fertiliser and to a lesser extent environmental concerns. Cane yields have also declined since the 1990s but there is no definitive evidence that it has been caused by reduced N-use even in Central Queensland where the decline is greatest.

Despite the reduction in N-application rates, significant quantities of N are exported from sugarcane districts via river systems and this causes adverse effects on the Great Barrier Reef. Bell et al. (2014) provide a comprehensive review and highlight the potential benefits of improving nutrient-use efficiency while at the same time reducing exports to the Great Barrier Reef.

5.2.4 Dryland cropping

As noted earlier, increased use of N fertilisers has been a key factor in lifting crop yields in dryland cropping systems, especially from the 1990s onwards. The application rates are still only moderate by world standards and there is limited evidence in cropping districts of adverse environmental impacts apart from the increase in greenhouse gas emissions. Nitrogen fertiliser is a key determinant of yield and profitability in dryland farming. It also represents a substantial proportion of input costs for farmers (i.e. in some cases exceeding 30%). Not surprisingly, the grains industry invests a lot of resources and effort into optimizing N-fertiliser usage.

5.2.5 Nitrate in groundwater

Bolger and Stevens (1999) reviewed the significance of nitrate contamination in groundwater in Australia. They documented agricultural practices that had associated high concentrations of nitrate in groundwater. The most significant associated with agriculture were as follows.

- High application of fertilisers in excess of plant nutrient demand
- Animal urine, especially in intensive farming systems including feedlots.
- Over-application of effluent above plant demand and soil moisture requirements. This includes manure from dairy, piggery and poultry operations
- Natural soil nitrogen mobilised by tillage and clearing of native vegetation
- High nutrient loads through the soils from fertilisers on pasture
- Nitrogen fixing pasture, often coupled with intensive grazing

Bolger and Stevens (1999) concluded that significant loads have been applied over broad areas from grazing, cultivation and fertiliser application. Furthermore, it was unlikely that farming practices at that time would lead to significant reductions in environmental nitrate loads that would migrate to the water table. Given that the nitrogen application rates have increased sharply over the last 20 years, their calls for changes to management practices and better education have an urgency and relevance that requires attention today. While reliance on groundwater as a source of drinking water is less common than in North America and Europe, the associated health issues are serious (Ward 2005).

5.2.6 Nutrient mining

In contrast to the risks associated with nutrient excess, nutrient mining continues to be a widespread problem, especially in systems where soil organic matter is being lost. There are significant areas in Queensland where depletion of organic matter and nutrient reserves have been a feature of past and current farming systems (Dalal et al. 1986, Dalal and Chan 2001, Bell et al. 2010, Page et al. 2014). Nutrient inputs in these farming systems are insufficient to replace nutrient exports due to product removal and other losses. There is a threshold beyond which economically viable management options are not available particularly when fertiliser prices are high (e.g. Bell et al. 2010).

5.3 Phosphorus

The use of phosphorous fertilisers in Australia is relatively inefficient (SoE 2011; McLaughlin et al. 2012; Weaver and Wong 2012; Gourley et al. 2014). About 75% of the phosphorus applied in Australian agriculture accumulates in the soil (Simpson et al. 2012). Soil testing to determine available soil P levels in Australian soils (i.e. Olsen 1954; Colwell 1965) along with a measure of the soil P-retention capacity (Burkitt et al. 2001) are important for managing P-fertiliser requirements (Burkitt et al. 2002; Simpson et al. 2011).

Based on Weaver and Wong (2011) most agricultural soils used to support sheep, beef, dairy and crop production, within 100 km of the coast of Australia (63% for beef and sheep pasture, 87% for wheat, 89% for dairy pasture) have reached or exceeded their non-limiting Colwell P value for 80-95% of maximum production. Most accumulation has occurred in southern Australia where the application rates have been the greatest – in these areas, there is sufficient phosphorus to meet crop and pasture requirements and only maintenance applications are required. This is true even in districts with soils that are considered to be of low fertility such as the Western Australian wheatbelt (DAFWA 2013).

Apart from the environmental risks caused by the accumulation of phosphorus (e.g. potential losses to the environment and detrimental impacts on waterways (e.g. Ruprecht et al. 2013)), the inefficiency has an economic cost that will increase as fertiliser prices rise. In contrast, many grazing systems (particularly in northern Australia) have pastures and animal production systems that are limited by phosphorus availability (McIvor et al. 2012).

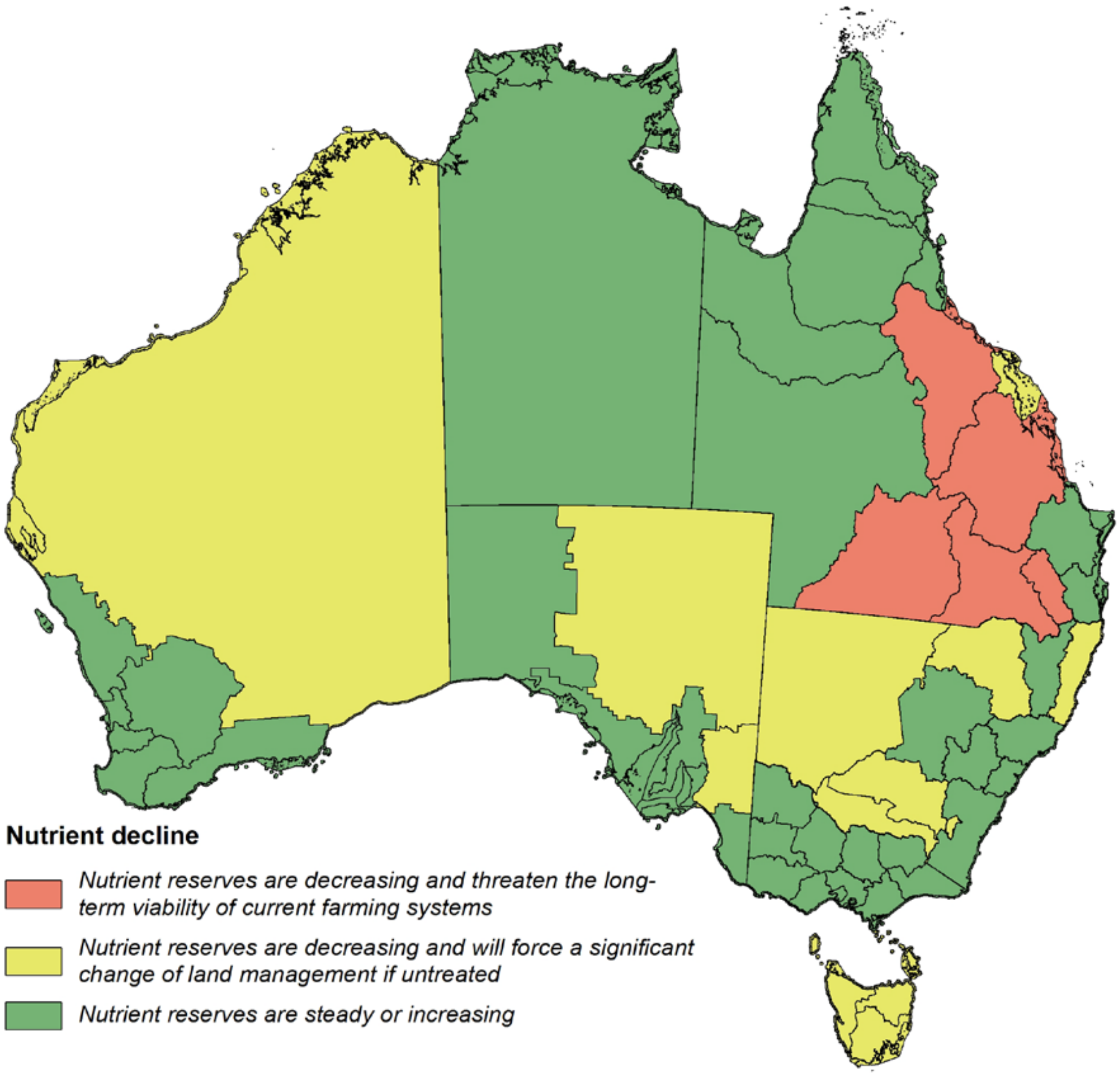
Environmental impacts involving phosphorus are most commonly associated with intensive agricultural systems, especially dairy (e.g. Gourley and Weaver 2012; Gourley et al. 2016).

5.4 Status and trend

Table 5.3 and Figure 5.4 provide a summary of nutrient imbalances across the 56 NRM regions where agriculture is a significant land use. Note however that nutrient imbalances can occur under other land uses, even in the rangelands where altered fire regimes, erosion by water and wind, climate change (e.g. increased atmospheric CO_2, higher temperatures, changed water balance), new grazing pressures and changes in species composition all affect nutrient cycling to some degree. There are also situations where the natural concentrations of nutrients are hazardous; for example, in Central Australia high concentrations of nitrate in groundwater are associated with nitrogen fixation in Acacia communities and subsequent leaching (Barnes et al. 1991). In summary, the most significant issues highlighted by Table 5.3 are as follows.

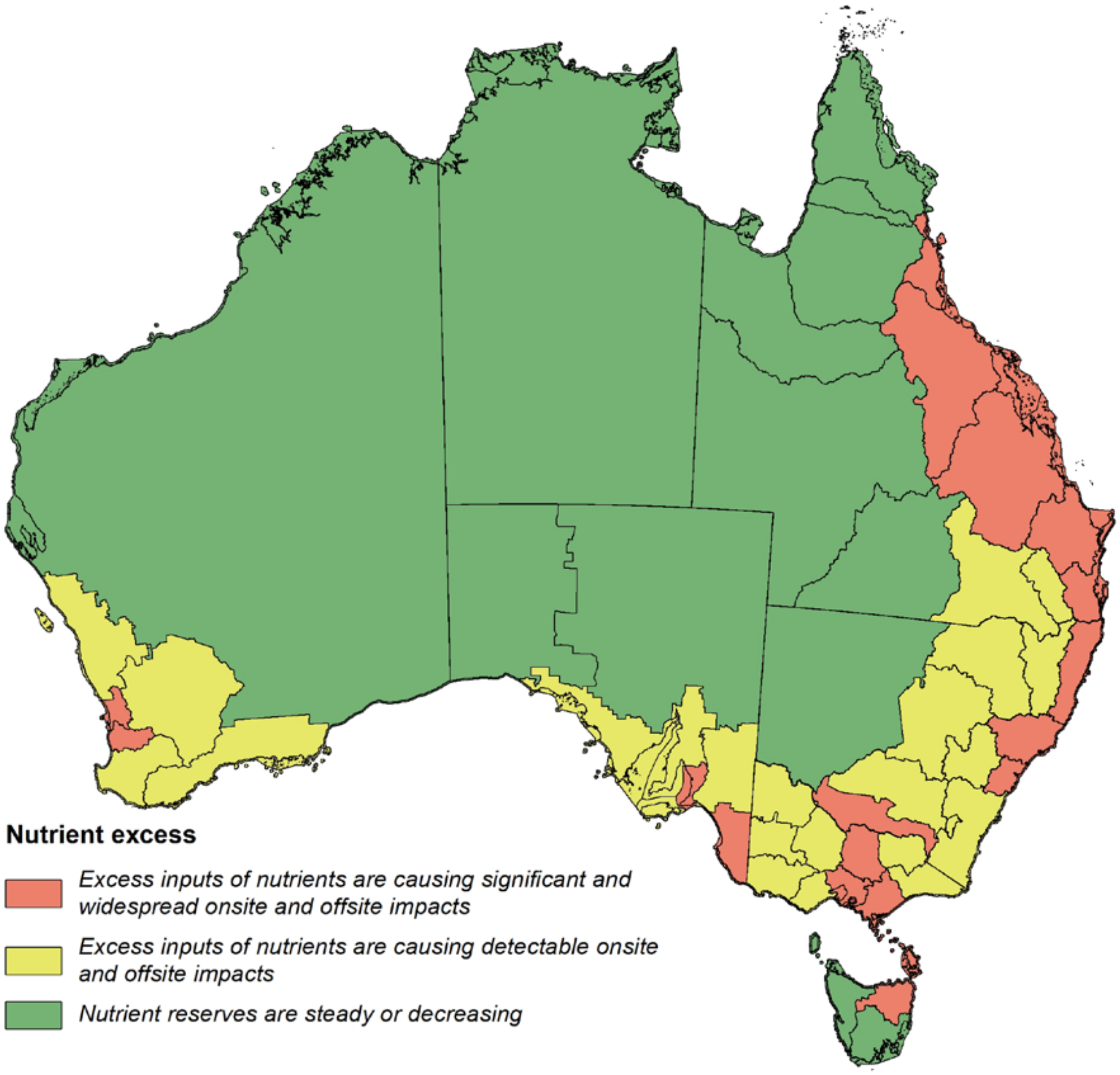
- Ongoing intensification of agriculture is occurring in most districts and the most notable feature is a steady and large increase in N-usage. The proportionally greater inputs of N will eventually cause problems (e.g. deficiencies of other nutrients or increasing losses of N). This is because the stable fine-fraction pool of soil organic matter has a near-constant ratio of C:N:P:S which is approximately 200:17:4:3 (Kirkby et al. 2013).

- The ratio of nutrients in soil organic matter is an important consideration in any management system that aims to increase soil carbon. Any long-term sequestration of soil carbon has to have an associated ‘sequestration’ of nutrients in the proportion noted above. This constraint has been overlooked in many proposals for restoring soil health across Australia.
- Nutrient mining is still occurring (e.g. parts of the northern cropping region (Bell et al. 2010)) and remediation is not simple because carbon and multiple nutrient deficiencies are involved – this requires much more than simple addition of fertilisers. Viable rotations including legumes are needed along with a detailed understanding of the multiple-nutrient deficiencies at play in any given situation.
- Nutrient decline is also likely to be occurring wherever soil carbon levels are decreasing (e.g. areas cleared for pasture over the last 30 years in Queensland).
- There is increasing awareness that P is generally sufficient or in excess in temperate cropping systems but deficient in most northern systems except sugarcane – either way, it needs to be managed carefully to avoid unnecessary economic costs and off-site impacts
- Widespread deficiencies of potassium occurred in Western Australia and they were rectified (NLWRA 2001). However, the increasing imbalance in the ratio of nutrient inputs suggest that they may once again appear. In particular, there are increasing incidences of multiple nutrient limitations in northern grains cropping systems; yield responses to P-K applications often exceed those due to either nutrient applied alone.
- Depletion of subsoil nutrients (particularly P, K and S) and nutrient stratification in the surface soil is becoming prevalent in minimum or zero till dryland cropping systems in northern Australia that rely on stored soil water. These issues will require the development of appropriate soil P, K and S test interpretations for subsurface samples (0.1–0.3m), and deep banding of fertilisers.
- Potassium excesses occur in some intensive forms of livestock production (especially piggeries and dairy) and this can lead to soil structure decline and deteriorating water quality.



NRM Regions (2017)

Figure 5.4: Summary of nutrient decline across Australia’s Natural Resource Management Regions (farming systems with nutrient declines (e.g. low-input cropping) and others with excesses (e.g. dairy) can occur in the one region).



NRM Regions (2017)

Figure 5.5: Summary of nutrient excess across Australia's Natural Resource Management Regions (farming systems with nutrient declines (e.g. low-input cropping) and others with excesses (e.g. dairy) can occur in the one region).

Table 5.3: Summary of nutrient imbalances across the 56 NRM regions where agriculture is a significant land use. The colour coding is the same as Figures 5.4 and 5.5.

NRM ID	NRM_REGION	Nutrient decline	Nutrient excess	Comments
1010	Central Tablelands	G	Y	
1020	Central West	G	Y	
1030	Greater Sydney	G	R	Diverse landscape with significant nutrient loadings from horticulture and urban land uses.
1040	Hunter	G	R	Significant nutrient inputs due to intensive agriculture (livestock, horticulture and viticulture). Major disruption to natural landscapes due to mining.
1050	Murray	Y	R	Dryland cropping, irrigated agriculture and grazing with the latter dominant in the west. Slight declines under dryland cropping systems although farming practices may halt this.
1060	North Coast	Y	R	Intensive agriculture and large nutrient inputs in areas used for sugarcane and horticulture.
1070	North West NSW	Y	Y	Land used for grazing of modified and natural pastures and nature conservation. Significant losses of soil carbon and nutrient stocks particularly in the east due to intensification of cropping.
1080	Northern Tablelands	G	Y	
1090	Riverina	Y	Y	Dryland cropping, irrigated agriculture and grazing. Reduced soil carbon and nutrient stocks under dryland cropping systems although improved farming practices and increasing inputs are changing this.
1100	South East NSW	G	Y	Significant areas of intensive agriculture on coastal alluvial flats and adjacent hills. High nutrient inputs in areas used for dairying.
1110	Western	Y	G	Soil carbon losses are largely due to wind erosion.
2010	Corangamite	Y	Y	Areas of mixed farming have significant nutrient inputs and seasonal conditions that exacerbate nutrient losses.
2020	East Gippsland	G	Y	Dairy and intensive agriculture restricted to alluvial plains on major water courses
2030	Glenelg Hopkins	G	G	Mainly grazing, cropping and plantation forestry. Adoption of minimum tillage and increasing nutrient inputs may have stemmed the decline in soil carbon.
2040	Goulburn Broken	G	R	Dryland cropping, irrigated agriculture and grazing with significant areas of dairying.
2050	Mallee	G	Y	Cropping, grazing and nature conservation with irrigated agriculture along the Murray River. Improved farming practices have improved soil condition some areas but soil carbon levels are probably still declining.
2060	North Central	G	Y	Dryland cropping, irrigated agriculture and grazing with the latter dominant in the west. Slight declines under dryland

NRM ID	NRM_REGION	Nutrient decline	Nutrient excess	Comments
				cropping systems although farming practices may halt this.
2070	North East	G	Y	Dryland cropping, irrigated agriculture and grazing. Slight declines under dryland cropping systems although farming practices may halt this.
2080	Port Phillip and Western Port	G	R	Intensive agriculture and urban expansion
2090	West Gippsland	G	R	Extensive dairy and intensive agriculture with significant off-site impacts on water bodies
2100	Wimmera	G	Y	Mainly cropping and grazing. Adoption of minimum tillage and increasing nutrient inputs may have stemmed losses although soil carbon is still likely to be declining in this region.
3010	Burnett Mary	G	R	Intensive agriculture, large nutrient inputs and high rates of soil erosion
3020	Cape York	G	G	
3030	Condamine	R	Y	
3050	Desert Channels	G	G	
3060	Fitzroy	R	R	Intensive agriculture, large nutrient inputs and high rates of soil erosion across much of the catchment
3070	Burdekin	R	R	Intensive agriculture in the BIA with large nutrient inputs and high rates of soil erosion across much of the catchment
3080	Northern Gulf	G	G	
3090	Border Rivers Maranoa-Balonne	R	Y	
3100	Mackay Whitsunday	Y	R	Intensive agriculture, large nutrient inputs and high rates of soil erosion
3110	South East Queensland	G	R	
3120	South West Queensland	R	G	Mainly low inputs across the extensive areas used for grazing. Restricted areas of dryland farming most likely with reducing carbon and nutrient stocks.
3130	Southern Gulf	G	G	
3140	Wet Tropics	G	R	Intensive agriculture, large nutrient inputs and high rates of soil erosion
4010	Adelaide and Mount Lofty Ranges	G	R	High nutrient loadings in areas used for intensive agriculture (horticulture, viticulture, dairy, livestock production). Significant impacts on water quality.
4020	Alinytjara Wilurara	G	G	Decline in carbon predicted due to wind erosion

NRM ID	NRM_REGION	Nutrient decline	Nutrient excess	Comments
4030	Eyre Peninsula	G	Y	Mainly dryland cropping and grazing. Adoption of minimum tillage and increasing nutrient inputs may have stemmed the decline in soil carbon.
4040	Kangaroo Island	G	Y	Mainly grazing in the east of KI with increasing inputs in areas used for horticulture and dairy.
4050	Northern and Yorke	G	Y	Mainly dryland cropping and grazing. Adoption of minimum tillage and increasing nutrient inputs may have stemmed the decline in soil carbon.
4060	South Australian Arid Lands	Y	G	Carbon loss due primarily to wind erosion
4070	South Australian Murray Darling Basin	Y	Y	Mainly grazing, cropping and plantation forestry. Adoption of minimum tillage and increasing nutrient inputs may have stemmed the decline in soil carbon.
4080	South East	G	R	Extensive dryland farming and grazing with significant areas of more intensive agriculture (viticulture, dairy). Micronutrient deficiencies have been rectified and there are significant nutrient inputs to low fertility soils.
5010	Northern Agricultural	G	Y	Extensive dryland farming with significant excesses of phosphorus and potential deficiencies of other nutrients including potassium.
5020	Peel-Harvey	G	R	Urban and agricultural land uses are dominant. Significant excesses of phosphorus in agricultural areas with off-site impacts on water quality. Potential deficiencies for other nutrients including potassium and sulfur.
5030	Perth	G	R	Urban and agricultural land uses are dominant. Significant excesses of phosphorus in agricultural areas with off-site impacts on water quality. Potential deficiencies for other nutrients including potassium and sulfur.
5040	Rangelands	Y	G	Wind and water erosion reducing carbon stocks
5050	South Coast	G	Y	Extensive dryland farming with significant excesses of phosphorus in cropping and grazing systems but potential deficiencies for other nutrients including potassium and sulfur.
5060	South West	G	Y	Extensive dryland farming with significant excesses of phosphorus in cropping and grazing systems but potential deficiencies for nutrients including potassium and sulfur.
5070	Wheatbelt	G	Y	Extensive dryland farming with significant excesses of phosphorus in cropping and grazing systems but potential deficiencies for other nutrients including potassium and sulfur.
6010	Cradle Coast	Y	G	More frequent and/or hotter fires in conservation reserves are causing losses especially in Organosols. Northern areas dominated by production forestry with no potential for soil carbon sequestration.
6020	North	Y	R	Significant nutrient inputs and erosion in the farming lands of northern Tasmania, especially in areas used for horticulture.

NRM ID	NRM_REGION	Nutrient decline	Nutrient excess	Comments
6030	South	Y	G	Irrigated cropping in the southeast and northeast is causing declines in soil carbon but nutrient inputs are significant.
7010	Northern Territory	G	G	Carbon and nutrient declines in areas developed for agriculture. Increases in nutrient loadings in horticultural areas in the vicinity of Darwin.
8010	ACT	Y	Y	

5.5 Priorities and potential interventions

The quality of nutrient management has improved substantially in recent decades due to initiatives such as the Better Fertiliser Decisions projects for crops and grazed pastures (e.g. Gourley et al. 2007). Industry programs such as Fertcare® also generate many benefits including improvements in profitability and better environmental outcomes. Kraak (2016) provides a good overview. Despite these advances, knowledge of nutrient management still appears to be deficient in many industries and districts. Improvements in soil testing and interpretation are needed to improve profitability and achieve better environmental outcomes. An integrated approach is essential because nutrient management involves far more than optimizing fertiliser inputs based solely on the testing soils and plants. It requires an understanding of nutrient balances, economics and the management of other soil factors including acidification, soil organic carbon and soil erosion by wind and water.

Potential interventions to overcome nutrient imbalances in nearly all cases should involve close collaboration with the relevant agricultural industries. Most soil testing is done to guide decisions on fertiliser application rates. Fertiliser companies often provide these testing services so there is an obvious focus on selling fertiliser. This can lead to suboptimal outcomes. For example, a company selling fertilisers but not lime may not be inclined to recommend cessation of nutrient inputs even when soil acidification is evident. However, it is in the fertiliser company’s long-term interest to promote best practice even if sales are reduced in the short term. This more enlightened approach to nutrient management is embodied in industry guidelines on best management practices (e.g. right rate, right time, right place and right product) and accreditation schemes such as the Fertcare Accredited Advisor scheme and certification of laboratories providing soil and plant analyses through the Australasian Soil and Plant Analysis Council.

A good starting point would be to explore opportunities for expanding current industry programs so that they achieve a broader audience, especially in districts that appear to have either significant nutrient declines or nutrient excesses (Table 5.3).

It is also important to ensure that the significant advances made by the National Soil Carbon Program and the National Agricultural Nitrous Oxide Research Program are not lost. It would be beneficial to avoid the of boom and bust cycle seen in soil acidification research, development and extension.

In summary, interventions are required in the following circumstances.

1. **When there’s information failure in the market**. The low rates of soil testing and ongoing rapid increase in N-usage are signals that indicate information failure may be more widespread than expected.
2. **When externalities are being generated**. Large public investments have been made in response to environmental concerns over nutrient imbalances, particularly in relation to the Great Barrier Reef, eutrophication of freshwater systems and greenhouse gas emissions.
3. **When nutrient imbalances have an impact soil biodiversity.** This is the most complex area for public intervention. The Australian Government has obligations to international treaties and legislative responsibilities (e.g. to ensure compliance with the Convention on Biological Diversity and provisions under the EPBC Act). This report identifies districts across Australia where soil biodiversity is undoubtedly being affected by threats to soil function (i.e. soil acidification, hillslope erosion, soil carbon decline and nutrient imbalances). Information systems necessary to set and meet soil biodiversity targets are in their infancy although there are some very promising developments (e.g. the BASE project).

6 Discussion

6.1 Achieving sustainable soil management

The analyses presented in this report provide a framework for directing resources to the districts with the greatest need. However, ensuring impact and achieving sustainable soil management also requires:

- coordinated programs of soil research, development and extension
- experienced and highly motivated technical and scientific specialists who are effectively engaged with regional activities
- technical solutions for erosion control, sequestering carbon and sustainable farming
- up-to-date soil mapping and monitoring at resolutions relevant to farm management.

The National Committee on Soil and Terrain (NCST 2013) provided a blueprint for developing the latter although difficulties in finding institutional and funding mechanisms to implement their program is putting at risk the achievements of recent decades. Of critical importance is the need to integrate public sector and private sector data streams so that farmers, industries and governments are not flying blind on key threats to soil function. The contrasts between the national and state-based assessments of acidification in South Australia and Western Australia (Section 2.7) highlight the problem.

The report has also highlighted some important areas where there is either insufficient knowledge or uncertainty about implications of current threats to soil function. Acidification has already been mentioned and an important cause relates to ongoing intensification of agricultural land-use in Australia. In particular, there needs to be careful consideration of the implications of the large and ongoing increase in the use of nitrogen fertiliser. Likewise, the intensification of land use in Northern Australia requires a close attention to the principles of sustainable soil management outlined in Section 1. Intensification should be precluded from areas with erodible and dispersive soils if extensive gully erosion and the mistakes of the past are to be avoided.

This desktop analysis involved the equivalent of one person working for 12 months. The team undertaking the work was able to draw on a large advisory network of experts and it had access to high-performance computing to undertake the spatial analyses for several themes. While there have been important advances in the quality and spatial resolution of source data sets, the analyses have significant shortcomings. Most important are those relating to soil acidification where there is sufficient evidence to suggest that the extent and severity of the problem is being underestimated by the national-scale analysis.

6.2 Management Principles and Practices

The Voluntary Guidelines for Sustainable Soil Management (FAO 2017) provide a sound framework for outlining preferred management principles and practices at the national level. We have adopted the relevant sections of the Voluntary Guidelines in the sections below for the themes addressed by this study (erosion, soil carbon, acidification, nutrient imbalances). A much larger effort is required to develop the specific technical manuals at the district and state/territory level. The technical manuals and recommended practices for controlling hillslope erosion in each jurisdiction (see Section 4.3.4) provide good examples of such locally specific practice-guidelines.

6.2.1 Minimize soil erosion

Soil erosion causes the loss of surface soil layers containing organic and mineral nutrient pools, partial or complete loss of soil horizons and possible exposure of growth-limiting subsoil, as well as off-site impacts such as damage to private and public infrastructure, reduced water quality and sedimentation. Soil erosion is accelerated by human activities through, amongst others, reduced plant or residue cover, tillage and other field operations, and reduced soil stability leading to soil creep and landslides.

- Land-use changes such as deforestation or improper grassland-to-cropland conversion that cause removal of surface cover and loss of soil carbon should be avoided or carefully planned and appropriately implemented if unavoidable.
- A cover of growing plants or other organic and non-organic residues that protects the soil surface from erosion should be maintained through implementation of appropriate measures such as mulching, minimum tillage, no-till by direct seeding with attention to reduced herbicide use, cover crops, agro-ecological approaches, controlled vehicle traffic, continuous plant cover and crop rotation, strip cropping, agroforestry, shelter belts, and appropriate stocking rates and grazing intensities.
- Erosion by water on sloping and relatively steep lands should be minimized by measures that reduce runoff rates and velocity such as strip cropping, contour planting, crop rotation, intercropping, agroforestry, cross-slope barriers (e.g. grass strips, contour bunds and stone lines), terrace construction and maintenance, and grassed waterways or vegetated buffer strips.
- Where appropriate, riparian buffers, buffer strips, wetlands, water harvesting and cover crops should be used/installed to minimise export of soil particles and associated nutrients and contaminants from the soil system and protect the downstream areas from damaging impacts.
- Erosion by wind, including dust storms, should be minimized and mitigated through vegetative (trees and shrubs) or artificial (walls) wind breaks to reduce wind velocity.

6.2.2 Enhance soil organic matter content

Soil organic matter (SOM) plays a central role in maintaining soil function and preventing soil degradation. Soils play a critical role in regulating climate and mitigating climate change through trade-offs between greenhouse gas emissions and carbon sequestration. For this reason, SOM is strategic for climate change adaptation and mitigation, and national stores of SOM should be stabilized or increased. A loss of soil organic carbon (SOC) due to inappropriate land use or the use of poor soil management or cropping practices can cause a decline in soil quality and soil structure, and increase soil erosion, potentially leading to emissions into the atmosphere. On the other hand, appropriate land use and soil management can lead to increased SOC and improved soil quality that can partially mitigate the rise of Greenhouse Gas Gases.

Management practices should aim to achieve the following.

- Increase biomass production by increasing water availability for plants using methods (e.g., irrigation with drippers or micro-sprinklers; irrigation scheduling; monitoring of soil moisture or loss of water via evapotranspiration) that maximize water-use efficiency and minimize soil erosion and nutrient leaching, using cover crops, balancing fertiliser applications and effective use of organic amendments, improving vegetative stands, promoting agroforestry and alley cropping, and implementing reforestation and afforestation.
- Protect organic carbon-rich soils in peatlands, forests and grazing lands.
- Increase organic matter content through practices such as: managing crop residues, using forage by grazing rather than harvesting, applying integrated soil fertility management and integrated pest management, applying animal manure or other carbon-rich wastes, using compost, and applying mulches or providing the soil with a permanent cover.
- Fire should preferably be avoided, except where fire is integral to land management, in which case the timing and intensity of burning should aim to limit losses of soil functions. Where fire is a naturally occurring event, steps to minimize erosion and encourage revegetation after fire should be considered, where practical.
- Make optimum use of all sources of organic inputs, such as animal manure and properly processed human wastes.
- Management practices such as cover crops, improved fallow plant species, reduced- or no-tillage practices, or live fences should be adopted to ensure the soil has a sufficient organic cover.
- Decrease decomposition rates of soil organic matter by practicing minimum or no-tillage without increasing the use of herbicides.
- Implementing crop rotations, planting legumes (including pulses) or improving the crop mix.

6.2.3 Prevent and minimize soil acidification

Human-induced acidification of agricultural and forest soils is primarily associated with removal of base cations and loss of soil buffering capacity or increases in nitrogen and sulfur inputs (e.g. legume pastures fertiliser inputs, atmospheric deposition). Management practices should include the following:

- regular monitoring of soil acidity
- minimizing surface and sub-surface soil acidity by using proper amendments (such as lime, gypsum and clean ash)
- balanced fertiliser and organic amendment applications
- appropriate use of acidifying fertiliser types.

6.2.4 Foster soil nutrient balance and cycles

The concepts of sufficiency and utilization efficiency apply especially to nutrient dynamics in the soil- water-nutrients-plant root continuum. Plant nutrition should be based on crop needs, local soil characteristics and conditions, and weather patterns. Plant nutrition can be enhanced through nutrient recycling or additions including mineral (chemical) fertilisers, organic fertilisers and other soil amendments including primary sources (e.g. rock phosphate) and secondary sources (e.g. phosphorus from sewage sludge). It is crucial to select an appropriate plant nutrient management system and approach alongside assessing the suitability of the land for a given land use.

The benefits of sufficient and balanced nutrient supply for plant needs are well-established and include: production of food, feed, fibre, timber, and fuel at levels at, or close to, the optimum potential in the specific geographical context; reduced need for pest control measures, external application of organic and inorganic amendments, and mineral fertilisers; less pollution resulting from inappropriate use of agro-chemicals; and enhanced soil carbon sequestration through biomass production and restitution to the soil.

The lack of basic nutrients leads to the underdevelopment of plants and decrease in yields and crop nutritional value. The consequences of excess nutrients in soils are: the loss of excess nutrients (especially nitrogen and phosphorus) from agricultural fields, causing eutrophication and deterioration of water quality in terrestrial and aquatic ecosystems; increased release of the greenhouse gas nitrous oxide from soils to the atmosphere; leaching of mobile forms of nitrogen to water used for human consumption, with potential human health impacts; and d) crop failure.

Management practices should aim to achieve the following.

- Natural soil fertility and natural nutrient cycles should be improved and maintained through the preservation or enhancement of soil organic matter. Improved soil fertility can be attained through soil conservation practices such as the use of crop rotations with legumes, green- and animal manures, and cover crops in combination with reduced- or no-tillage with attention to reduced herbicide use, as well as agroforestry. Nutrient cycles are best managed in integrated systems such as crop-livestock systems or crop-livestock forest systems.
- Nutrient use efficiency should be optimized by adopting measures such as applying balanced and context adapted soil organic and inorganic amendments (e.g. compost and liming agents, respectively) and/or innovative products (e.g. slow and controlled release fertilisers), as well as the recycling and reuse of nutrients.
- Fertiliser application methods, types, rates and timing should be appropriate to limit losses and promote balanced crop nutrient uptake. This should be based on soil and plant analyses and be a long-term endeavour rather than short-term action.
- The addition of soil micronutrients should be considered when planning soil fertilisation.
- Practical sources of plant nutrients should be used, including the precise and judicious use of organic and mineral amendments, inorganic fertilisers, and agricultural bio-products. These amendments and bio-products include liquid, semi-solid or solid manures, crop residues, composts, green manures, household refuse, clean ash generated during bioenergy production, soil amendments and inoculants. In order to increase their efficiency, such measures should be combined with the mitigation of other limiting factors (such as water deficiency). Safe use (including tolerable levels of contaminants and pollutants, and worker health) of the amendments should be ensured.
- Soil and plant-tissue testing and field assessments should be adopted and used. This provides valuable guidance in diagnosing and correcting limiting factors in crop production

related to plant nutrients, salinity, sodicity, and extreme pH conditions. Such guidance is key for making informed decisions and monitor progress.

- Where appropriate, livestock movement and grazing should be managed to optimize manure and urine deposition.
- Application of liming agents in acid soils is a prerequisite for optimal nutrient use efficiency in such soils, while application of organic amendments such as compost, as well as appropriate soil-crop management should be considered for alkaline and other soils.
- Naturally occurring mineral fertiliser resources like rock phosphate or potash should be allocated efficiently and strategically to ensure the continued availability of adequate amounts of mineral inputs for future generations.

6.3 Summary of soil management practices and regional priorities

Table 6.1 provides a summary of the beneficial soil management practices outlined in the preceding sections. Summaries of the rankings for acidification, soil carbon, hillslope erosion by water, nutrient decline, nutrient excess and wind erosion are provided in Tables 6.1 and 6.2. The regional priorities for wind erosion (Leys et. al 2017) have been included for the convenience of readers.

Several of the analyses in this report have associated fine-resolution data sets that can be used for district planning within each NRM region. Most notable are the assessments for hillslope erosion by water (e.g. Figures 4.2 to 4.5), acidification (e.g. Figure 2.6) and to a lesser extent soil carbon (e.g. Figure 3.13).

Table 6.1: Summary of land management practices and their likely effect on soil condition.

Management practice	**Soil condition improvement**				
	Soil acidification	**Soil carbon stocks**	**Hillslope erosion**	**Nutrient decline**	**Nutrient excess**
Monitor soil acidity	✓	✓			
Apply lime to maintain soil pH	✓	✓			
Avoid overuse of acidifying fertiliser types	✓				✓
Increase biomass production		✓			
Reduce tillage		✓	✓		
Include pasture phase in rotation		✓	✓		
Manage crop residues		✓	✓		
Grow cover or green manure crops		✓	✓		
Utilise organic amendments		✓		✓	
Integrate crop and livestock systems		✓		✓	
Reduce bare fallow		✓	✓		
Maintain ground cover (avoid over grazing)		✓	✓		
Monitor ground cover and pasture condition		✓	✓		
Reduce runoff rates		✓	✓		
Use vegetation to minimise offsite movement of sediment		✓	✓		
Carefully plan and implement any land use change		✓	✓	✓	
Soil test - monitor soil nutrients	✓	✓		✓	✓
Fertilise to maintain nutrient levels				✓	
Alleviate soil compaction		✓	✓		

Table 6.2: Summary of priorities for addressing soil acidification, increasing soil carbon, controlling hillslope erosion by water, managing nutrient deficiencies and excesses and wind erosion. The definitions of each colour class are presented in Table 6.3.

NRM Region	Acidif-ication	Carbon	Hillslope erosion	Nutrient decline	Nutrient excess	Wind erosion
Central Tablelands	R	Y	Y	G	Y	G
Central West	R	Y	R	G	Y	G
Greater Sydney	Y	Y	Y	G	R	G
Hunter	Y	Y	Y	G	R	G
Murray	R	R	Y	Y	R	Y
North Coast	R	R	R	Y	R	G
North West NSW	Y	R	G	Y	Y	G
Northern Tablelands	R	R	Y	G	Y	G
Riverina	R	R	G	Y	Y	Y
South East NSW	R	Y	Y	G	Y	G
Western	G	R	Y	Y	G	R
Corangamite	R	Y	Y	G	Y	G
East Gippsland	Y	Y	G	G	Y	G
Glenelg Hopkins	R	Y	Y	G	Y	G
Goulburn Broken	R	Y	Y	G	R	G
Mallee	Y	R	G	G	Y	R
North Central	R	Y	Y	G	Y	Y
North East	R	Y	Y	G	Y	G
Port Phillip and Western Port	R	Y	G	G	R	G
West Gippsland	R	Y	Y	G	R	G
Wimmera	R	Y	Y	G	Y	Y

NRM Region	Acidif-ication	Carbon	Hillslope erosion	Nutrient decline	Nutrient excess	Wind erosion
Burnett Mary	Y	Y	Y	G	R	G
Cape York	G	G	Y	G	G	G
Condamine	G	R	R	R	Y	G
Co-operative Management Area	G	G	Y	G	G	G
Desert Channels	G	G	G	G	G	R
Fitzroy	Y	Y	R	R	R	G
Burdekin	Y	Y	R	R	R	G
Northern Gulf	G	G	Y	G	G	G
Maranoa Balonne and Border Rivers	Y	R	Y	R	Y	G
Mackay Whitsunday	Y	Y	Y	Y	R	G
South East Queensland	Y	Y	Y	G	R	G
South West Queensland	G	R	G	R	G	Y
Southern Gulf	G	G	R	G	G	G
Wet Tropics	R	Y	Y	G	R	G
Adelaide and Mount Lofty Ranges	R	R	Y	G	R	Y
Alinytjara Wilurara	G	R	G	G	G	R
Eyre Peninsula	Y	Y	Y	G	Y	R
Kangaroo Island	R	Y	Y	G	Y	G
Northern and Yorke	R	Y	Y	G	Y	Y
South Australian Arid Lands	G	R	G	Y	G	R
South Australian Murray Darling Basin	Y	R	G	Y	Y	R
South East	R	Y	Y	G	R	Y
Northern Agricultural	R	Y	Y	G	Y	R

NRM Region	Acidification	Carbon	Hillslope erosion	Nutrient decline	Nutrient excess	Wind erosion
Peel-Harvey Region	R	Y	G	G	R	G
Swan Region	R	Y	G	G	R	G
Rangelands Region	G	R	Y	Y	G	R
South Coast Region	R	Y	Y	G	Y	Y
South West Region	R	Y	Y	G	Y	G
Avon Basin Region	R	Y	Y	G	Y	R
North West NRM Region	Y	R	Y	Y	G	G
North NRM Region	Y	R	G	Y	R	G
South NRM Region	Y	R	G	Y	G	G
Northern Territory	G	G	R	G	G	R
ACT	Y	Y	Y	Y	Y	G

Table 6.3: Definition of classes used in Table 6.2.

Class	**Acidification**	**Soil carbon**	**Hillslope erosion by water**	**Nutrient decline**	**Nutrient excess**	**Wind erosion**
R	Widespread acidification threatening the long-term viability of agricultural businesses if untreated	Carbon stocks are declining under current land management	Hillslope erosion by water threatening the long-term viability of agricultural businesses if untreated	Nutrient reserves are decreasing and threaten the long-term viability of current farming systems	Excess inputs of nutrients are causing significant and widespread onsite and offsite impacts	Widespread wind erosion is threatening the long-term viability of agricultural businesses and/or reducing the ecosystem services of clean air
Y	Locally significant acidification threatening the long-term viability of some agricultural businesses if untreated	Carbon stocks generally steady with significant potential for increases under current or altered land management	Locally significant hillslope erosion by water threatening the long-term viability of some agricultural businesses if untreated	Nutrient reserves are decreasing and will force a significant change of land management if untreated	Excess inputs of nutrients are causing detectable onsite and offsite impacts	Locally significant wind erosion is threatening the long-term viability of agricultural businesses and/or reducing the ecosystem services of clean air
G	Minor acidification not posing a threat to agricultural viability in the short to medium term	Carbon stocks generally steady with limited opportunities for increase due to one or more constraints	Hillslope erosion by water occurs but not to a degree that threatens the viability of agricultural businesses in the long term	Nutrient reserves are steady or increasing	Nutrient reserves are steady or decreasing	Wind erosion is not posing a threat to the long-term viability of agricultural businesses and/or reducing the ecosystem services of clean air

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Appendix 1: Derivation of lime requirement equation

- Experimentally, pHBC is determined in units of cmol$^+$/kg soil/pH unit.
- This must be converted to Mg $CaCO_3$/ha/depth to give a lime requirement (LR). As shown below, this involves using the molecular weight of $CaCO_3$ to convert moles of charge to a mass basis and also division by 100 to convert moles to centimoles.
- The molecular weight (MW) of $CaCO_3$ is 100 (i.e. molecular weights of Ca, C and O being 40, 12 and 16 respectively) so the mass of 1 mole of $CaCO_3$ is 100 g by definition.
- Calcium is a divalent cation so 100 g of $CaCO_3$ contains 2 moles of charge and 50 g $CaCO_3$ contains 1 mole of charge. The required conversion from mol$^+$ to cmol$^+$ means that 1 cmol$^+$/kg soil/pH unit = 0.5 g $CaCO_3$/kg soil/pH unit
- The lime requirement also requirements translation from a gravimetric to a volumetric basis. We first need to calculate the mass of soil to 1 m depth (because m is the unit of depth used for the soil layer thickness) at an assumed bulk density (BD) of 1. This provides a conversion factor or scalar that is then multiplied by the actual soil layer thickness and bulk density for the layer under consideration.
- The volume of soil in 1 ha to a depth of 1 m is 100 m x 100 m x 1 m = 10,000 m^3. At a BD of 1 this is 10,000 Mg of soil (=10,000,000 kg). Therefore, a pHBC of 1 cmol$^+$/kg soil/pH unit = 0.5 x 10,000,000 g $CaCO_3$/ha/pH unit = 5 Mg $CaCO_3$/ha/pH unit to 1 m at a BD of 1. Thus the "5" in the equation below represents the conversion of pHBC from cmol$^+$/kg soil/pH unit to Mg $CaCO_3$/ha/pH unit assuming a soil depth of 1 m with a BD of 1.0. The inclusion of the actual thickness of the layer in question and its bulk density completes the calculation of the LR for an individual layer:

$$LR = (pHBC \times 5 \times Tc \times BD) \times (TpH - CpH)$$

where:

- LR is lime requirement (Mg/ha)
- pHBC is in cmol+/kg soil/pH unit
- Tc is the thickness of the layer contributing to the total depth (m)
- BD (Mg/m^3)
- TpH is target pH
- CpH is current pH

This is for pure $CaCO_3$ and if the liming agent is not pure $CaCO_3$, the LR is adjusted according to the neutralising value of the liming product

$$LR = (pHBC \times 5 \times Tc \times BD) \times (TpH - CpH) \times \frac{100}{NV}$$

where NV is neutralising value of the liming product compared to $CaCO_3$ (%)

If there is a substantial amount of coarse fragments the LR can be further adjusted to account for the non-reactive components of the soil

$$LR = \left(pHBC \times 5 \times Tc \times BD\right) \times \left(TpH - CpH\right) \times \frac{100}{NV} \times \left(1 - \frac{CF}{100}\right)$$

where CF is coarse fraction (%).

Appendix 2. Details of Nutrient stock calculations used in the soil erosion section

Equation 4.3 was implemented using the following approach.

Data

The Soil and Landscape Grid of Australia[13] (SLGA) provided data on total phosphorus (%), total nitrogen (%), soil organic carbon (%), bulk density (gcm^{-3}) and depth of soil (m) for the Australian continent at 3 arc second resolution (approximately 90 m).

There are six depth layers for each of the SLGA National Soil Attributes (except Depth of Soil):

Upper Bound (m)	Lower Bound (m)
0.00	0.05
0.05	0.15
0.15	0.30
0.30	0.60
0.60	1.00
1.00	2.00

Data processing

The Teng et al. (2016) RUSLE grid for Australia has a coarser spatial resolution than the SLGA datasets. In order to use the extra information within the SLGA datasets, the RUSLE grid was bilinearly resampled from 0.01 decimal degrees to 3 arc second resolution (0.0008333333333 decimal degrees), with the new cell origin snapped to the SLGA grid.

Equations

For each soil attribute (total phosphorus, total nitrogen and soil organic carbon), the following steps were used to calculate the total mass (t) in the soil profile, the loss (tha^{-1}y^{-1}) from the 0-5 cm layer, and the relative nutrient loss rate (%y^{-1}).

- Calculate cellArea (m^2) from the grid cell size and latitude in decimal degrees
- For each depth layer:
    - layerThick (m) = lowerBnd - upperBnd
    - thickness (m) = where(soilDepth > lowerBnd, layerThick, where(soilDepth > upperBnd and soilDepth < lowerBnd, soilDepth - upperBnd, nodata))

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[13] http://www.clw.csiro.au/aclep/soilandlandscapegrid/index.html

  - cellVol (m^3) = cellArea * thickness
  - massSoil (g) = cellVol * bulkDensity * 1000000
  - massAttr (g) = massSoil * soilAttr / 100
- massAttrTot (t) = (massAttr5 + massAttr15 + massAttr30 + massAttr60 + massAttr100 + massAttr200) * 0.000001
- massAttrTot (tha^{-1}) = massAttrTot / (cellArea * 0.0001)
- massAttr0-5loss ($tha^{-1}y^{-1}$) = (soilAttr0-5 / 100) * RUSLE
- massLossRate ($\%y^{-1}$) = massAttr0-5loss / massAttrTot * 100

Appendix 3: Summary of threshold cover levels from Australian studies of soil erosion by water and wind

Reference	Threshold	Comment
Lang et al. (1979)	70% cover	Water erosion. Gunnedah, north central NSW.
Leys et al. (1991)	Not specified	Wind erosion. No clear recommendation but data only in the 0–50% cover range
Silburn et al. (2011)	50% cover	Water erosion in semi-arid central Qld
McIvor et al. (1995)	40% cover	Water erosion in grazing lands
Greene and Hairsine, (2004)	50% cover (results in 20% of bare soil erosion rate)	Water erosion. A review of several studies – mainly from North America
Freebairn and Wockner (1986)	20–30% cover?	Water erosion in cropping land “where 20-30% of the soil surface is covered, soil erosion is dramatically reduced.”
Queensland Government (2015b)	Low risk (30–40% cover) Very low risk (50–60% cover)	From summary table. Soil erosion and water quality risk associated with grazing land management

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