Final report

Scoping Study of Soil Management in Livestock Grazing Systems

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1 Abstract

As an initial step for MLA to develop a Business Case and Investment Plan for soil-related research, development, extension, and adoption (RDE&A) projects to provide sustainability and productivity benefits for red meat producers, a scoping study to meet MLA's requirements and to review previous studies, reports, literature, and other information was commissioned by the Soil CRC and produced by the South Australian Research and Development Institute, Federation University and NSW Department of Primary Industries.

The review was extensive, covering outputs and outcomes from soil-related MLA investments over the past 10 years, significant changes in relevant soils based RDE&A over the past 10 years, regional soil constraints and opportunities, a review of international and national policies and frameworks, and several specific areas requiring more detail.

A draft review was presented to MLA members on 11 April 2023. Feedback from MLA provided a final version of the review and a framework to guide MLA investment in soils. The framework had an overarching goal "To manage soil health and improve resilience to climate events and impacts to support the future prosperity and sustainability of the red meat industry".

The framework identified four key theme areas underpinning an enabling theme of soils extension and adoption. The four key theme areas are:

- overcoming regional soil constraints,
- optimising soil carbon storage and soil health,
- managing soil impacts form extreme events, and
- leveraging natural capital and marketing access.

The four themes in the framework also provide the context to incorporate statements in MLA's future strategic plans to explicitly recognise the importance of soil to the future prosperity and sustainability of the red meat industry.

Executive Summary

Meat and Livestock Australia (MLA) has commissioned a review on existing soil research, development, extension and adoption conducted by both the MLA and externally. This review will guide future investment priorities that will provide sustainability and productivity benefits for red meat producers. The review identifies past R, D, E and A and emerging areas of interest to inform future investment.

Since livestock enterprises cover more than 50 per cent of Australia's landscape, the MLA have a responsibility to prioritise soils. Additionally, since more than 60 percent of cattle are in rangelands systems, the review group ensured that rangelands were specifically sought out in terms or prioritising soil issues.

In a review of MLA documents, the review team found that, while the MLA strategic plan did not explicitly mention soils, their importance was implicitly assumed. While there is no need to change the strategic direction of MLA to cater for soil needs, we recommend MLA's future strategic plans include a statement that specifically recognises the importance of soil to the future prosperity and sustainability of the red meat industry. The statement should include the role of soil metrics with reference to reporting obligations and future market access. Meat and Livestock Australia projects tracked closely with the broader publication of soil projects in the livestock sector. Specific recommendations were made to monitor progress on biological indicators and the soil microbiome.

A review of external literature (Section 3) found that over the last ten years, interest had moved from single or a small group of indicators to multiple indicators. Defining soil health is difficult and indicators for soil health will change in different regions so there will be no universal soil indicator of soil health. Defining local soil health challenges and local soil management techniques should be a focus.

The quality of data underlying maps for key soil types and soil constraints varies considerably from state to state (Section 4). While data is often dated, and new maps for some issues in some areas have not been updated for some decades, the latest spatial information available for soil issues and constraints are provided in Section 4.

Extreme events (Section 5) are likely to increase in a changing climate, posing more challenges for the livestock industry. A review of the literature found that while resilient soils are preferable, a lot of factors contributing to resilience are inherent in the soils, and sometimes only few of those factors can be changed through management practices. A better understanding on permanent impacts of extreme events versus temporary impacts is needed, as recovery from these extreme events is often rapid.

Soil carbon (Section 6), particularly in terms of carbon storage, is currently very popular. The benefits of accumulating soil carbon in terms of soil health and resilience should be promoted. Cycling of soil carbon is also important in a healthy soil and carbon will be moving in and out of healthy soils. However, care needs to be taken regarding measuring or modelling carbon storage and any subsequent selling of carbon credits. In terms of using carbon for trading and carbon neutrality, a robust verification system will be vital.

Of all the sectors of the economy, agriculture is the most dependent on natural capital (Section 7). Natural capital is seen in two ways: natural capital accounting, and natural capital risk assessment.

There are significant natural capital risks and opportunities for farms. Some of these opportunities may come with productivity trade-offs.

Soils are likely to be increasingly used in reporting and demanded by supply chains (Section 8). There are many international, European, and Australian soil initiatives which have the potential to impact or be used in future market access agreements and supply chain identification. While the red meat industry currently only aligns with the United Nations sustainability Development goals, there is potential to integrate with other frameworks. This integration will be complex and require significant thought.

In terms of monitoring, extension, and adoption (Section 9), only 25-30 per cent of farmers regularly soil test, a figure that has remained stable for the past 20 years. Many farmers report using field observations rather than laboratory testing to assess soil health, and developing locally relevant soil health cards would work well to support this practice. The MLA already has a vast selection of soil health material on their Healthy Soils Hub and there is much more information available both in Australia and nationally. The Healthy Soils Hub is a high quality resource and the MLA should endeavour to maintain and expand this resource. Adoption or implementation of improved soil management practices on-farm has been relatively slow and can require strong economic, environmental, market or regulatory drivers.

Remote sensing (Section 10) relies on a relatively small suite of sensors but has the potential to provide large amounts of useful spatial information if the data from the sensors can be well-correlated with performance measures. In many cases for soil, remote sensing information is useful from bare ground only. Proximal sensors have the potential to supplement information from remote sensing, though are likely to be practicable only on smaller holdings.

The information provided in this review was incorporated into a framework to guide investment by the MLA in soil issues (Figure i). The framework identified four key theme areas underpinning an enabling theme of soils extension and adoption. The four key theme areas are:

- overcoming regional soil constraints,
- optimising soil carbon storage and soil health,
- managing soil impacts form extreme events, and
- leveraging natural capital and marketing access.

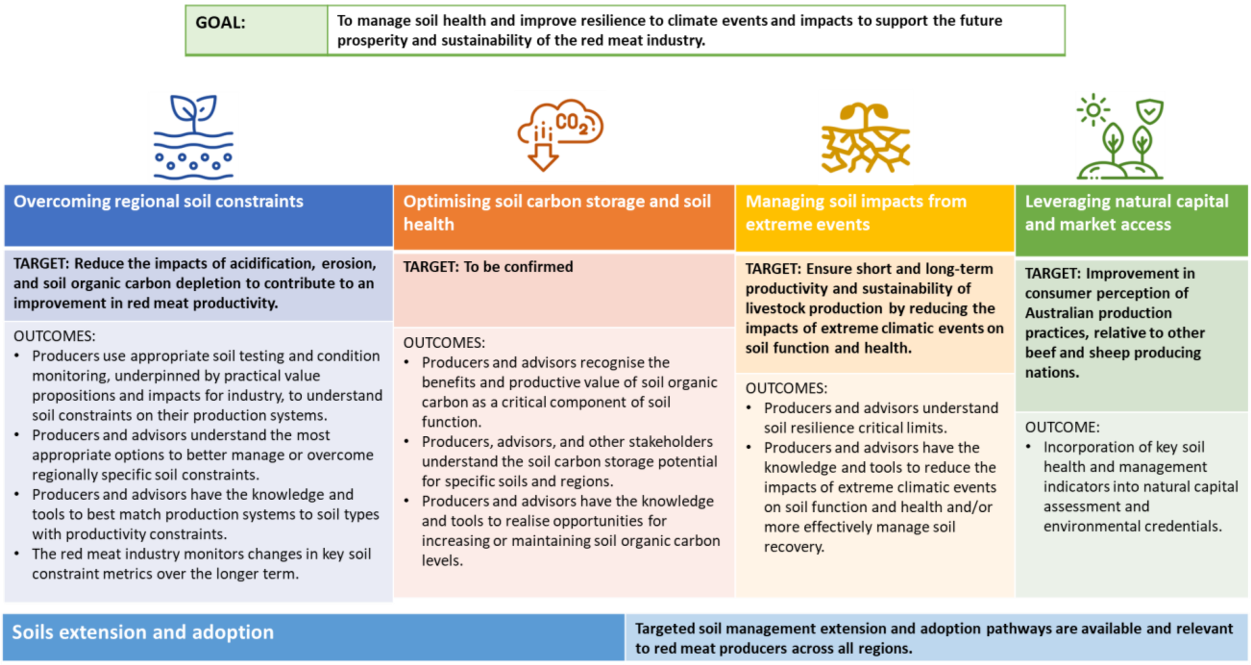

Figure i. The MLA investment framework summary.

Note: The Soil Carbon target needs to be reviewed for practical measurement and applicable scale. The target will demonstrate progress improving or maintaining attainable good soil carbon levels for the inherent soil properties, environmental conditions and best management practices.

The four themes in the framework also provide the context to incorporate statements in MLA's future strategic plans to explicitly recognise the importance of soil to the future prosperity and sustainability of the red meat industry.

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1 Introduction

1.1 Background

Soils are the basis for life on earth. Soil provides the habitat for a vast biodiversity and biomass of soil organisms, and stores most of the nutrients and retain the water that plants and soil organisms depend on to survive (Silver et al. 2021). Soil is increasingly being seen as a solution to environmental issues such as climate change, eutrophication and contamination of water, land degradation, and desertification (Lal 2008). The Australian beef industry is custodian to more than 50 per cent of this nation's land mass (MLA 2022). The services provided by soils in Australia are therefore more dependent on good management by livestock industries than any other group that manage soils.

The last review on soil priorities conducted by MLA was a soil biology review and project prioritisation for the feedbase investment plan in 2013 (Hannam 2013). This review encompasses all aspects of soil and considers it within the context of the MLA strategic plan. This review continues from the last review, concentrating on the past ten years of work completed.

MLA is seeking to develop an Investment Strategy for soil-related research, development, extension, and adoption (R, D, E & A) to guide future investment priorities that will provide sustainability and productivity benefits for red meat producers. The development of this conceptual framework will inform future priorities for soil investment and industry impact along the value chain.

1.2 Objectives of review

The objectives of this review are to:

- Provide MLA with a review and the evidence base developed from published and grey literature, reports and other information for a clearer understanding of the current state of soil related R, D, E & A in relation to the livestock industry.
- Deliver a scoping study that identifies livestock production and feedbase management options that should be pursued in the future to improve sustainability and productivity through enhanced soil performance.
- Identify gaps in knowledge and test the recommended soil R, D, E & A priorities of relevance to red meat producers with MLA Managers through a workshop process that develops a Logic Framework and Investment Strategy.

The sections are laid out with key points in a blue box at the beginning of the section. Information that we have wanted to highlight is in a green box. At the end of each section, there are broad recommendations that we have made.

2 MLA investment to date in soils

2.1 MLA Strategic plan

Key points:

- the MLA Strategic Plan aligns with Australian Government Science and Research priorities, Rural R, D, E & A priorities and the Red Meat 2030 Plan
- soils are only explicitly mentioned in the strategy regarding new sources of revenue, and otherwise they are only implicitly assumed
- care will need to be taken that soils are not just considered from an environmental perspective, but also when considering productivity, market access and grazing systems.

The MLA Strategic Plan 2025 (Anon 2020) has been written in the context of the broader red meat industry and national research and development priorities. The MLA 2025 Strategic Plan has six guiding principles which "will guide delivery of the strategy and will ensure our portfolio is focussed on delivering and maximising impact". These six principles are:

- connecting the supply chain through alignment with Red Meat 2030
- focusing on delivering impact through 'fewer, bigger, bolder' programs of work
- maximising impact by connecting programs and R&D investments to customer, consumer and community insights and establishing clear adoption or extension pathways at inception
- our investments contribute to a socially, environmentally and economically sustainable Australian red meat industry
- taking a continuous improvement approach to the delivery of essential services
- our strategy and programs undergo a constant cycle of review, refresh and inform that includes meaningful consultation with our stakeholders.

There are a number of key performance indicators which could relate to soil although none specifically mention soil:

- increased compliance to quality assurance and integrity systems
- the number of producers deriving revenue from environmental services and/or natural capital trading markets has increased year-on-year
- increased utilisation of data and evidence to inform production-led environmental outcomes
- progress towards CN30 with improvement in carbon net position
- significant contribution to improving preferential access to key markets and to a $1b reduction in technical trade barriers

Alignment with the Red Meat 2030 plan (Red Meat Advisory Council 2019) priorities is central to the MLA Strategic plan. The six priorities within Red Meat 2030 are:

- our people
- our customers, consumers and communities
- our livestock
- our environment
- our markets

- our system

Soils are mentioned in Red Meat 2030 in the context of "advancing sustainability frameworks and supporting their adoption" and "optimising animal production for the environment and the market". While this may seem like a scant mention of soils, they clearly can fit within four of the six priorities: our livestock, our environment, our markets and our system.

The Australian Government sets Science and Research priorities and Rural Research, Development and Extension (R, D, & E) priorities. Soil is explicitly named in both of these priorities. Soil and Water is one of the nine Science and Research Priorities. "Soil, Water and managing Natural Resources" is one of the four Rural RD&E priorities with the stated goal "to manage soil health, improve water use efficiency and certainty of supply, sustainably develop new production areas and improve resilience to climate events and impacts".

Given the strong focus provided through the Australian Government's Science and Research Priorities, and their RD&E Priorities, the review team felt while soils weren't specifically mentioned in many areas of the MLA 2025 strategic plan other than 'enabling new sources of revenue', they were implicitly assumed, providing a reasonable framework on which to build integrated soil research programs. The MLA will need to be aware that soils are not just something to be addressed in environmental considerations but also to be considered in productivity, market access and grazing systems.

2.2 MLA projects

Key Points:

- eighty-eight projects were selected based on measurement of soil indicators.
- where soils were a key focus, grazing management projects were most common and included assessment of amendments such as alternative fertilisers, targeting fertiliser (especially phosphorus (P)) and lime applications to suit soil carrying capacity and effect on biomass production.
- where soils were an incidental focus, there is often a broader view of the feedbase. Introduction of new legumes into farming systems, use of soil monitoring or remote sensing in digital agriculture, and P supplementation for animal health on P deficient soils (especially in the rangelands) were important.

2.2.1 Analysis of soil related projects

A search on the MLA website using 'soils' as a key word identified 880 records that was refined to 431 records by filtering the search type as R&D. The records were collated into a spreadsheet and suitability determined if the project (i) measured or considered a single or multiple soil parameter/s and (ii) commenced post 2010[1].

Eighty-eight projects were identified and further divided into:

[1] Project brief was to consider the last 10 years.

(i) those that had soil as a key focus of the project measuring several parameters, and those where soil was not the key focus but reported soil property as an incidental measure often soil type/texture, soil cover or estimate of soil moisture.
(ii) MLA website areas.[2]
(iii) Australian and New Zealand Standard Research Classification (ANZSRC)[3] to enable an assessment of trends in soil research over time for projects.

A summary of key trends is presented below, detailed tables are provided in Appendix 1 with a complete listing of projects in the MLA Soil Investment 2010-2028 spreadsheet.

As expected, there were fluctuations in the number of projects funded each year (Figure), with large peaks in years 2014, 2015 and 2022 for all projects and those where soil is a key focus. Interestingly there were a low number of projects (1) funded in 2020 where soil is a key focus compared to where soil has an incidental focus (12). Incidental projects completed during this time included environmental sustainability (greenhouse gas frameworks), producer adoption (forage systems) and animal health and welfare.

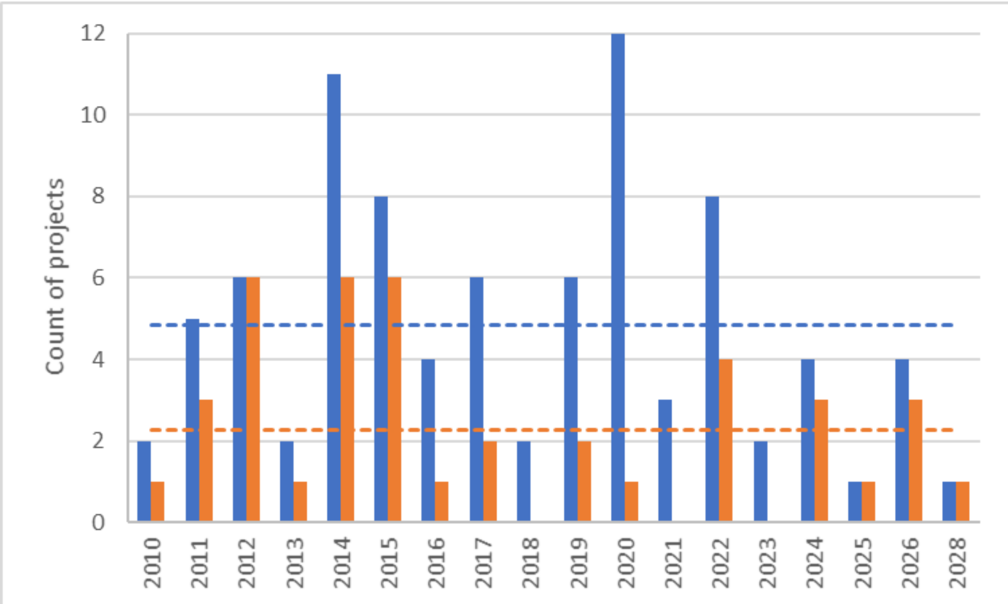

Figure 2.1: Number of soil related projects to be completed between 2010 and 2028 in total (blue) and for those where soil is a key focus (orange). The dashed line denotes average number of samples for the 18 year period.

Where projects had a soil focus, grazing management projects were most common and included, assessment of amendments such as alternative fertilisers, targeting fertiliser (especially P) and lime applications to suit soil carrying capacity and effect on biomass production (

[2] MLA website areas included animal health and welfare, animal nutrition, capacity building, digital agriculture, environmental sustainability, feedbase, food safety and traceability, grazing land management, livestock production, processing productivity, producer adoption, producer demonstration sites.
[3] ANZSRC categories land capability and soil productivity, pedology and pedometrics, soil biology, soil chemistry and soil carbon sequestration, soil physics, other

Table 2.1). Producer demonstration sites are used to assess practice or application differences at the local scale. Where projects had soil as an incidental focus (soil was mentioned or often cursory assessment of the parameter) there is often a broader view. The feedbase, particularly introduction of new legumes into farming systems and use of soil monitoring or remote sensing in digital agriculture were important.

Table 2.1 Ranked MLA areas for projects where soil was a key or incidental focus based on the proportion of total samples.

Rank	Soil key focus	Proportion	Soil incidental focus	Proportion
1	Grazing land management	46%	Feedbase	30%
2	Environmental sustainability	15%	Environmental sustainability	20%
3	Feedbase	10%	Producer adoption	13%
4	Producer demonstration sites	10%	Digital agriculture	9%

The Australian and New Zealand Standard Research Classification (ANZSRC) enabled trends to be identified (Table 2.2, Appendix 1). Measurement of soil chemistry, where soil fertility was of interest for biomass production, was of high interest for both groups.

For projects where soil was the key focus, biology, general fertility particularly P, and carbon were important, and recommendations often defined by and depended on soil texture. Where soil was an incidental focus, soil texture (often suitability for pasture species or selection of amendment on a sandy or clay soil) or moisture content (e.g. high or low). Soil cover for erosion control was mentioned for both groups.

Projects with a biological measure were interested in a variety of issues including understanding the microbiome for drought resilience and pasture dieback, soil borne root diseases in the Southern region, rhizobia selection or establishment, and in the Northern region the potential of biocrusts to fix nitrogen (N) and unique use of soil microbes as a natural tick control for cattle (Probio-TICK).

From 2019, there was a move away from measuring single soil parameters (e.g. chemistry or biology) and a move towards measuring multiple parameters, trying to unravel the complexity that comes with inherent or induced soil characteristics and the associated biological community.

Table 2.1. Examination of ANZSRC categories identifying areas of interest where soil was a key or incidental focus based on the proportion of total samples. There were a number of projects that measured more than one soil parameter.

ANZSRC	Detail	Soil key focus n=41	Soil incidental focus n=47
Chemistry	Fertility	32%	26%
	Carbon	27%	9%
	Phosphorus	15%	2%
	pH	2%	4%
Physical	Texture	17%	11%
	Erosion	5%	4%
	Moisture	2%	9%
Biology		34%	13%

2.2.2 Intensive and mixed farming zones

Projects in the intensive and mixed farming zones focussed on improving production of pastures through selection of suitable species according to soil properties, fertility particularly N and P, application of amendments including lime to address acidification, overcoming soil constraints to production and assessment of soil organic carbon (SOC) as an indicator of soil function and for greenhouse gas mitigation.

2.2.3 Rangelands

Projects in the rangelands focused on high level soil properties, soil cover for water movement and erosion, soil texture/type for suitability of introduction of legumes to improve forage. Specific areas were of interest such as P mapping to determine soil levels to improve animal health and productivity, constraints to production (sodicity), and soil carbon to mitigate greenhouse gases. Feed budgeting from remote sensing and refinement to map land types, land condition was also important.

2.2.4 Project Highlights

There are many notable projects with soil properties as a measured indicator and the three below are of interest for further discussion on how to improve skills and knowledge of healthy soils and pasture production, review of a novel process to manipulate methanotrophs to improve methane capture in soils and evaluating to use of biocrusts to fix N and improve pasture production and animal health in northern Australia.

The Healthy Soils Project
https://www.mla.com.au/globalassets/mla-corporate/extensions-training-and-tools/documents/soil-poster_small.pdf

L.FAP 1902, 2022 Southern Farming System

The healthy soils package was developed as part of the Feedbase Adoption Plan and targeted at producers and advisors to use visual indicators to inform about the underlying soil condition, improve skills in soil assessment and identifying soil issues that are impacting pasture production.

This project piloted the use of discussion groups and a variety of media posters, web-based information (booklet and learning module) and videos to build participant skills. It was reported that the discussion groups were not the best delivery method to improve producers' skills in this context. Sessions that built on knowledge and skills learnt in previous sessions were a key ingredient in producer skill development rather than having different guest speakers on standalone topics. Sessions that were designed to be as hands-on as possible were the most successful to build the skills in assessing different soil profiles and using appropriate tests (soil lab and field tests, plant tissue tests, check plant roots/nodules, assess ground cover, test strips) and ability to diagnose soil constraints.

The discussion groups increased knowledge, but skill development needs a more targeted approach such as the delivery of smaller short course modules as a feeder course into PGS training packages. The suggested approach was two to three sessions of half day workshops related to soil assessment and management. They could concentrate on developing knowledge and less complex skills and be directed into the PGS pathway for more advanced skill development. Producers could choose modules, consisting of a two-hour inside training session, 1 hour field session to practice skills, half hour of dedicated discussion and half hour chat time (social interaction) which was deemed important for producers to share ideas and thoughts and strengthen the appeal of attendance. The modules created could add further value by being converted into online learning modules. Popular modules could be soil organic carbon, liming, waterlogging, nutrients, and soil biology all linking back to assessment of soil condition and improving pasture production.

The visual poster and web information had high appeal for producers to identify their soil constraints affecting pasture production. There is a recommendation to simplify the five easy steps to P tool including simplifying the language and to include other macronutrients and soil constraints such as acidity and sodicity.

Future research and recommendations were:

- to develop updated information based on producer questions collated in the project for soil acidity and soil carbon.
- for MLA to take an active role in promoting science backed soil management information and that conventional agriculture can create healthy soil systems that lead to highly productive pastures.
- to present science-based facts in an easy to understand format.
- to develop smaller, well-designed short course modules as feeder courses into PGS training packages with a complementary stand-alone training method to practice learnt skills and increase skill development.

Biological-based or biological models for methane capture

https://www.mla.com.au/globalassets/mla-corporate/research-and-development/final-reports/2019/b.cch.2110-final-report-1.pdf

B.CCH.2110, 2019 The Biomimicry Institute

The project reviewed biological methods relating to methane sources or sinks in livestock grazing systems to inform producers on different agricultural practices that producers could adopt to improve soil and grassland health and increase methane (CH_4) uptake. The largest anthropogenic source of methane in Australia is agriculture, releasing 3-5 Tg of methane per year largely from ruminants. In Australia, methane sinks are the troposphere (the lowest layer of the atmosphere of Earth) that removes approximately 12 teragrams per year (Tg/yr) of methane from the atmosphere, and soils via microbes are estimated to remove another 2 Tg/yr. Certain species of trees also have the potential to absorb methane from the atmosphere.

Methanotrophs are bacteria that **metabolise** methane and act as a methane sink. Methanotrophs differ depending on the environment's oxygen conditions and can be aerobic or anaerobic. Methanogens are organisms that **produce** methane in hypoxic (little to no oxygen) conditions. They most commonly use carbon and hydrogen to make methane and water and are most commonly found in wetlands, landfills, rice paddies, and ruminant stomachs.

Because the production and consumption of methane from soils occurs as a result of different microbial processes, controlling the factors that influence the growth of microorganisms may help to increase CH_4 uptake and decrease CH_4 output from the soil. These factors include precipitation, soil moisture, soil temperature, soil pH, nutrient availability, and fertiliser where best practice generally improves microbial activity and CH_4 drawdown for methanotrophs.

A recent review (Wang et al. 2022) determined that the greatest abundance of methane-oxidizing bacteria (methanotrophs) is in dryland soil with good aeration. About 82% of CH_4 is absorbed and utilised by methane-oxidizing bacteria in the soil before being discharged into the atmosphere, and then enters the soil ecosystem. However, they did not recommend the use of methanotrophs as a feasible technology to control soil greenhouse gas emissions.

Boosting natural regeneration of the nitrogen capital in grazing lands
B.PAS.0502, 2019-2024 – Rangelands, Northern Australia

In extensive grazing systems in Northern Australia, it is difficult to affect pasture productivity, quality and animal performance through fertiliser due to the impracticalities and cost of application. This project is evaluating the potential of biological soil crusts (biocrusts) containing soil microbes to fix N in grazing lands to determine the impact of grazing, spelling, and fire practices on N capture by biocrusts and how it is recycled and made available to plants. The project will develop insight into the potential of biocrusts to improve pasture production, build SOC stores, and how management methods (fire, stocking and spelling) affect biocrust formation with added environmental (soil stability) outcomes.

The project will create N-smart management strategies and is linked to international efforts on soil carbon sequestration, and in conjunction with Smart SAT-CRC, is appointing a PhD student to include on ground management of soil health through integration of proximal and remote sensing platforms.

2.3 Recommendations

- Monitor and provide information for producers and industry for biological parameters once the most suitable indicators to measure sustained change are assessed and understood.
- Monitor work on understanding the soil microbiome and its effects on soil health. Provide information and monitoring when more information is available.
- Include a statement to MLA’s future strategic plans that specifically recognises the importance of soil and the role of soil metrics to the future prosperity and sustainability of the red meat industry, including reporting obligations and future market access.

3 Scan of literature

We searched using keywords and scanned the literature for recent publications related to soil properties and grazing management. Review papers, special issues of Australian journals, and grey literature of R, D, E, & A programs were assessed.

3.1 Analysis of soil related projects

Key Points:

- in the last 10 years, there has been a change of focus in the scientific literature from largely measuring soil indicators from one maybe two of the ANZSRC categories e.g. chemical, physical biological to including indicators from all three categories
- in the last 5 years, there has been an abundance of review and discussion papers defining what soil health is but not a huge consensus on what should be measured.
- regenerative agriculture is discussed initially with a focus on soil carbon storage but not as many in recent years
- soil health is a concept of capacity. We measure a soil's ability to function compared to a reference state or standard.
- in agriculture, we ask more from our soils than natural systems, so it is not effective to compare soil indicators to undisturbed native vegetation sites.
- relevant soil health indicators will change with location, soil type and management system.
- as soil and environment change across a landscape, so should the references used for comparison. A soil's health is best evaluated against a local reference with similar capacity.
- it is difficult to have a universal soil health index as factors that developed the soil and climate cause variations in the chemical, physical and biological soil properties across the landscape.

A search of Soil Research (an Australian based journal) and Google Scholar using keywords 'soils' AND 'grazing' identified over 30,000 records during the last 10 years. On review, 119 records were compiled with suitability determined by publications that had a key focus on one or a combination of soil properties, soil health, soil management and grazing and/or pastures. Similar to the analysis of MLA projects in S2.2, records were collated into a spreadsheet and the Australian and New Zealand Standard Research Classification (ANZSRC)[4] assigned to identify trends in soils and grazing research over time.

A summary of key trends is presented below with a complete listing of projects in the spreadsheet 'Scan of Non MLA soils and grazing publications':

- single measurement of soil factors has declined, except for biology that had a number of papers investigating role of macroinvertebrates in a healthy soil (Figure).
- there has been a change of focus in the scientific literature in the last 10 years, from largely measuring soil indicators from one maybe two of the ANZSRC categories e.g. chemical, physical biological to including indicators from all three categories and often

[4] ANZSRC categories land capability and soil productivity, pedology and pedometrics, soil biology, soil chemistry and soil carbon sequestration, soil physics, other

trying to understand these from a land capacity and/or productivity point of view (Figure and Figure).

- in the last 5 years there has been a marked decrease in the number of publications with a major focus on soil carbon stocks with an increase in combined chemical, physical and biological indicators (Figure 3.3). Soil carbon is still measured but soil function assessment is as, if not more, important than the greenhouse gas mitigation aspect. This is largely due to heightened discussions on soil health since 2018 and a broader recognition of the multi-functionality of soils.
- a large proportion of publications were global reviews, discussion papers or meta-analysis of data predominantly on soil health indicators (Table 3.1). There was a spread of publications from Australia, New Zealand, North and South America, Asia (predominantly China), Europe and Africa. The highest proportion (25%) of publications were from Australia, 5% were from the Rangelands and 80% of Australian papers assessed were published in Soil Research, an international peer-reviewed scientific journal published by CSIRO Publishing. Interestingly 10% of publications were from USA and none were published in Soil Research.

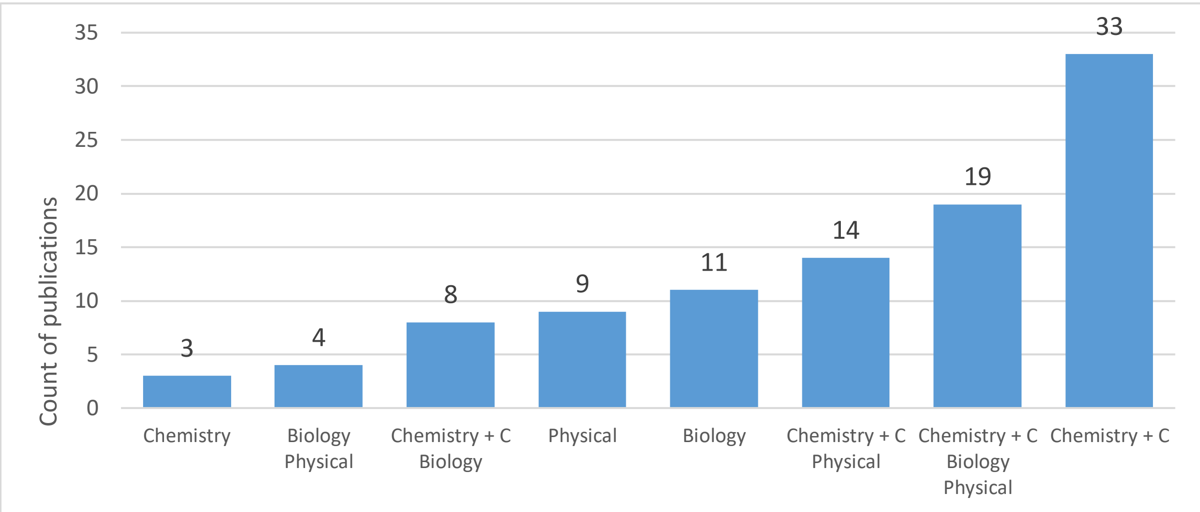

Figure 3.1. The number of publications sorted by the ANZSRC classification between 2014 and 2023. Note classifications with 1 publication are not displayed.

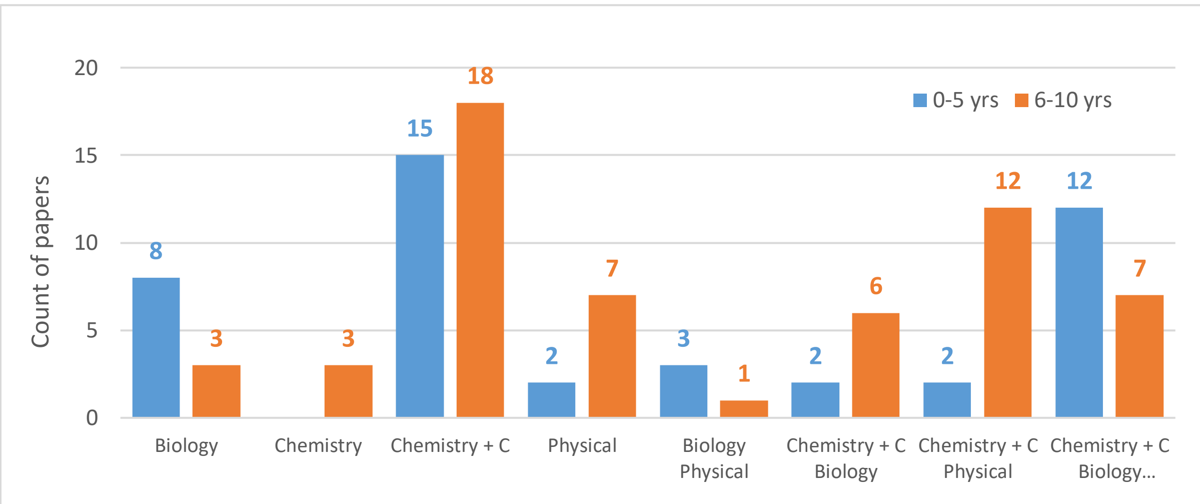

Figure 3.2. Comparison of the number of publications sorted by the ANZSRC classification between 0-5 years (2019-2023) and 6-10 years (2014-2018).

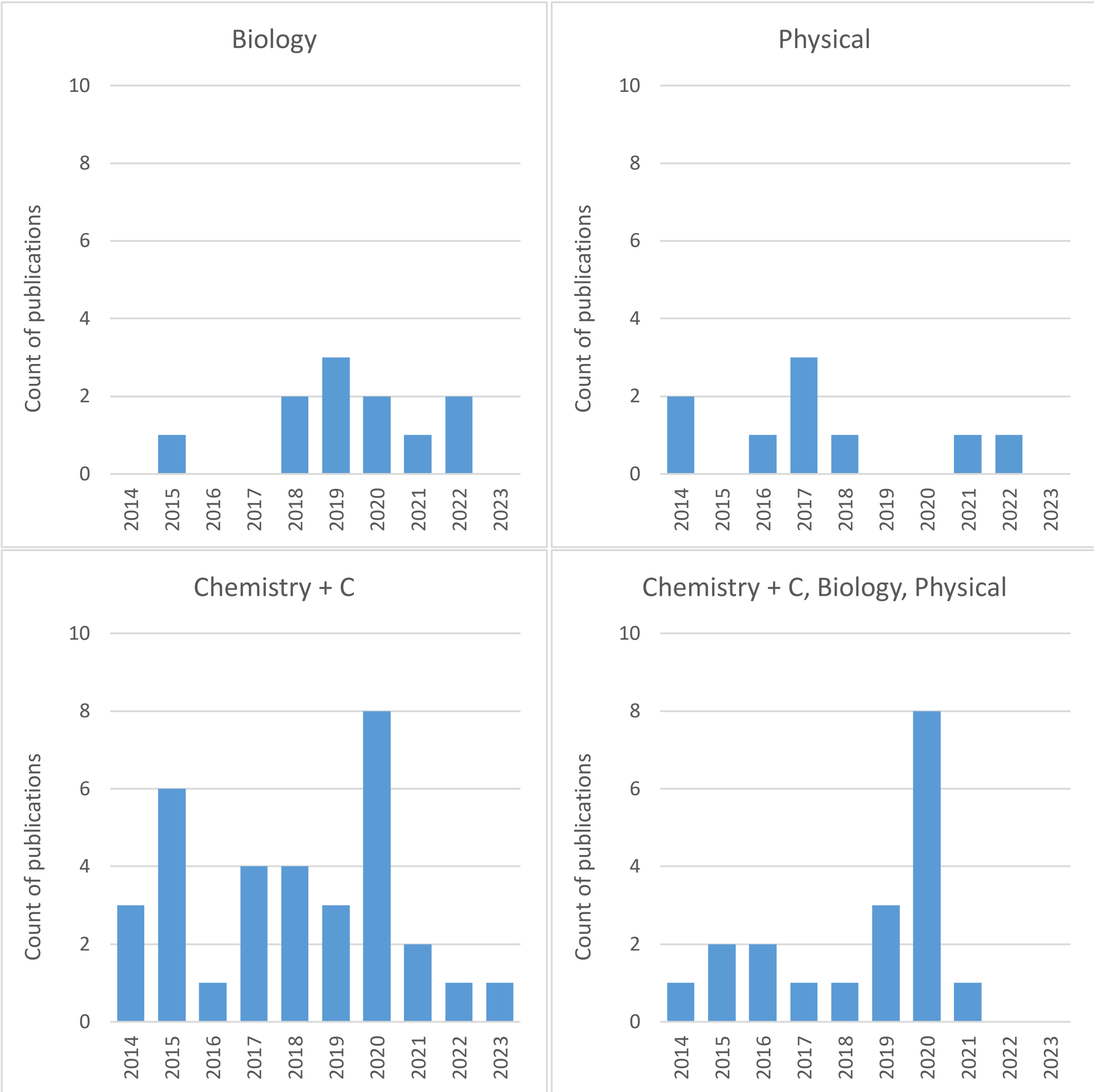

Figure 3.3. Number of publications for key ANZSRC categories by year to highlight change over time.

Table 3.1. Number of publications reported by Continent.

Continent	Number	Comments
Global	24	Global reviews or meta-analysis
Australia	27	5% from the Rangelands, 80% are published in Soil Research
New Zealand	16	100% published in Soil Research
North America	15	10% (of total number) from USA, mostly published in other locations, not Soil Research. Also includes Canada and Mexico
Asia	7	6% (of total number) from China
Europe	7	Ireland, Spain
South America	5	Brazil, Uruguay
Africa	1	
Total	102	Publications with data allocated to Continent

3.2 So what does this all mean?

At a broad level, soil health assessment determines soil functions that relate to multiple important ecosystem services, including environmental protection (e.g. water and air quality, prevention of erosion), production of food and fibre (e.g. storing and cycling nutrients), climate and greenhouse gas regulation, biodiversity and human health.

In this report, we are largely considering agricultural soil health as it relates to the ecosystem services of food and fibre production, water supply and regulation, nutrient cycling, biodiversity and carbon cycling and climate mitigation. However, quantification of soil health is still dominated by chemical indicators, even if there is growing awareness and appreciation of biological measures. This shift largely comes from a focus on plant production, and that whilst an important agroecosystem measure, it is only one of many ecosystem services.

3.2.1 Soil Health and Sustainability

Definitions and contemplations

Soil health is the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals and humans, and connects agricultural and soil science to policy, stakeholder needs and sustainable supply-chain management (Lehmann et al. 2020).

Agricultural sustainability is defined as the ability of a food and fibre production system to continuously produce without environmental degradation.

Regenerative agriculture is both an attitude and a suite of practices that is stated to restore and maintain soil health and fertility, support biodiversity, protect watersheds, and improve ecological and economic resilience. It is often at the centre of discussion around soil health as soil is at the heart of all decisions made on-farm. The five core principles are to minimise soil disturbance, keep soil covered, maximise living roots year-round, maximise crop diversity and integrate livestock and align with sustainable agriculture principles that are already adopted by many producers. However, there is another principle regarding synthetic chemicals that depending on groups or countries, moves from a ‘limit the use of’ to ‘apply no’ synthetic chemicals. This principle is often the one that polarises producers to identify or not identify with regenerative agriculture.

Inherent soil properties include texture, depth, clay type, gravel and are hard to change through management.

Managed soil properties are dynamic and include soil nutrients including N and P, soil organic matter, biological activity and bulk density.

There is a lot of discussion around soil health, what are the most appropriate indicators to use and how to consistently measure them. More importantly, there is a drive to use soil health indicators and indices in environmental and natural capital reporting.

Natural soil is a living ecosystem and can therefore be healthy or unhealthy. The health of a soil reflects its capacity to function and provide desirable ecosystem services. Healthy soil is the foundation of sustainable agriculture and can be deteriorated by improper land use and management practices (Guo 2021).

Not all soils can provide all ecosystem services equally nor simultaneously. There are often trade-offs between food and fibre production and other ecosystem services in agricultural soils (Norris et al. 2020). Due to how soils are formed, their chemical, physical and biological properties vary across the landscape. The inherent soil properties (texture and parent material) and location (climatic parameters) largely determine the soils capacity to function (food and fibre production, water cycling, nutrient cycling, biodiversity, greenhouse gas mitigation). In effect, sands generally have lower capacity than loams to clays, as do soils in low rainfall environments compared to high rainfall environments. Management systems (e.g. intensive or extensive grazing) and applied practices impact the soil health that is measured.

As so many factors influence soil function, a soil's health is best evaluated against a local reference with similar capacity. An agricultural soil in the Queensland rangelands will be very different from a high rainfall soil in Victoria but both could be classified as healthy if using local references.

This variability makes it difficult to have one set of indicators to measure soil health and the reason for so much debate and a challenge for scientists to determine reliable and robust measures for producers and policymakers that promote soil health for agricultural and environmental sustainability across the landscape (Norris et al. 2020).

To be useful as a soil health indicator (Figure), a parameter needs to satisfy several criteria. It needs to be (i) relevant to soil health, its ecosystem functions and services, (ii) sensitive – able to detect change quickly and able to distinguish between seasonal fluctuations, (iii) cheap, practical and short turn-around and (iv) informative for management (Lehmann et al. 2020).

Soil texture and depth, whilst falling outside of the 'useful' indicators, are both essential to provide the context to the measured parameters and can be used to identify the soils potential or capacity (Lehmann et al. 2020).

Guo (2021) summarised soil health indicators as identified by the Soil Health Institute in the USA (Table 3.2; National Soil Health Measurements to Accelerate Agricultural Transformation - Soil Health Institute). At a local scale, soil health indicators can be used to monitor change over time. Furthermore, there needs to be a consistency in the selected test or method used for comparison to ensure data is accurate and comparable.

"Researchers should embrace soil health as an overarching principle to which to contribute knowledge, rather than as only a property to measure. In this way, soil health could become better established as a scientific field to which many disciplines can contribute." (Lehmann et al. 2020).

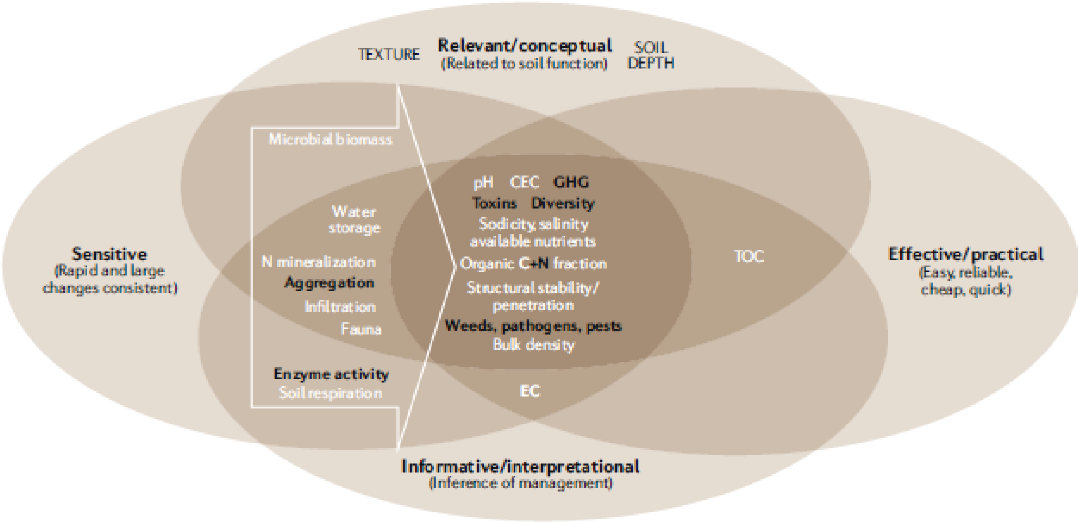

Fig. 4 | **Soil-health indicators and relevance to assessments.** Soil-health indicators ideally are informative, sensitive, effective and relevant[4,53]. Some do not fulfil all criteria but are still relevant (such as texture or soil depth, which do not change readily and are not managed and, therefore, also called capability indicators[55]). Bold text denotes indicators that expand the utility of soil-health quantification beyond crop production towards sustainability and planetary health; the white arrow outline encompasses indicators that should be further developed to be effective and practical. Note, diversity includes biota in soil, diversity of soil types in landscape, molecular/structural diversity in soil organic matter and plants growing in soil, some of which might not be readily quantified through analytical or modelling approaches. C, carbon; CEC, cation-exchange capacity; EC, electrical conductivity; GHG, greenhouse gases; N, nitrogen; TOC, total organic carbon.

Figure 3.4: Soil health indicators and relevance to assessment – extracted from (Lehmann et al. 2020).

Table 3.2: Different tiers of soil health indicators as shown by Guo (2021).

Soil Health Indicators	Criteria	Examples
Tier 1	• Widely considered effective to indicate soil health • Defined regionally and by soil groupings • Known thresholds to index outcome-based soil health status • Responsive to land use and management practices for soil function improvement	Soil texture Soil bulk density Soil aggregate stability Available water-holding capacity Saturated hydraulic conductivity Soil pH Soil electrical conductivity Cation exchange capacity Base saturation Extractable P, Ca, Mg, K, Fe, Mn, Cu, Zn Extractable Al, As, B, Ba, Cd, Co, Cr, Mo, Ni, Pb, Si, Sr Soil total nitrogen content Nitrogen mineralization rate Soil organic carbon content Short-term carbon mineralization Crop yield
Tier 2	• Proven relevant to soil health • Impacting trends on soil health are clear • Ranges and outcome-based thresholds are known for some regions • Improvement strategies can be suggested • Additional research is needed for further validation	Soil sodium adsorption ratio Macro-aggregate stability Soil stability index Soil active carbon Soil protein index Soil β-glucosidase Soil N-acetyl-β-D glucosaminidase Soil phosphomonoesterase Soil arylsulfatase Soil phospholipid fatty acid (PLFA) profile Soil fatty acid methyl ester (FAME) profile Soil microbial genomics Soil reflectance
Tier 3	• Has the potential to be a soil health indicator • More research is needed before users can have adequate confidence in its measurement, use, and interpretation	Soil microbial community structure Soil microbial DNA extraction and sequencing

3.2.1.1 *Is a score card or single soil health index approach useful?*

As there is a multitude of soil-health indicators, a desire exists among some scientists and stakeholders to integrate them into one single test score (an index). However, Lehmann et al. (2020) found only 5 single indices in over 500 studies, with the greatest difficulty in developing a single score for broad scale reporting being the overriding influence of climate, soil and mangement system on indicators.

This difficulty to generally apply a single indicator means that different indictors should be used in different systems. A weighting factor would need to be applied to each indicator to enable creation of a single score so there is a balance between the chemical, physical and biologal components. However, the balance would be defined by what the key focus of soil health assessment is for plant production (more chemical), water health (more physical), biodiversity (more biological) and climate (more physical and biological).

Lehmann et al. (2020) suggest that the development of soil-health-quantification standards should be spearheaded by governmental or intergovernmental organisations such as the Global Soil Partnership. International standards need to be developed for suitable indicators, analytical or visual methods and weighting factors to develop a single soil health index. This considered and comprehensive soil health index should then be referenced by local, regional or national jurisdictions and organisations to guide decisions that impact soil and its functions to benefit sustainability goals.

3.2.2 Generalised Effect of Grazing on Soil Properties

Key Points

Grazing can affect the soil by changes to:

- fertility, through biomass removal and redistribution of nutrients via manure.
- physical properties, through trampling that affects the soil density and pores spaces and thus water movement and availability, and through removal of aboveground biomass that encourages pasture root growth and production of exudates.
- biological properties, largely as a result of physical changes affecting shelter and chemistry which in turn affect food source and nutrients for soil microbial activity and function.

A number of meta-analyses in recent years have investigated the effect of grazing intensity on soil health (Byrnes et al. 2018, Lai and Kumar 2020, Tobin et al. 2020, Zhan et al. 2020). Similar findings are reported that grazing:

- does not negatively affect the majority of soil properties studied except those listed below.
- increases soil compaction (bulk density) in moderate and high intensity compared to no or light grazing.
- at a high intensity decreases soil water storage, nitrate and SOC concentration, and microbial biomass C.
- at a moderate intensity can increase root biomass compared to light and high intensity.
- at a light intensity increases SOC and ammonium.
- at a reduced intensity through rotation or moving from high to moderate intensity can improve SOC, bulk density and microbial activity.
- cattle had higher impact than sheep.

The next sections examine in greater detail the effect of grazing in Australian systems for the Intensive and Mixed farming zones and Rangelands.

3.3 Intensive and mixed farming zones

Key Points:

- addition of cover crops and good grazing management to cropping systems can improve soil organic carbon, carbon fractions, bulk density and water infiltration at some sites and depths but will depend on site specific factors.
- correct soil sampling technique, selection of appropriate soil indictors and analytical or observational method is critical for successful interpretation of results.
- good pasture soil standards for phosphorus, potassium and sulphur.
- soils under dairy and cropping are likely to have adequate P whilst those grazed for meat and wool production are likely to be deficient in P.
- surface and subsurface acidity are becoming an increasing problem. Regular and more refined monitoring is required and if necessary, liming programs need to be established.
- little evidence for a positive change in SOC stocks where management (e.g. rotational, regenerative) has been changed in existing livestock systems and could be due to a number of reasons.
- fires are an inescapable part of Australian systems and contribute carbon in the form of charcoal to the soil. Charcoal is now commonly estimated by MIR spectroscopy as recalcitrant organic carbon (ROC) or pyrogenic organic carbon (PyOC).
- pasture growth responses to the addition of organic or microbial amendments can be variable and often occur where a soil constraint has been addressed e.g. plant nutrients, organic matter or plant growth substances.

3.3.1 Soil fertility

Gourley et al. (2019) conducted a meta-analysis of data from a large number of sites and established fertility benchmark ranges for P, potassium, and sulphur in pasture soils. These fertility benchmarks provide a basis of national standards for soil test interpretation and fertiliser recommendations for the grazing industry. Guidelines do exist for other nutrients derived from research undertaken for certain soils or plants (Peverill et al. 1999, Brennan et al. 2019). Efforts to understand and refine fertility management continues through field measurements, modelling, and isotopic and spectroscopic studies including P use efficiency. A common discrepancy which persists in some sectors of the industry is how to interpret soil test results. While not in the last 10 years, the messages of Kopittke and Menzies (2007) and Menzies et al. (2011) still hold, that while pursuing an 'ideal' ratio can be productive, doing so is generally a more expensive and inefficient means of reaching the same goal as reaching a sufficiency level.

Plants take up nutrients in inorganic forms, regardless of whether the nutrients may have been applied or cycled as inorganic ions or been applied as organic materials that have been mineralised to inorganic forms. There are close beneficial interactions between plants and the soil biological community, interactions that continue to be discovered (Coonan et al. 2020; Hermans et al. 2020; Majdura et al. 2023). The lack of established general benchmarks for most of the essential nutrients, and the interest around alternative sources and systems, invites trialling products and rates. Such trials may be the use of common ameliorants such as manufactured fertilisers, lime, gypsum, or a growing number of products such as composts, microbials, humic teas etc (Edmeades 2011). The utility of various products in grazing systems in southern NSW was assessed recently over a six-year trial where P was a limiting factor by Leech et al. (2019). They applied the products as recommended commercially and found that those applications with substantial quantities of P resulted in significantly higher pasture growth and clover content, of which superphosphate provided the most effective source of P, a finding generally consistent with Edmeades (2002). While Leech et al. (2019) observed large differences in pasture growth between their treatments, there was no major effect of the on soil microbial community structure, particularly where P or other factors such as acidity was still limiting. Which microbial indicators may be actually useful to assess soil health is an ongoing area of investigation (Fierer et al. 2021).

Crawfordet al. (2020) assessed soil fertility and pH across 234 paddocks in East Gippsland and found that many paddocks are now strongly or very strongly acidic and deficient in molybdenum (Mo) and boron (B). They identified that dairying and cropping are more likely to have adequate P but those grazed for meat and wool are likely to be deficient in P. These findings are in broad agreement with McKenzie et al (2017), who reported that induced acidity and the application of P and N fertiliser generally reflect the intensity of production, but other nutrients can be lacking, and nutrient mining still occurs where native fertility supports production.

All agricultural production systems acidify soil through the application of N based inputs (including fertilisers, legumes or manures) or elemental S, and redistribution or export of product. Low soil pH reduces the availability of nutrients for plant growth, can increase aluminium in the soil solution that is toxic and can impair root growth, and detrimentally affects nodulation of Rhizobia in most pulses. Surface and subsurface acidity are becoming an increasing problem and regular monitoring is required and if necessary, liming programs need to be established. Precision soil pH mapping offers an alternative to traditional paddock or zone sampling and provides detailed information on soil pH zones and recommended liming rates (e.g. https://acidsoilssa.com.au/). There needs to be refinement of the sampling technique for successful use in pastures due to artefacts of practices emerging to the cropping and pasture phases. Increasingly high-performance cropping phases have accelerated the development of stratified acidification in the rootzone (Condon et al. 2021). Meanwhile, decreased tillage in the cropping phase or the absence of the disturbance has led to alkaline residue at the surface (B. Hughes, pers comm). Without refined sampling these artefacts can lead to misleading results.

Correct soil sampling so as to provide sensible information from laboratory testing is still very important. It is important to remove natural variability of soil properties as much as possible at the source, during sampling, so references to benchmarks for relative yield or expected responses to fertiliser can be done reliably (Gourley et al. 2019). The basic importance of correct sampling for fertility assessment is not new (Colwell 1971, Webster and Butler 1976), but its importance has been reiterated recently to ensure the industry provides reliable guidance to producers (Webster 2011, Gourley and Weaver 2019, Schut and Giller 2020, Singh and Whelan 2020, Hayeset al. 2022).

3.3.2 Grazing

Tobin et al. (2020) investigated the short-term impacts (1-2 years) of implementing good grazing management (40% - 60% biomass removal) and adding cover crops to cropping systems and found, at some sites and depths, a positive effect on total SOC and fractions, bulk density and water infiltration rate. Site specific properties such as soil type, mineralogy, climate, and inputs would affect the results as would the starting SOC and fertility levels.

The majority of studies assessing a change in grazing management (e.g. rotational, regenerative) in existing livestock systems have found changes to pasture productivity but no significant change to SOC stocks (Sanderman et al. 2015). This could reflect the short-time frame in which projects were assessed (often 1-3 years), the limitation of adjacent paddock or farm comparisons, or that many pasture soils are near their SOC capacity, or are limited by other factors such as nutrients, rainfall, biomass inputs etc. or have reached equilibrium with the microbial community. These interactions will be discussed in Section 6.

Capturing and utilising soil moisture is important for productivity in grazing systems, particularly with the decrease in southern rainfall being observed and expected with climate change (CSIRO and BoM 2018). Selection of pasture types, be they legumes, native grasses or shrubs, tropical or temperate grasses, or forage crops, influences infiltration and water use efficiency through the effective groundcover they provide, their effective rootzone, and the timing of growth (Murphy et al. 2017, Murphy et al. 2019). Species selection, adequate fertility management, and flexibility around grazing management can be used to manage grazing systems with variable rainfall patterns (Badgery et al. 2017, Boschma, et al. 2017, Murphy et al. 2017, Hayes et al. 2019, Murphy et al. 2019).

3.3.3 Effects of fire on soil

The legacy of historic fire on soils is evident in visible charcoal in soil profiles (Badgery et al. 2014). The hotter a burn, and the longer burn time, the greater the effect on soil properties, including SOC combustion (Santin and Doerr 2019). The effects of different fire intensities were reviewed after the Warrumbungles fire in 2013 by Tulau et al. (2019) and is being undertaken post the 2019-2020 fires (Purdie et al. unpublished), and in a cultural burn across NSW from the SE rangelands, south coast and northern tablelands (M. Tulau, pers comm). The abundance of charcoal is commonly estimated by MIR spectroscopy as ROC, or more recently termed PyOC (Lutfalla et al. 2017, Tulau et al. 2020).

3.3.4 Effects of organic and microbial products

There is a burgeoning industry in organic and microbially based soil amendments (e.g. manures, composts, humic products, microbial teas etc) to improve pasture productivity. A number of trials and reviews have been conducted across Australia and New Zealand and have found varied pasture response. A positive pasture response often occurs where a constraint has been overcome – for example, provision of depleted nutrient/s or response to changed soil conditions resulting from physical incorporation of the product into the soil. Little to no plant response often occurs in soils with few production constraints (e.g. good fertility, soil structure and biological activity) or where the product does not contain sufficient concentrations of plant nutrients, organic matter or plant growth substances ((Edmeades 2002).

Despite differences in pasture production with the addition of products, there are often no significant changes to the microbial community structure reported ((Leech et al. 2019). Short term microbiome changes could be expected with change/s to food provided, soil structure and water availability. So, in effect the microbiome is highly dynamic in response to its environment so changes to the structure and function of the soil microbiome would occur over short periods, but over longer timeframes (months to years) would be self-regulated and dependant on the functions required to address the change in the soil.

3.4 Rangelands

Key Points:

- rangeland soils are commonly more alkaline, more saline and have less leaching of nutrients than higher rainfall areas
- pasture benchmarks have limited applicability due to the uneconomic prospect of applying fertilisers
- where P is a key limiting factor of livestock productivity it is more effectively supplied through direct animal supplementation than application of fertiliser through the soil
- the use of remote sensing data combined with field data for vegetation condition and cover, rainfall and fire history used to recommend adjustments to livestock grazing number to avoid degradation in Western Australia could be applied more broadly
- soil erosion is an area of key research for soil conservation, redistribution of soil carbon, the role of crusts to stabilise soil, rehabilitation of 'scalded' areas to improve plant establishment and water infiltration, and for the protection of significant assets such the Great Barrier Reef
- grazing management focusses on long-term carrying capacity of livestock numbers to minimise soil erosion and sustain the pasture
- links between concentration of soil carbon stock and tree density and surface litter in the Darling Riverine Plains and the Cobar Pedeplain in NSW
- early season burns may be an order of magnitude cooler than late season burns. Fire intensity and the effect on soil may change due to future climate scenarios.

Rangelands cover approximately 80% of Australia and are characterised by rainfall too low or irregular to generally support cropping (https://www.dcceew.gov.au/environment/land/rangelands/acris) as well as challenging the management of grazing systems (Stone et al. 2021). Characteristic features of the relatively low rainfall results in soils that are commonly more alkaline, and often more saline, in the profile (see Section 4). There were 115 publications identified for grazing Rangeland soils in the last 10 years. Below are topics with relevant recent research.

3.4.1 Soil fertility

The benchmarks developed for P, K, and S in pasture soils (Gourley et al. 2019) have limited applicability due to the uneconomic prospect of applying fertilisers. A key limiting factor of livestock productivity in large parts of the northern rangelands is P deficiency, which can be more effectively supplied in the extensive systems through direct animal supplementation than via fertilisers applied to soil (Bowen, Chudleigh et al. 2020, Dixon et al. 2020, Schatz et al. 2023).

The limited leaching of the rangelands soils does mean that nutrients are not as naturally depleted as in higher rainfall areas, though their solubility, for example P, may be limited by high soil pH (Andersson et al. 2016). Little soil testing is routinely undertaken in the rangelands, though doing so would be a useful guide as for producers to understand where they sit in relation to level of nutrient excess or depletion (McKenzie et al 2017). Accurate sampling would again be important

(Gourley et al. 2019, Gourley and Weaver 2019), as will selecting the appropriate test for the conditions (Speirs et al. 2013, Gourley et al. 2019).

Soil organic matter and soil carbon is a common topic that crosses over research of other soil attributes and management practices and will be addressed separately in Section 6.

3.4.2 Soil erosion

The condition of pastoral rangelands at a regional level in Western Australia is summarised annually in the pastoral rangeland condition and trend reports (Department of Primary Industries and Regional Development 2020). The reports use remotely sensed and field data of vegetation condition and cover along with rainfall and fire history to recommend adjustments to livestock numbers to avoid degradation including decreased infiltration, diverted flows, soil erosion, and decline in the feed base.

Bulk loss of soil by gully erosion has been an area of research in Queensland reflecting concern over the effects on the Great Barrier Reef (Koci et al. 2020, Bartley et al. 2023). Monitoring and stabilisation of wind erosion is a common topic, both regarding soil conservation (Zhang et al. 2022, Yang et al. 2023) and relative C enrichment in lost sediments (Webb et al. 2014, Chappell et al. 2019). Specialised research including the role of soil biocrusts in stabilising rangeland soil is a less common area than other topics but continues in the lower rainfall zones of the rangelands, e.g. (Webb et al. 2014, Williams et al. 2022). Recovery of eroded soils in the rangelands, where the topsoil has been lost leaving a 'scalded' subsoil as the new surface, is an area of interest because plant establishment and infiltration are both slow (Williams et al. 2022, Bartley et al. 2023, Vincent and Mihailou 2023). Understanding biocrusts in a stabilising and pioneering role is important when some advice promotes disturbance as a necessary component of rangeland recovery and functioning (Briske et al. 2014).

3.4.3 Grazing

Grazing research rangeland systems inherently concerns soil and focusses on the livestock numbers that can be carried in the long term while sustaining pasture condition and minimising soil erosion (Johnston et al. 1996). Following three decades of research, synthesized findings involving modelling have been incorporated in a recent publication for Queensland (Stone et al. 2021, Zhang et al. 2021). Waters et al. (2017) investigated the effect of grazing intensity on soil and biodiversity in the Darling Riverine Plains and the Cobar Pedeplain in NSW, finding correlations between the concentration of soil carbon stock and tree density and surface litter. Other research demonstrating increased groundcover with effective grazing management suggests that grazing management has the potential to positively influence SOC levels, though statistically significant effects may not be evident for as long as 20 years (McDonald et al. 2018, Waters et al. 2019, McDonald et al. 2020, Bartley et al. 2023). However, more intensive grazing management (cell grazing) can have a negative effect on SOC levels compared to continuously grazed or grazing exclusion, e.g. various soil types and climatic regions throughout Queensland (Allen et al. 2013).

As a determinant of soil moisture, infiltration rates are a key driver of rangeland productivity. For the northern rangelands, Fraser and Stone (2016) found that there was an underlying effect of soil texture on infiltration rate (with a minimum rate at 64% sand), while aboveground biomass had the dominant influence. Minimising disturbance of soil structure and compaction by livestock are important, as they found that the highest infiltration rates were where grazing had been excluded. Grazing animals may disturb physical crusts that can allow plants to establish in an otherwise hard surface, however compaction and the destruction of biocrusts can decrease infiltration and have the opposite effect on germination (Neilly et al. 2016).

There is a long history of disparity between producer observations and scientific findings on the effects of grazing management practices on soil properties (e.g. Norton 1988, Briske et al. 2011, Teague et al. 2013, Gosnell et al. 2020). Resolution may lie in recognising that what can work for one situation or set of management objectives does not necessarily apply generally, and a framework linking experience with experiments is required for flexible rangeland management (Briske et al. 2011). Broad guiding principles to do so proposed by Hacker and McDonald (2021) were to 1) manage grazing within a risk management framework based on the concept of tactical grazing, 2) develop infrastructure to allow best management of both domestic and non-domestic grazing pressure, 3) incorporate management of invasive native scrub, where required, into overall, ongoing property management, and 4) manage grazing to enhance biodiversity conservation at landscape scale.

3.4.4 Effects of fire on soil

Reid and Murphy (2022) recently reviewed tropical savanna burns in Australia. Prescribed or early-season burns in the tropical savannas occur close to the surface because the canopy cannot sustain a crown fire. The early season burns are generally patchier and may also be an order of magnitude cooler than late season burns. Future climate scenarios could lead to fewer days available for hazard reduction so increasing the intensity of fires. Similarly, increased fuel loads with the encroachment of invasive grasses may increase fire intensity. Fire management in the savanna rangelands is also relevant to emissions reduction programmes (Maraseni et al. 2016), from which potential income streams may result in a greater capacity to manage burn programmes (Reid and Murphy 2022).

3.5 Gaps

In the last two decades, the level of producer participation in soil testing has remained steady across Australia and USA with only 25-30% undertaking soil analysis (Lobry de Bruyn and Andrews 2016). In Australia, most of the results come from the more intensive cropping and grazing areas (McKenzie et al. 2017). Benchmarks are based on these samples and will be skewed to these areas and management practices, leaving a large gap of information in the Rangelands.

The National Soil Strategy led Pilot Soil Monitoring Incentives program intended to collect and collate soil data from across Australia but unfortunately uptake wasn't large, and the program ceased (https://www.agriculture.gov.au/agriculture-land/farm-food-drought/natural-resources/soils). While there are robust and reliable soil chemical and physical standards for the intensive cropping and pasture areas, there could be local refinement for new tests being developed, especially for biological indicators (Fierer et al. 2021). Identification of the most suitable soil indicators in the mixed and intensive farming and rangeland areas to measure soil function in relation to the soil ecosystem services of food and fibre production, water supply and regulation, nutrient cycling, biodiversity and carbon cycling and climate would be welcome.

There is a gap in cohesive collation, storage and assessment of soil data in Australia that can be used for monitoring, establishing benchmarks and creating local/regional soil references for comparison of soils capacity and capability.

3.6 Recommendations

- Collation and interpretation of measured and observational data and the metadata (contextual information) should be a priority for all MLA projects. This can provide a basis for assessment of change in soil properties and soil health due to a number of management practices in different areas in Australia.
- Targeted soil sampling should occur in regions where there is limited soil data – this will need to be funded by industry, state, or federal initiatives, especially in the rangelands where information is limited.
- A universal soil health index will be difficult to develop and is best left to governments or organisations such as the Global Soil Partnership to determine relevant indicators and weighting factors with subsequent local refinement.
- Local soil health references could be developed for areas that have sufficient, reliable indicators by industry, or States at the regional scale. There is likely to be more information for chemical and physical indictors, but as more information becomes available for suitable biological tests, they can be incorporated. The local soil health references can be used as a way for producers to benchmark their soil in their local (potentially regional) areas and provide a measure of capacity (e.g. how close their soil is to reaching a good or bad standard).
- Define local soil management challenges and priorities that are suited to the climatic, soil and farming system.
- Continue to remain abreast of trends in soil research including soil health and environmental and sustainability reporting requirements nationally and internationally.
- Validate and calibrate remote sensing tools and combine with artificial intelligence to determine accuracy and sensitivity to changes in ground cover, length of greenness, pasture productivity (biomass) and soil properties, inherent and managed (particularly carbon).

4 Key soil types, difficult soil types, soil constraints in the context of grazing systems.

Key Points:

- Grazing systems occur across a wide range of soil types in Australia. It is very likely that stocking intensity reflects a combination of soil and environmental limitations that preclude higher stocking rates. Testing of appropriate plant nutrient management systems and assessment alongside the suitability of the land for a given land use is required.
- Soil and land data and information (e.g. mapping) across Australia is inconsistent and often outdated for dynamic soil properties, especially where there have been significant changes in management practices and land use. Sodicity is a prime example. There are opportunities to leverage and work in combination with public and private data collections to gain further insights on evolving trends and behaviours for industries – dynamic monitoring.
- A suitability-based assessment should be undertaken to better consider agricultural versatility and where soils and lands are better suited for grazing purposes, they can then be prioritised for industry development and expansion, e.g. northern Australia, high rainfall zone of southern Australia.
- Soil acidification remains a key threat to grazing production systems with recommendations to better understand current practices and linkages with nutrient excess and increased use of N fertilisers.
- The integration of indicators that matter to the different production systems, and linkages to key soil functions and threats, is required to present land managers with tailored information that matters to their enterprise. The role of new information (e.g. fungi, bacteria) presents exciting opportunities.
- The intensification of land use in northern Australia has implications for soil and land condition and requires the provision of specific information on best management practices.
- Protection of on-farm assets such as organic carbon-rich soils in peatlands, forests and grazing lands may align with evolving national priorities in biodiversity protection and enhancement.
- A quantitative social science investigation into the factors that limit the uptake of soil conservation and sustainable management practices is required.

This assessment of key soil types, difficult soil types and soil constraints builds on a previous review by Orgill et al. (2018). This chapter provides a current synopsis of the latest mapping and key information in the context of grazing systems across Australia. An environmental scan includes the latest products accessible online or as published reports and papers including the national review of soil trends and priorities to improve soil condition (McKenzie et al. 2017). This may include confidential or yet to be publicised soil maps and products that are in preparation.

4.1 Key soil types and landscapes

Soils, their management, environmental factors, vegetation, disease and pestilence, water access, livestock and type of grazing system are all important factors in defining the key soil types and landscapes that are most conducive for these production systems (Figure 4.1). To date there have been limited attempts at identifying areas 'suitable' for grazing with most efforts focused on mapping pasture species suitability (e.g. Smith et al. 2019) including amelioration options, land suitability of mixed grazing systems (Fazel et al. 2012) and the GEMINI Project (Maskell and Griffiths 2019).

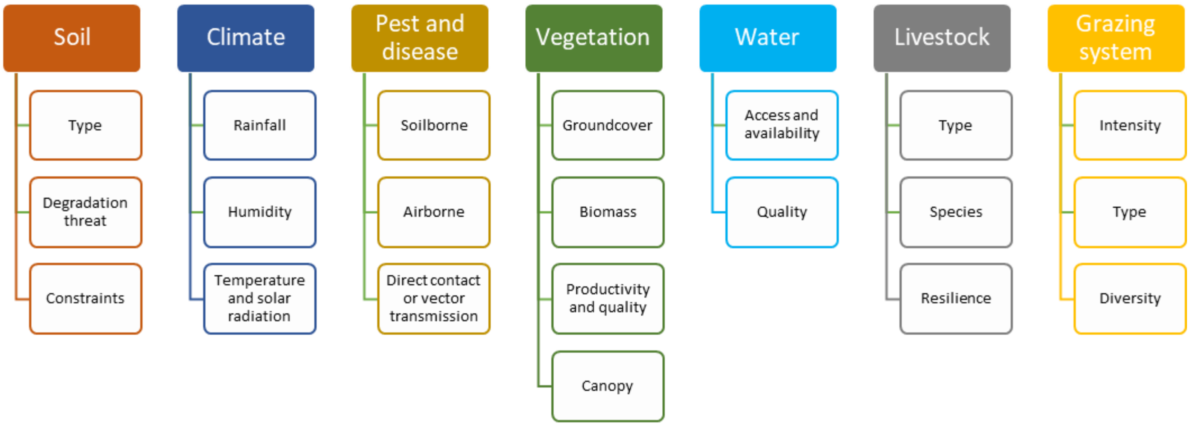

Figure 4.1: Potential factors and variables in consideration of soil suitability for different grazing systems.

4.1.1 Soil maps

The first national map of the soils of Australia was produced by Prescott in 1931, soon followed in 1944 by a detailed and large-scale continental assessment of the major soil zones and types. Prescott initially designated ten soil groups, of which at least four are prominently sandy soils. Maps and corresponding classification systems were generated in the following decades including Stephens (1953), Stace et al. (1968), Northcote et al. (1960-1968) and Isbell (1996) that built upon the foundational discoveries and understandings of Prescott. Ashton and McKenzie (2001) produced a national map of the Australian Soil Classification (Figure 4.2) that was founded on the scheme developed by Isbell (1996) and the continental map base of Northcote et al. (1960-1968).

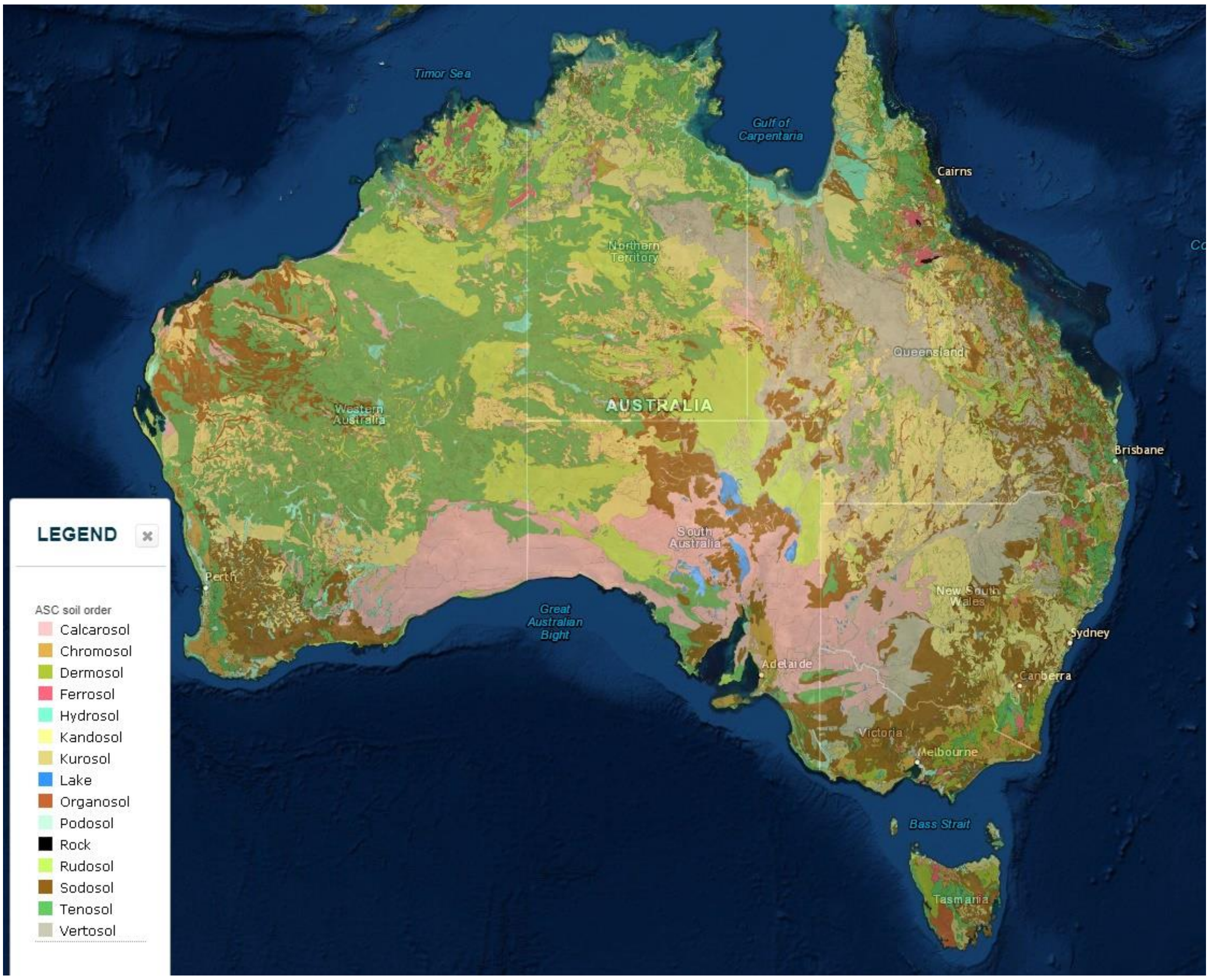

Figure 4.2: Soil orders of the Australia Soil Classification (Ashton and McKenzie 2001).

Recent mapping efforts at a continental scale include the Soil and Landscape Grid of Australia (SLGA: Grundy et al. 2015) which provides soil attribute predictions across Australia at a ~90 x 90 m resolution for 11 properties. All maps were made in compliance with GlobalSoilMap.net specifications including depth prediction intervals of 0-5, 5-15, 15-30, 30-60, 60-100 and 100-200 cm.

These maps include the soil properties:

- bulk density (g cm^{-3} for whole earth)
- organic carbon (%)
- particle size fractions (clay, sand and silt)
- pH($CaCl_2$)
- total N (%) and total P (%)
- effective cation exchange capacity (cmol/kg)

An update to these maps has recently been completed as part of a national investment through the Terrestrial Ecosystem Research Network (TERN) infrastructure (https://esoil.io/TERNLandscapes/Public/Pages/SLGA/index.html). This update, known as version 2 of the SLGA, also include maps of available phosphorus (Figure 4.3), SOC fractions (Figure 4.4), fungi and bacteria and ternary products (Figures 4.4 to 4.8), and modelled soil types according to the Australian Soil Classification (ASC). The new ASC modelled soil types (Searle 2021) have been used as a basis for soil type assessments across the NRM regions of Australia in this report (Figure 4.9).

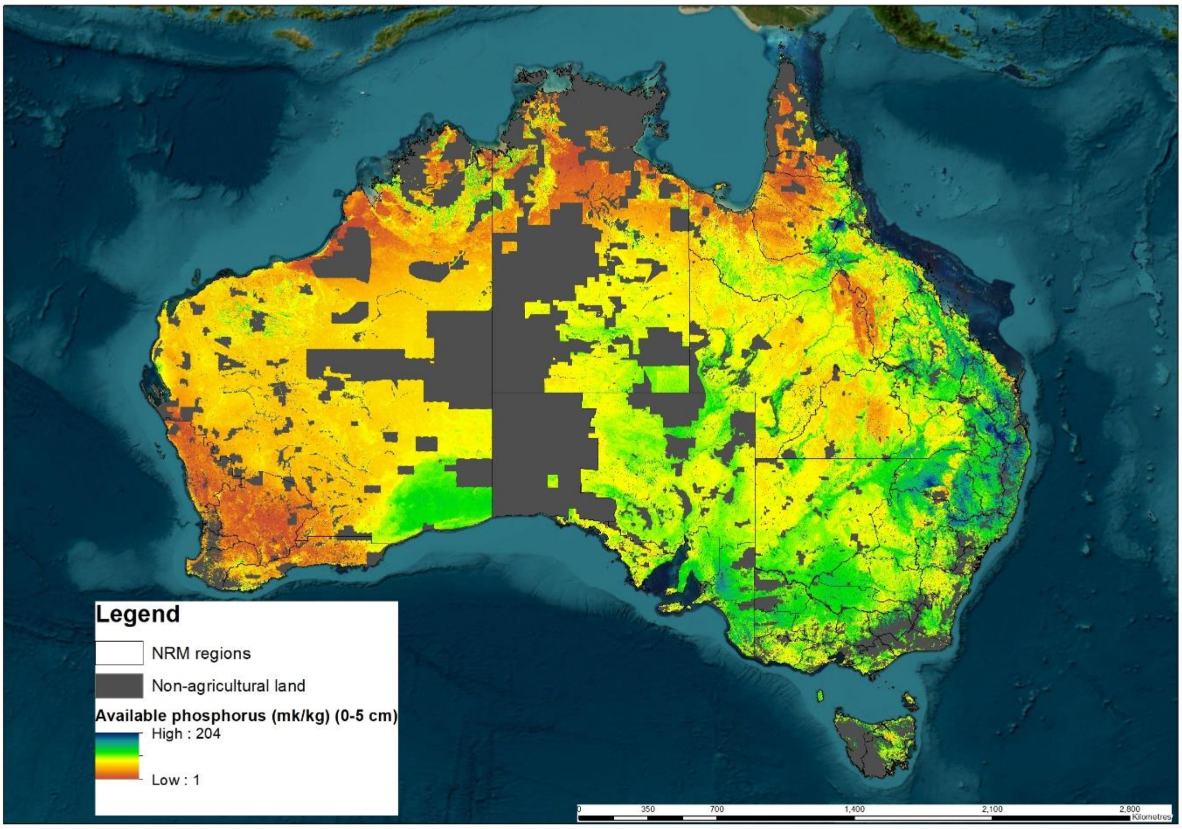

Figure 4.3. Available phosphorus (mg/kg) prediction for 0 to 5 cm.

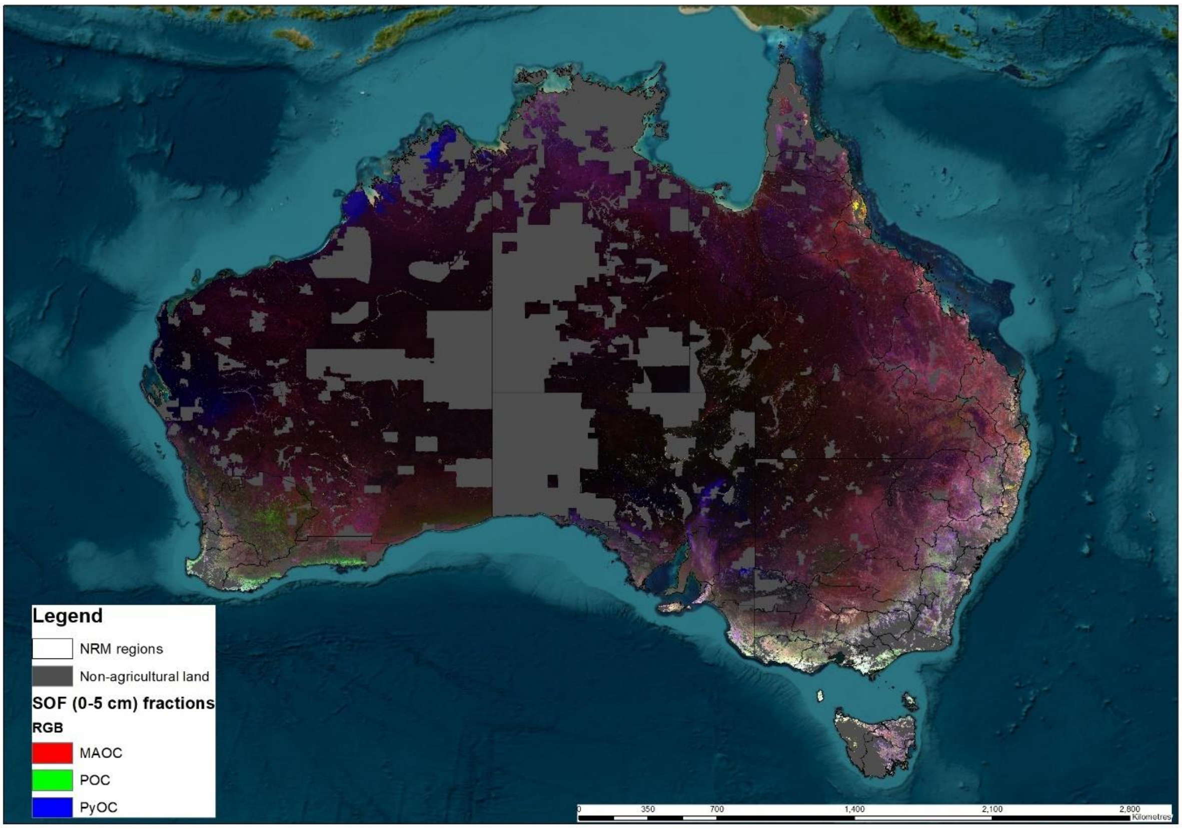

Figure 4.4. Soil organic carbon fractions (MAOC, POC and PyOC) ternary map of Australia.

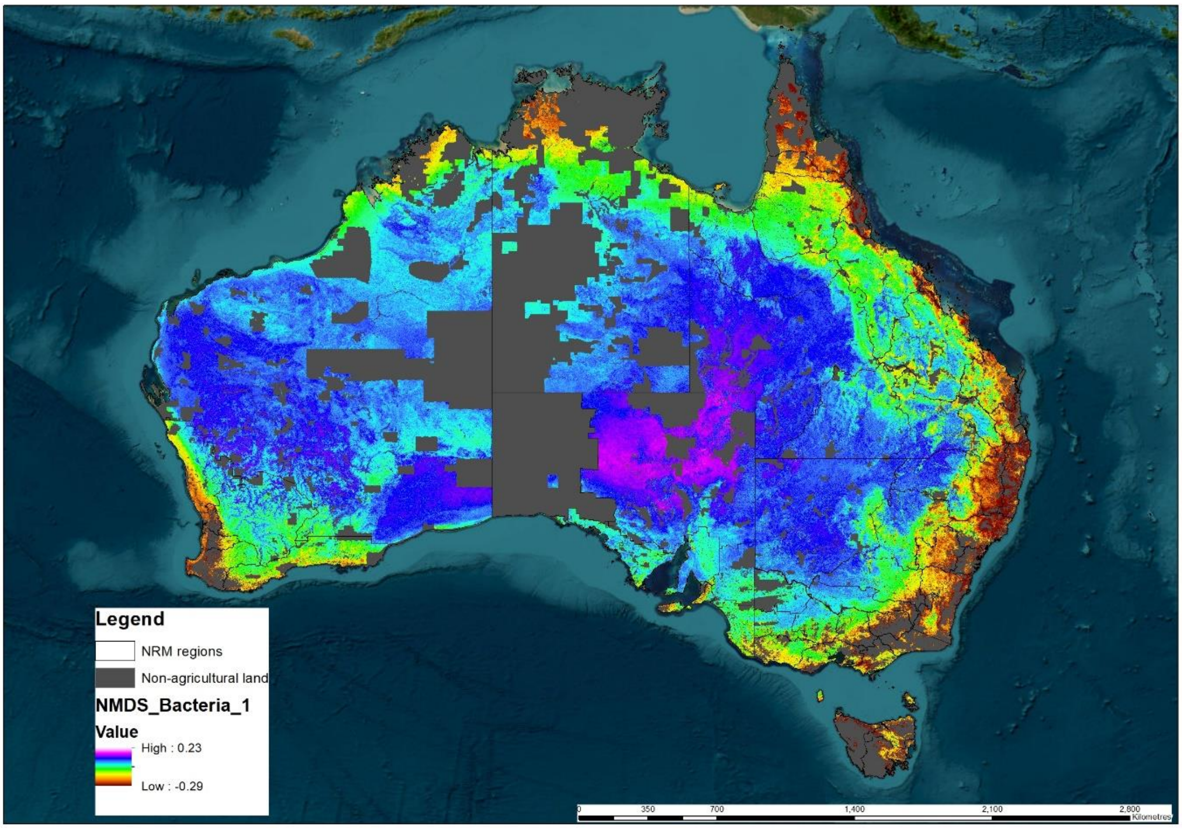

Figure 4.5. Non-metric multidimensional scaling (NMDS) 1 -bacteria.

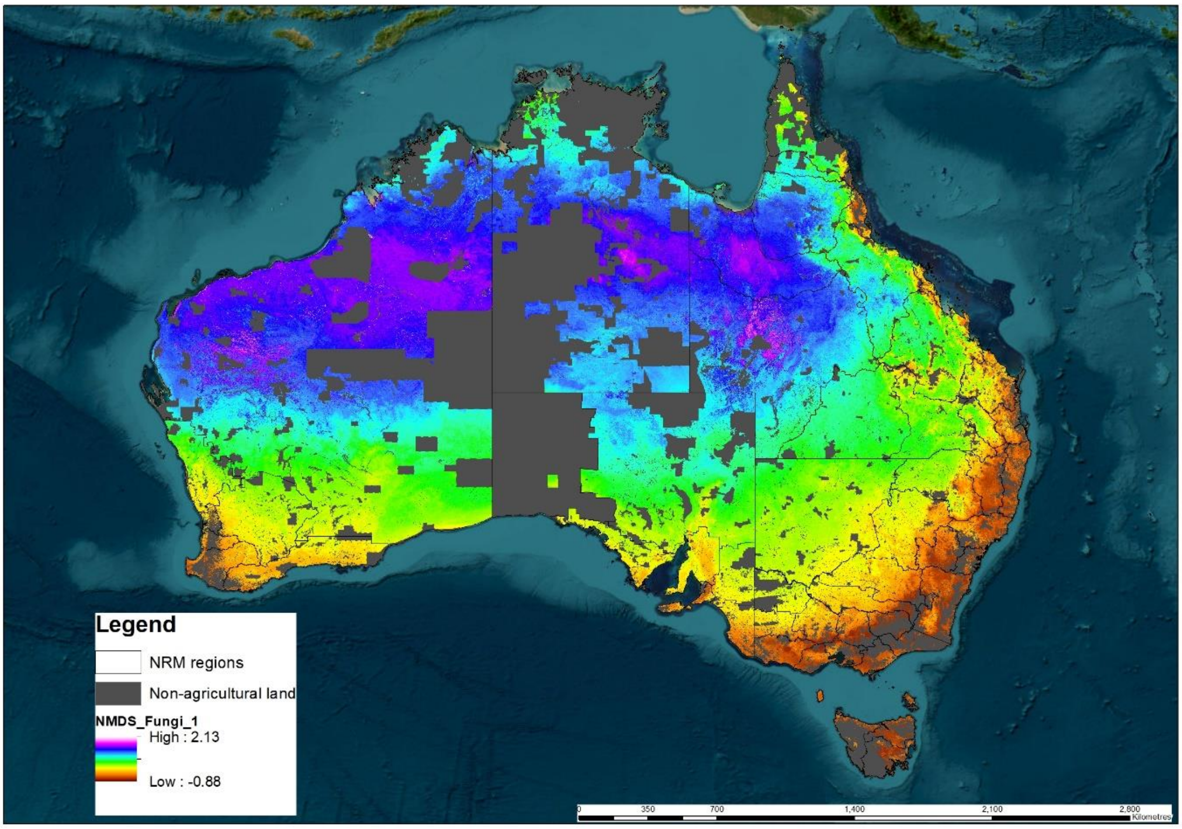

Figure 4.6. Non-metric multidimensional scaling (NMDS) 1 -fungi.

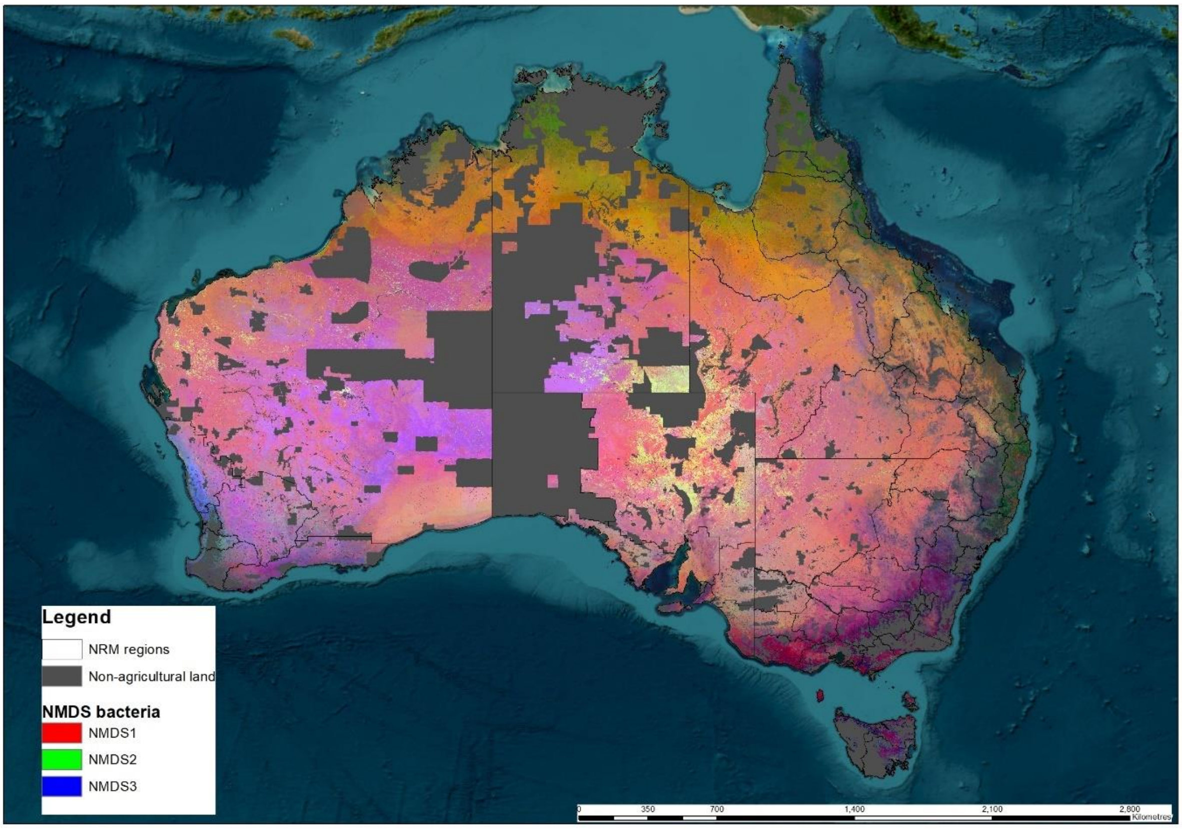

Figure 4.7. Soil bacteria NMDS ternary image of Australia.

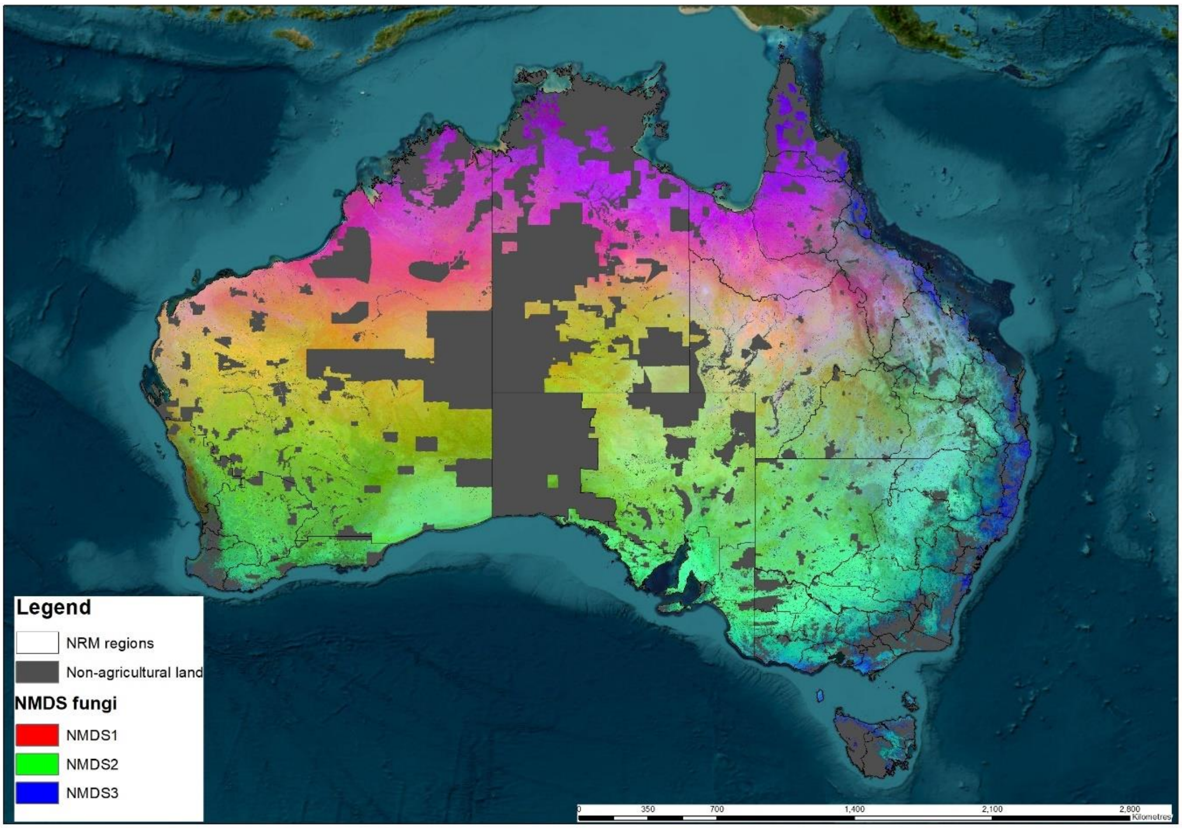

Figure 4.8. Soil fungi NMDS ternary image of Australia.

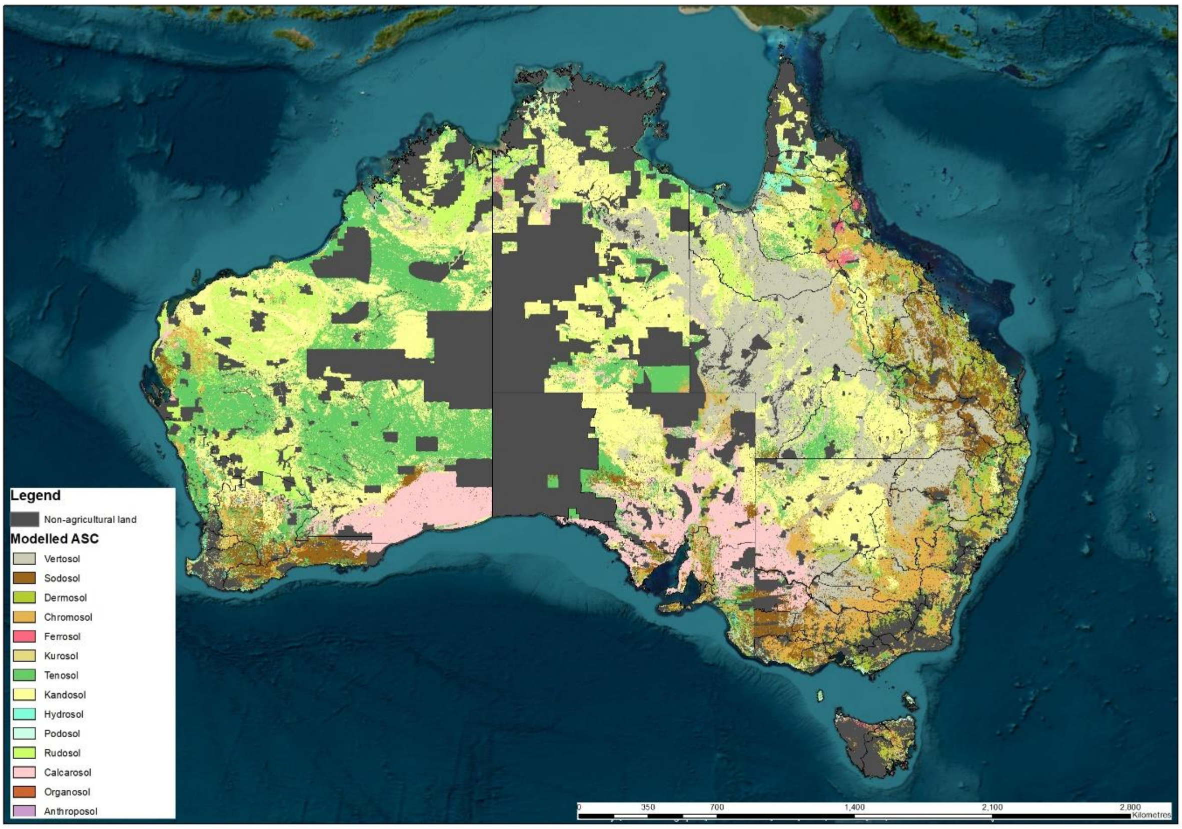

Figure 4.9. Modelled and fine scale map of the ASC orders: Data from Searle (2021).

An updated inventory of soil mapping by state and territory agencies is provided in Appendix 3, which includes soil constraints relevant to agricultural systems including grazing.

Primary productivity

Donohue et al. (2018) evaluated a remote sensing based model (DIFFUSE) for estimating photosynthesis of green vegetation, carbon fluxes and ultimately the gross primary productivity of vegetation. Known as a stress-scalar approach, the new diffuse-radiation based photosynthesis model (DIFFUSE) was deployed using MODIS satellite data and testing against vegetation classes including tree, C3 grass and C4 grass. Results against flux towers were favourable with daily errors across all sites of 0.12 mol CO_2/m^2/day.

From this research, Donohue et al. (2018) were able to generate national pasture productivity datasets using MODIS imagery for 2001-2018. This includes the dynamics of grassland/pasture Gross Primary Production (GPP), Net Primary Production (NPP) and Carbon mass. For this report we have presented the NPP which is the net rate of carbon fixed through photosynthesis (GPP minus plant respiration) for grasses, in units of g C/m^2/day. The grass carbon mass is the above ground mass of grasslands and pastures (t/ha). Note that for this report, NPP assessments for the NRM regions have not been included. For each year, there are 23 scenes (one every 16 days) that coincide with the interval of MODIS data collection. We present 4 scenes for 2018 for comparison purposes: February, May, August and November that demonstrate seasonal fluxes in primary productivity (Figure 4.10).

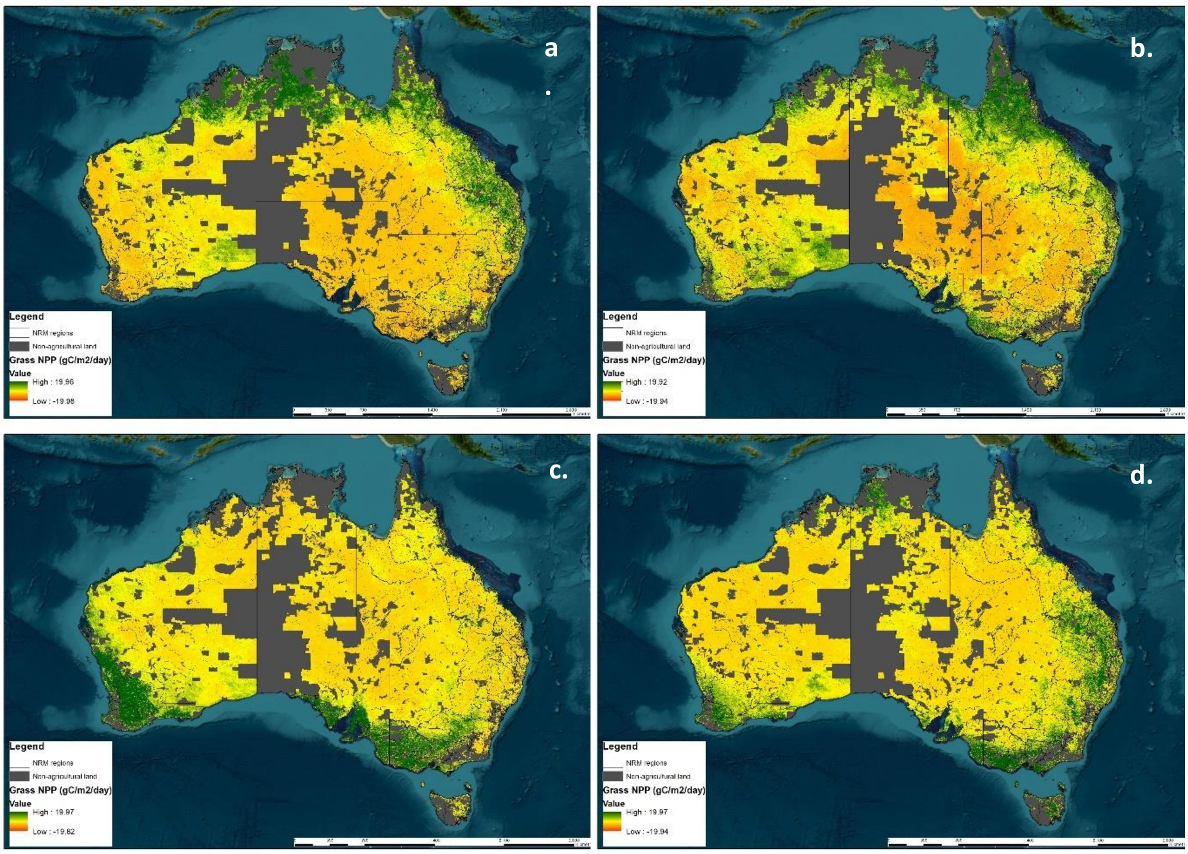

Figure 4.10. Net Primary Productivity (NPP) for Australia in 2018: **a**. February; **b**. May; **c**. August; **d**. November. Units are g C/m^2/day. Data from Donohue et al. (2018).

4.1.2 Soil type summary including difficulties and constraints - ASC soil orders (Isbell and NCST 2021)

A summary of the key diagnostic features, potential constraints and where the soils are found in Australia are provided in Table 1. Note that the new soil order (Arenosol) is detailed although not mapped as this map preceded this new addition to the Australian Soil Classification system.

Table 4.1. Key diagnostic features of soil orders associated constraints and where these soils are commonly found (NRM or IBRA7 regions).

Soil order	Key diagnostics	Key associated difficulties and constraints for grazing	Dominant areas found
Vertosol	Clay rich soils (>35% clay throughout) with shrink-swell properties and prone to cracking	• High shrink-swell soils causing local irregular ground surface (melon hole/gilgai) for livestock. Can cause rooting depth limitations. • Can be calcareous (soft segregations or nodules) and/or sodic at depth. • Subsoils can be dense and compacted. Surfaces can be self-repairing from compaction.	Queensland: Desert Channels; Southern Gulf; Condamine. Northern Territory: Michell Grass Downs. New South Wales: Liverpool Range, Darling Riverine plains, alluvial fans of the channel country and Mulga lands bordering Queensland; Riverina, Monaro. Victoria: Wimmera.
Sodosol	Soils strongly influenced by sodium (sodic B horizon) and strong texture contrast between A and B horizon	• Sodic and dense subsoil limiting root access and penetration. Can be cracking. • Potential surface sealing and compaction, water repellency. • Subsoils can be calcareous. • Surface often have low soil strength.	Queensland: Burnett-Mary; Fitzroy; Mackay-Whitsunday. Western Australia: South Coast; South West. New South Wales: Broken Hill complex, prior streams, lakes, and levees of the Darling Riverine plain and Riverina, sedimentary parent materials in the western slopes, tablelands and Alps. Victoria: Wimmera; Corangamite. South Australia: Kangaroo Island, Adelaide. ACT: eastern side.
Dermosol	Well-structured soils and lack a clear textural change with depth	• Can be stony and of variable depth. • Surface and sub-surface compaction can occur, limiting water and air movement.	Queensland: South East; Wet tropics. New South Wales: Hunter; North Coast; South Coast and Northern Tablelands, related to Ferrosols.

Soil order	Key diagnostics	Key associated difficulties and constraints for grazing	Dominant areas found
			Victoria: North East; East Gippsland; West Gippsland; Port Phillip and Westernport. Tasmania: all regions.
Chromosol	Soils with a strong texture contrast between A and B horizons and are not sodic or strongly acidic	• Surfaces can experience water repellency and nutrient loss where sandy. • Compaction of surface and sub-surface may occur in wet conditions. • Strongly dense subsoils may limit root growth and water extraction. • May be shrink-swell due to clay rich B horizon.	Queensland: Burdekin. New South Wales: granitic, sandstone and non-sodic sedimentary soils of the western slopes, tablelands, and North Coast. Victoria: North Central; Glenelg-Hopkins; Goulburn Broken. Western Australia: Peel-Harvey. South Australia: Adelaide Hills and Fleurieu.
Ferrosol	Soils that are high in free iron oxide in the subsoil and lack a texture contrast between A and B horizons	• Stoniness may vary along with depth of soil. • High clay content and compaction may occur due to trafficking. • Can be strongly acidic in the surface.	Queensland: Burdekin; Wet tropics. Tasmania: Northwest; North. Northern Territory: Ord Victoria Plain. NSW: basaltic tableland, western slopes and north coast soils
Kurosol	A strong texture contrast between the A and B horizons and strongly acid in the subsoil	• Strongly acidic throughout – limiting plant and animal nutrition. • Can be highly prone to water erosion – often located in high rainfall environments. • Periodic waterlogging often occurs due to dense subsoils. • Gravels may occur, also the surface may be quite weak under animal and machinery trafficking.	New South Wales: Hunter; North Coast, Northern Tablelands, central western slopes. Victoria: Corangamite. Tasmania: South. ACT: Western side.
Tenosol	Soil that are weakly pedal that have deep sandy profiles	• Water repellency is a major issue along with nutrient deficiency and leaching.	Western Australia: Rangelands; Northern Agricultural; Swan. South Australia: Southeast (Limestone Coast); Alinytiara-Wilurara.

Soil order	Key diagnostics	Key associated difficulties and constraints for grazing	Dominant areas found
		• Sub-surface pan may be present – limiting root growth and water movement into the subsoil. • May be acidic in higher rainfall environments.	New South Wales: Alps, tableland escarpment and gorges.
Kandosol	Strongly weathered soils with a weak to massive subsoil and little to no texture change with depth	• Soils can be quite deep and tend to be well drained (whole coloured). • Ironstone nodules and gravels are common. • Surface can be easily degraded by trafficking leading to surface crusting and sealing. • Tend to have low nutrition, hence predominantly native pastures.	Queensland: Cape York; Co-operative Management Area; Northern Gulf; Southwest. New South Wales: Sydney Basin, upper Hunter valley, western slopes, Cobar Peneplain, Mulga lands and Simpson-Strzelecki dunefields in the Northwest. Western Australia: Avon River; Rangelands. Northern Territory. South Australia: South Australia Arid Lands.
Hydrosol	Saturation of the greater part of the profile for prolonged periods (2-3+ months)	• Seasonally or permanently wet soils that are generally unsuitable for grazing. • Waterlogging is common, often with clay rich subsoils that can shrink-swell.	Queensland: Cape York; Co-operative Management Area; Northern Gulf. Western Australia: Avon River. Northern Territory: Pine Creek.
Podosol	Sandy soils with a Bh (organic-aluminium), Bhs (organic-aluminium or iron) or Bs (iron) horizon	• Nutrient deficiency and leaching and water repellency are major limitations of these sandy soils. • Sub-surface pan may be present – limiting root growth and water movement into the subsoil. • Tend to be acidic throughout with variable amounts of aluminium or organic compounds.	Victoria: Glenelg-Hopkins; Corangamite; West Gippsland. South Australia: Southeast. Tasmania: Northwest; North.
Rudosol	Negligible pedological organisation	• Nutrient retention is a limitation of these shallow soils. • Low water holding capabilities.	Queensland: Northern Gulf; Southwest. Western Australia: Avon River; Rangelands. Northern Territory: Victoria Bonaparte. South Australia: South Australia Arid Lands.

Soil order	Key diagnostics	Key associated difficulties and constraints for grazing	Dominant areas found
		• May have variable stone content.	
Calcarosol	Calcareous throughout	• Surfaces can be water repellent and can be prone to wind erosion. • Sodicity at depth is very common, limiting water access to plants. • Often weak to poorly structured in the surface and are vulnerable to structure decline due to trafficking. • Calcareous gravels and segregations may occur.	Western Australia: Rangelands. New South Wales: Murray Darling depression. Victoria: Mallee. South Australia: Eyre Peninsula; Northern and Yorke; Murraylands and Riverland; South Australia Arid Lands.
Organosol	Dominantly organic soil material	• Seasonally or permanently wet soils with peaty surfaces that are largely unsuitable for grazing. • Poorly drained, often with artificial drainage to remove water for agricultural purposes. • Quite acidic throughout the profile.	Tasmania: South; Northwest.
Anthroposol	Soils significantly impacted or altered by human activities including mixing, truncation, or burial	• Variable limitations, however, not used often for agricultural purposes (mainly urban development).	Major and rural urban centres across Australia.
Arenosol	Deep sandy soils with <15% clay within the upper 1m of the profile	• Nutrient deficiency and leaching and water repellency are major limitations of these deep sandy soils. • Vulnerable to wind erosion with little structure throughout the profile.	Western Australia: Rangelands; Northern Agricultural. Victoria: Mallee. Northern Territory: southern arid lands. South Australia: Alinytiara-Wilurara; Eyre Peninsula; Northern and Yorke; South Australia Arid Lands.

4.2 Land uses and grazing systems.

Grazing is Australia's largest land use at 3.7M km^2. Other land uses including *Other minimal use* (1.04M km^2), *Dryland cropping* (342,551 km^2) and *Irrigated pastures* (7,817 km^2) which are also used for grazing purposes (Figure 4.11). In total, two-thirds of Australia's land mass is used for grazing purposes. The Australian Rangelands cover 80% of Australia, overlapping with many of the grazing land uses (Figure 4.12). For this report, those land uses considered to be agricultural have been combined (Figure 4.13).

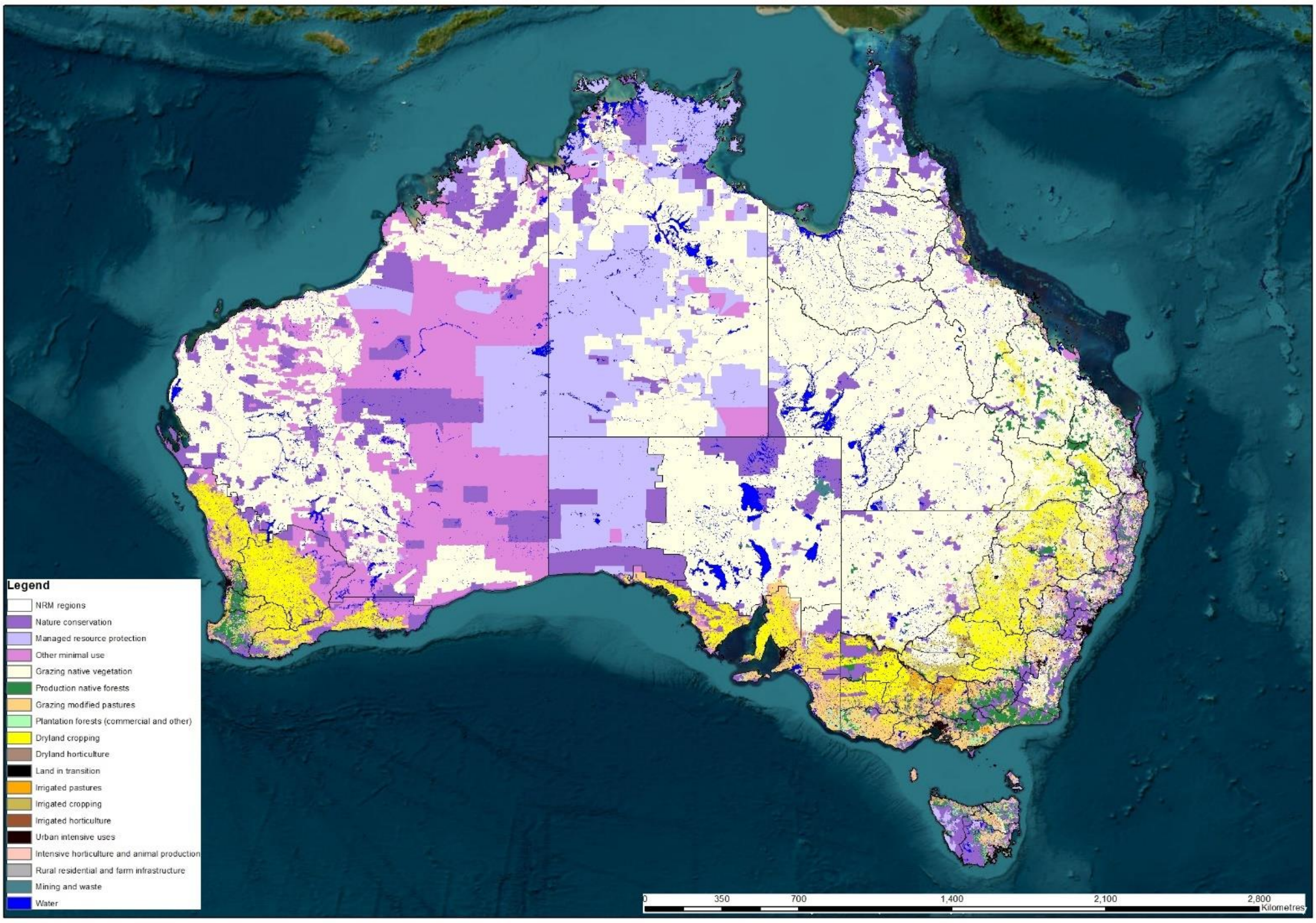

Figure 4.11. Australia land uses. Source: https://www.agriculture.gov.au/abares/aclump/land-use.

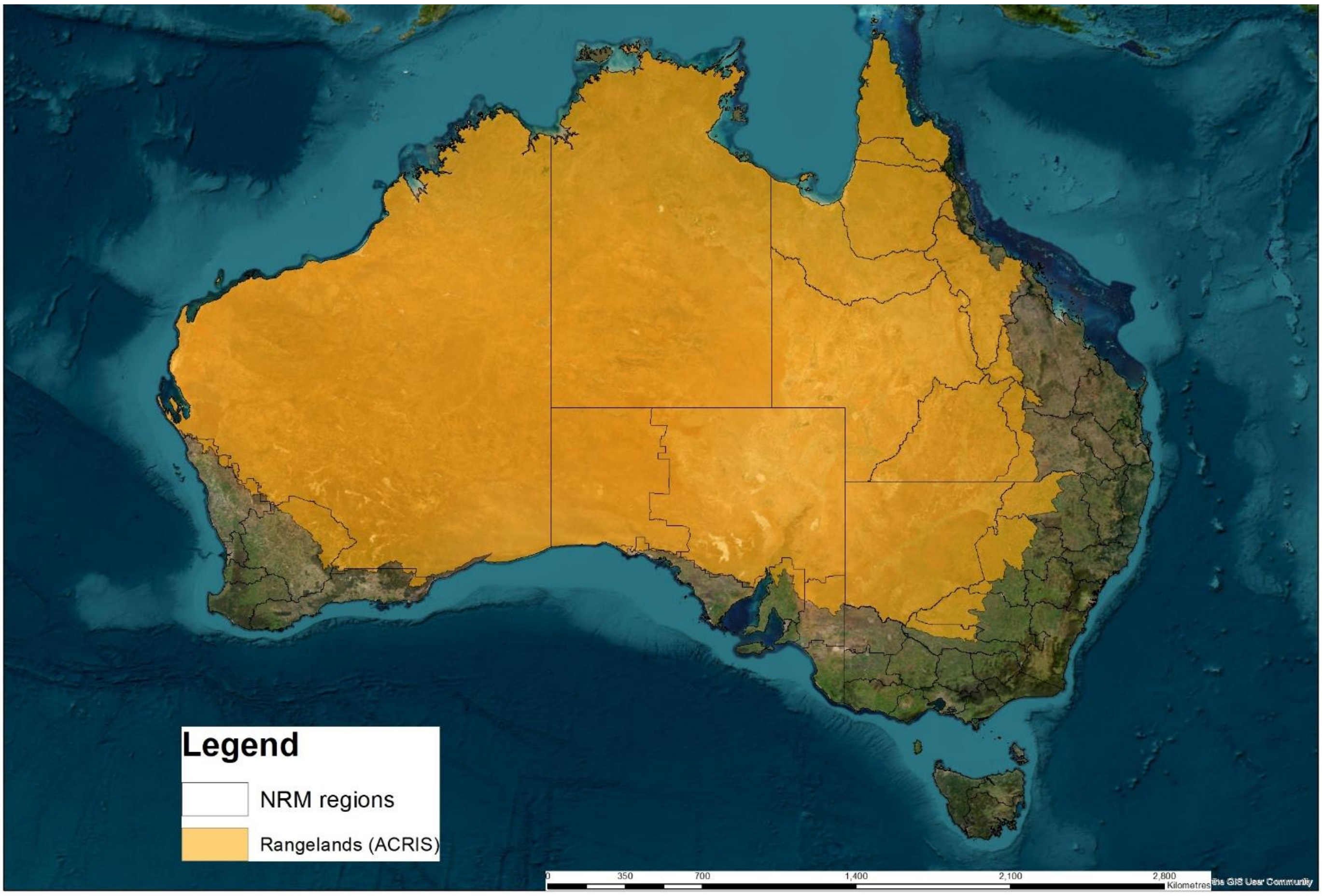

Figure 4.12. Australia Rangelands (Source: the Australian Government, Department of Climate Change, Energy, the Environment and Water and Australian Collaborative Rangelands Information System - ACRIS).

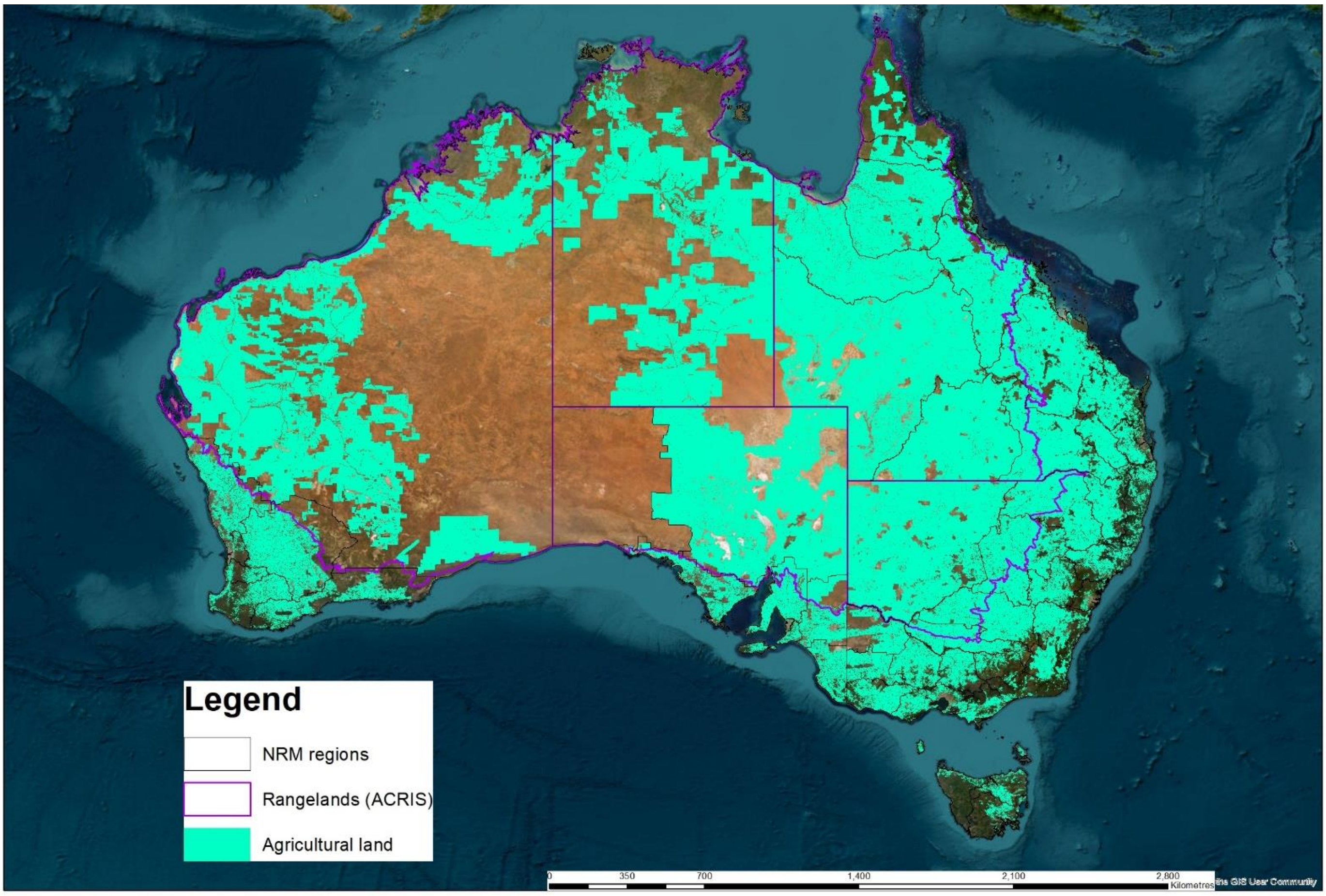

Figure 4.13. Agricultural land from the Catchment scale land use of Australia (update December 2018): https://www.agriculture.gov.au/abares/aclump/land-use/catchment-scale-land-use-of-australia-update-december-2018.

4.3 Soil constraints and threats in grazing systems

In this section, we summarise some key examples of available mapping products related to soil constraints in Australian grazing systems. These products have been reviewed and grouped according to a soil constraint 'theme' with additional mapping products that directly or indirectly relate to the soil theme also included. A brief overview of the soil constraint is provided to contextualise the maps.

- Sodicity and subsoil carbonate
- Acidity
- Salinity
- Waterlogging
- Structure decline (including compaction)
- Nutrient status
- Toxicity (e.g. boron, manganese)
- Water repellence
- Wind erosion
- Water erosion

Sodicity

Northcote and Skene (1972) estimated that around 2 million hectares are impacted and suffering side effects of structural, nutritional and salinization problems (Naidu 1993). High boron and other associated nutrient toxicities can occur, but invariably these soils limit the capacity of plants to make full use of stored soil water. Some of these sodic soils have high concentrations of exchangeable sodium (e.g. Exchangeable Sodium Percentage > 25%) in the subsoil at depths of 50-100 cm that reduce infiltration and restrict root growth.

Mapping of sodic soils has been a recognised priority for some time (Naidu 1993) and while there have been local and state/territory efforts at mapping sodicity, there are no contemporary national maps of Exchangeable Sodium Percentage (ESP) available. Estimates of the distribution of sodic soils for each state and territory vary or are incomplete. In Victoria, it is estimated that nearly 74 % of agricultural land is affected by sodicity (Ford et al. 1993) while in Tasmania, over 1.5Mha is believed to be impacted (Doyle and Habraken 1993). Isbell and National. Committee. on. Soil. and. Terrain (Australia) (20021) and the recent national map by Searle (2021) are the best examples noting where Sodosols are likely to occur (Figure 4.14).

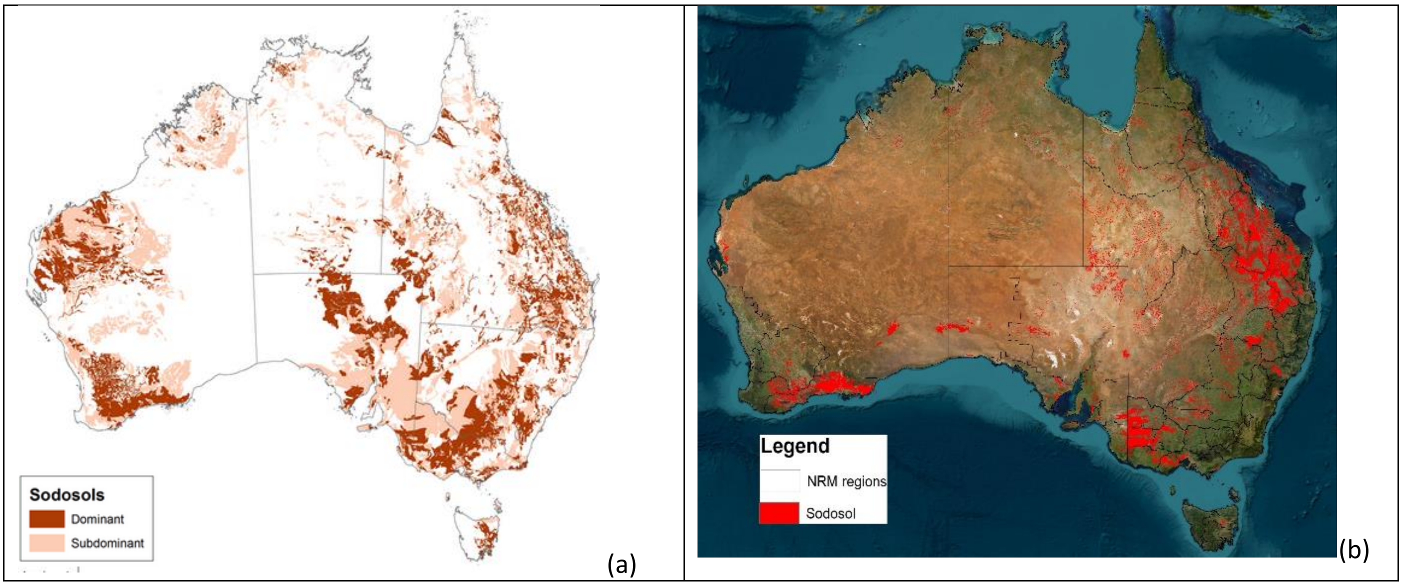

Figure 4.14. National Sodosol distribution maps of Isbell and National. Committee. on. Soil. and. Terrain (Australia) (2021) (**a**) and Searle (2021) (**b**). Note the maps have been generated using different techniques, therefore variations in the distributions of Sodosols.

Sodic soils are extensive across the grazing lands of Australia including south-west Western Australia, western Victoria, north-west NSW and south-east Queensland. The source for this sodium is attributed to the weathering of sedimentary parent materials of marine origin, atmospheric salt accessing or from groundwater or aeolian sources. In NSW for example, these soils are concentrated in the in the arid western regions and northern cropping districts where alkaline variants are widespread (McKenzie et al. 1993). A high proportion of land and impacts to primary production (pasture or crops) for these regions is attributed to sodicity (Orton et al. 2018). The distribution of sodic soils in the Australian Rangelands under-represents the prevalence of sodicity because Sodosols are duplex (texture contrast) soils, while most of the region has Vertosols and less developed Arenosols, Rudosols, Tenosols and Kandosols, which may still contain sodic materials (Figure 4.15). However, this may also be an artefact due to a paucity of soil sites and surveys undertaken for this extensive land expanse.

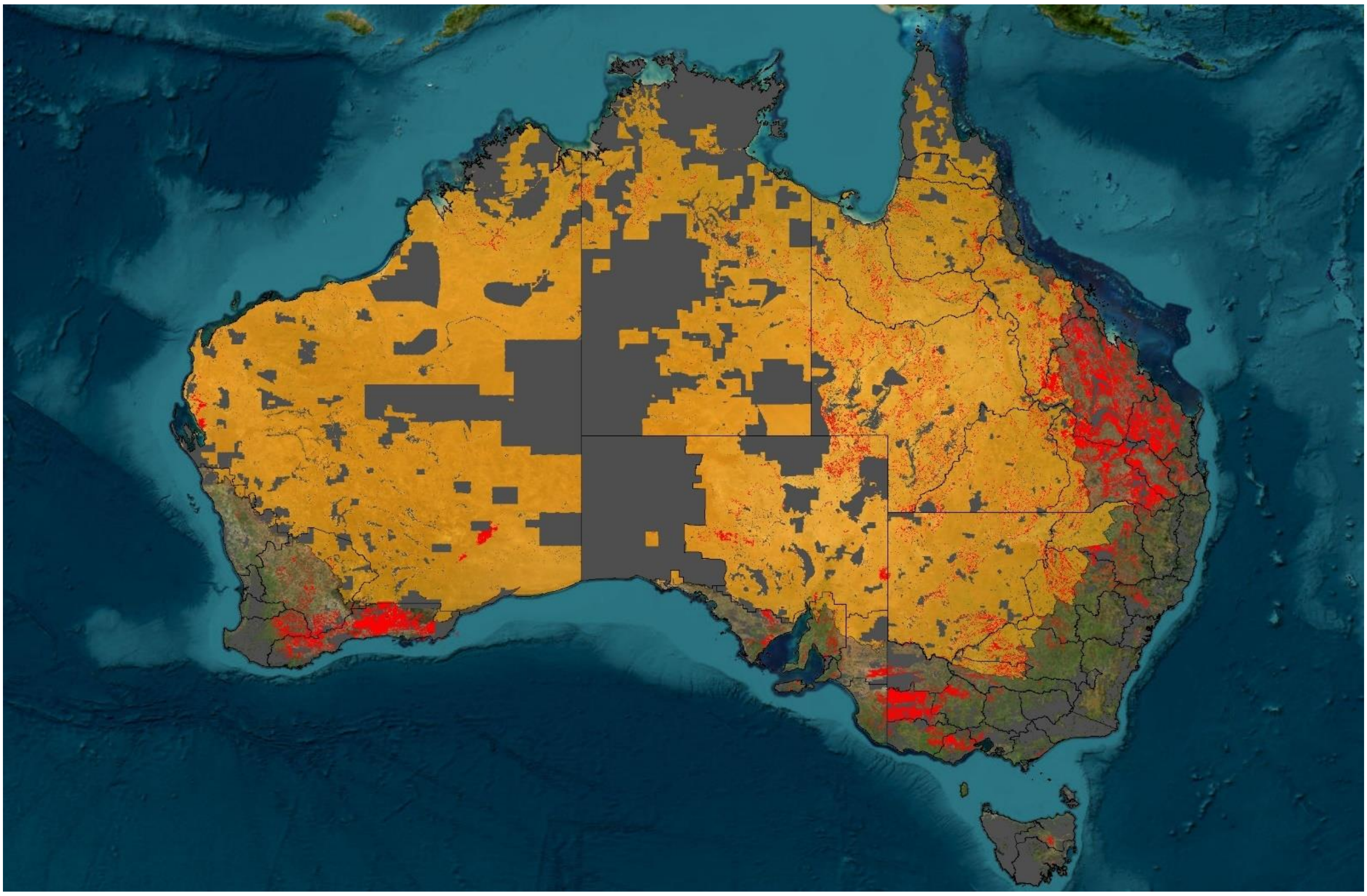

Figure 4.15. Distribution of Sodosols (red) for Australia with a noticeable absence in the Australia Rangelands.

Subsoil carbonate

Soils containing carbonates of calcium, and to a lesser extent magnesium, are widespread across southern South Australia and western Victoria (mainly Calcarosols: https://www.soilscienceaustralia.org.au/asc/ca/calcsols.htm), particularly in the less than 400 mm rainfall zone. They can occur as finely divided segregations mixed with sand and clay particles, as hard nodules or concretions (rubble), or as sheet rock or calcareous hardpan (calcrete). Fine carbonates reduce the availability of several nutrients, restrict the performance of a range of crops and pastures, and retard the breakdown of some herbicides. These effects are amplified in very highly calcareous soils. Hard carbonates reduce available water holding capacity, and in the case of calcrete, limit root zone depth. As an example, the presence and proportion of subsoil carbonate in South Australia has been mapped (Figure 4.16). Note that there would likely be an extension of subsoil carbonate into the southern rangelands, but the mapping was focused on the higher rainfall and more intensively used areas of South Australia.

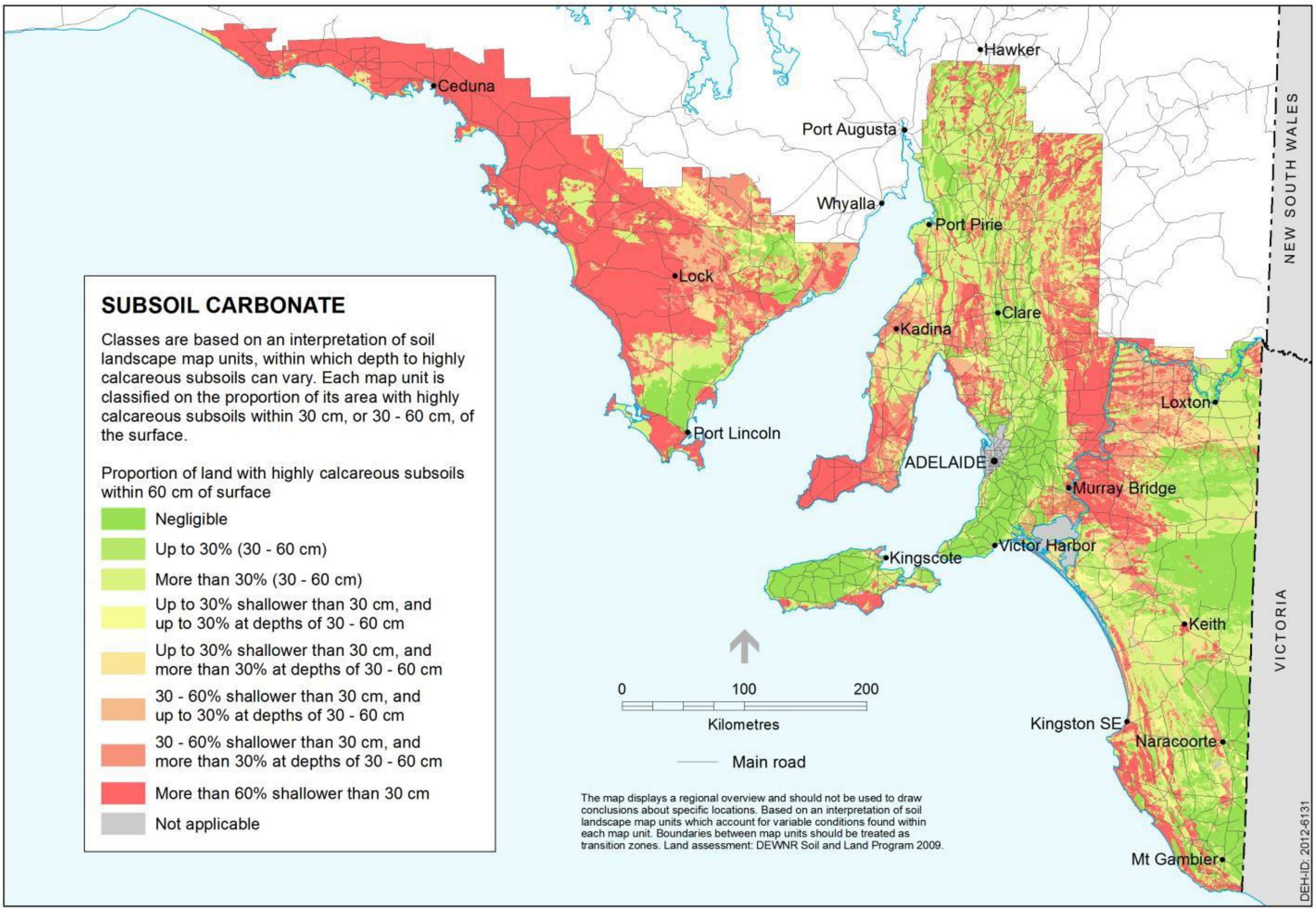

Figure 4.16. Subsoil carbonate presence and abundance map for agricultural lands of South Australia (https://data.environment.sa.gov.au/Content/Downloads/SoilAttrib_SA_SubsoilCarbonate.pdf).

Acidity

Soil acidity assessments over the last 3-decades suggest that nearly half of Australia's productive agricultural land is impacted by acidity (Figure 4.17). It is of greatest concern where management practices result in a net acid addition to the soil, where soils are poorly or lowly buffered against such practices, or where soils are inherently low in pH due to soil forming processes (McKenzie et al. 2017). Aluminium and manganese can also be of concern with many plants' sensitive at small concentrations where strongly acid soil conditions occur.

Significant areas of pasture and grazing land in south-west Western Australia, Tasmania, central and southern slopes of Victoria, eastern New South Wales and lands in northern Australia are all impacted by soil acidity. While potential productivity benefits of remediating acidity in cropping have been estimated at $380 million/annum (Orton et al. 2018), it is unclear what the likely future cost and benefits will be for grazing systems should acidity continue to increase as it is anticipated to do so if maintenance lime requirement rates are met (McKenzie et al. 2017). An emerging threat is the increased acidity of subsoils where amelioration options are currently difficult to implement and expensive.

Experience in some jurisdictions indicates that problems can be solved by supplying improved information on acidification risk and appropriate responses (e.g. precision liming, lime quality information, acid tolerant pastures and mixes), but identification of where such investments are best made is needed.

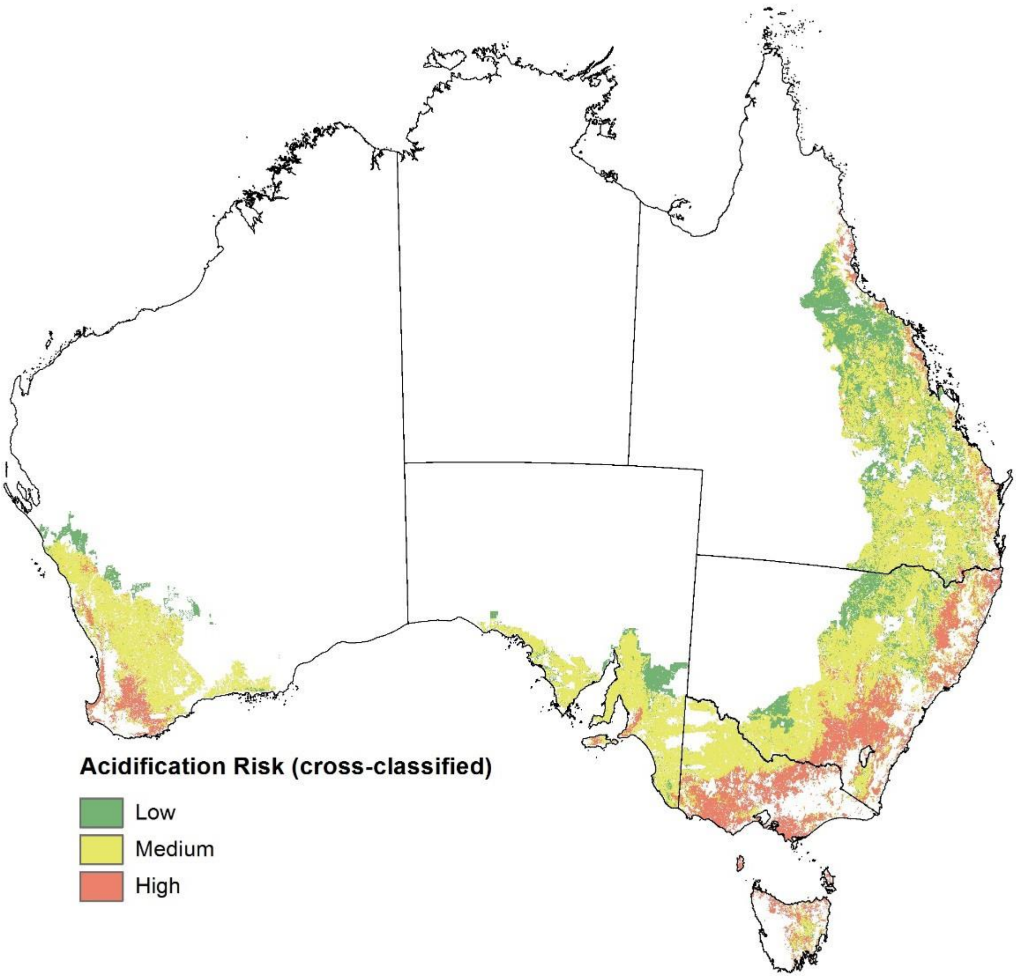

Figure 4.17. Acidification risk in agricultural lands: from McKenzie et al. (2017).

Salinity

Non-watertable salinity (otherwise known as 'dry saline land') is where soils contain elevated levels of soluble salts that are not associated with a watertable. Soil root zone salinity occurs throughout Australia, ultimately affecting plant performance and resilience. It is caused by natural processes (e.g. climate, landscape evolution and hydrological processes) and anthropogenic factors (e.g. land clearance, replacement of perennials with annual species). Generally, these accumulations of salt in soil occurred from aeolian accessions and subsequent leaching, marine aerosols, or via saline groundwaters which are no longer influencing the land surface. Salt accumulations in the subsoils, known as 'salt bulges', possibly reflect leaching processes and an impermeable subsoil layer that prevents further flushing of salts deeper into the substrate.

Salt in soils is widely distributed occurring in agricultural landscapes and rangelands alike. In Western Australia alone, agricultural productivity losses due to dryland salinity are estimated to be >$500M/yr from 1.75M ha of salt affected land (Caccetta et al. 2022). In South Australia, there are estimated to be 320,000 ha impacted by dryland salinity (Barnett 2000), Victoria has 262,000 ha impacted by dryland salinity (Clark and Harvey 2008), NSW has 120,000 ha impacted (Smith 2000), 107,000 ha in Queensland (ABS 2003) and 71,200 ha in Tasmania (Bastick and Walker 2000).

While there are some maps of salinity occurrence at the state and territory level, there are no recent national maps of soil salinity since that of Northcote and Skene (1972).

Waterlogging

Waterlogging occurs when all or part of the soil profile is saturated with water. The ASC soil order Hydrosol is an exemplar here where soils are saturated for at least 2 to 3 months each year. Some soils are effectively never waterlogged (e.g. sands or sites with good drainage), while others are saturated all the time. The degree to which a soil becomes waterlogged depends on how much water enters the soil and how quickly it leaves, either by deep percolation, lateral seepage or evapotranspiration. Low lying ground is more prone to waterlogging, particularly in high rainfall areas. Higher ground and areas with excessive runoff or little rainfall are unlikely to be significantly affected. The permeability of the soil, depth to watertable, and position in the landscape all affect susceptibility to waterlogging. It should also be noted that waterlogging also leads to N loss. Other significant considerations are degradation of soils and pastures due to animal trafficking (e.g. pugging) and in some cases plant death where insufficient oxygen conditions prevail. Waterlogging is also strongly linked to soil strength and its reduction when soil particles loose binding strength due to saturated conditions. Shaw et al. (2013) summarise the impacts and responses of plants to waterlogging conditions.

A direct impact on livestock should also be considered where waterlogging occurs. Lameness due to soils losing their strength (leading to pugging), or just generally being immersed in water and standing on wet ground, can also lead to other impacts such as abscesses and other foot and hoof problems.

In Australia, there are vast areas of grazing land that are susceptible to waterlogging and its impacts on net primary productivity. In Western Australia, it is estimated that 1M ha is highly to very highly susceptible to waterlogging with agricultural losses estimated at $46M/yr (https://www.agric.wa.gov.au/waterlogging/waterlogging-western-australia). In south-east South Australia, southern Victoria and Tasmania (Figure 4.18) and south-east NSW, these areas are also prone to seasonal waterlogging, although mapping and information on occurrence, frequency and impact is difficult to ascertain.

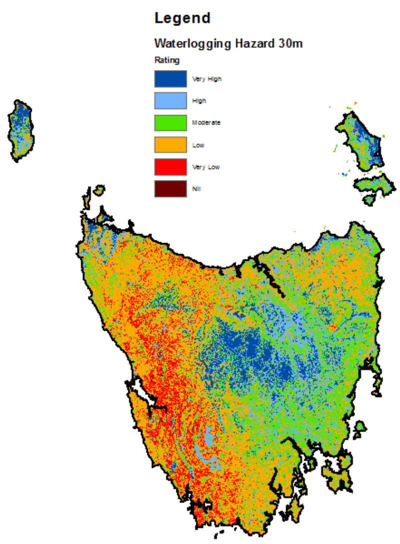

Figure 4.18. Waterlogging susceptibility map of Tasmania.

Compaction

Soil compaction can have a detrimental effect on root growth when bulk density (Figure 4.19) exceeds 1.6 g/cm^{-3}. When combined with wet soil conditions, livestock trafficking and a reduced soil strength, compaction can significantly impact water infiltration and nutrient access to plants. Appropriate grazing management on west soils is critical to avoiding subsoil compaction issues that can impact water movement and root development in the soil.

It has also recognised that this is an issue not just for agricultural lands, but in rangelands also where soil water limitations due to compaction in the topsoil have been noted (Donkor et al. 2002). Soil compaction is estimated to decrease the value of crop and pasture production in Western Australia alone by $330 M/yr (https://www.agric.wa.gov.au/soil-compaction/soil-compaction-overview) and cost Australian agriculture $850 M/year in lost production (Walsh 2002). In cotton, a recent study has identified that yields were reduced by 27% due to machinery impacts (Jamali et al. 2021). The production and financial impacts of compaction to grazing systems are unclear in an Australian context.

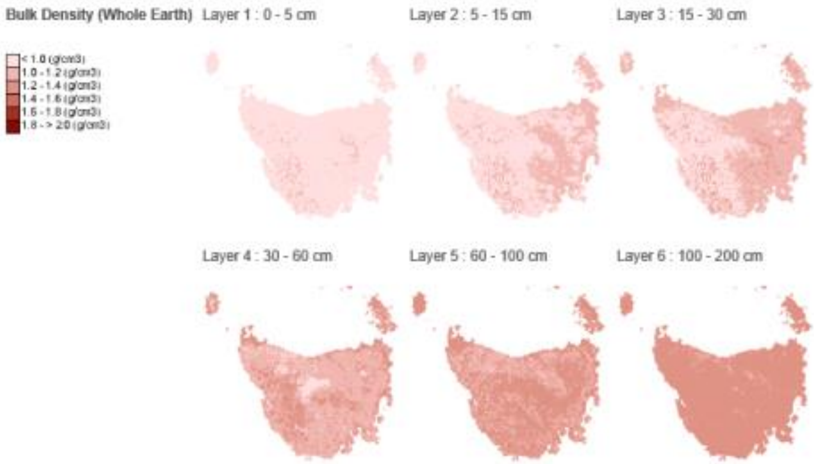

Figure 4.19. Bulk density estimated for Tasmanian soils.

Soil structure decline

Soil structure in this context refers to the degree of resistance offered by the soil to root penetration and seedling emergence; to the free movement of air and water; and to the ease of cultivation and other surface management operations. It is therefore an integration of assessments of strength, aggregation and porosity. Surface soil condition varies significantly across the landscape and is affected by management practice as well as by inherent properties of the soil.

Surface sealing, which can occur for hard setting soils, can result in low water infiltration, increased surface runoff and potentially erosion. Hard setting soils will have a narrow moisture range for effective working, which can result in patchy emergence of pasture seeds and crops. Often these soils have low organic matter, and the soil may be dispersive in wet conditions. An example for South Australia is presented below (Figure 4.20)

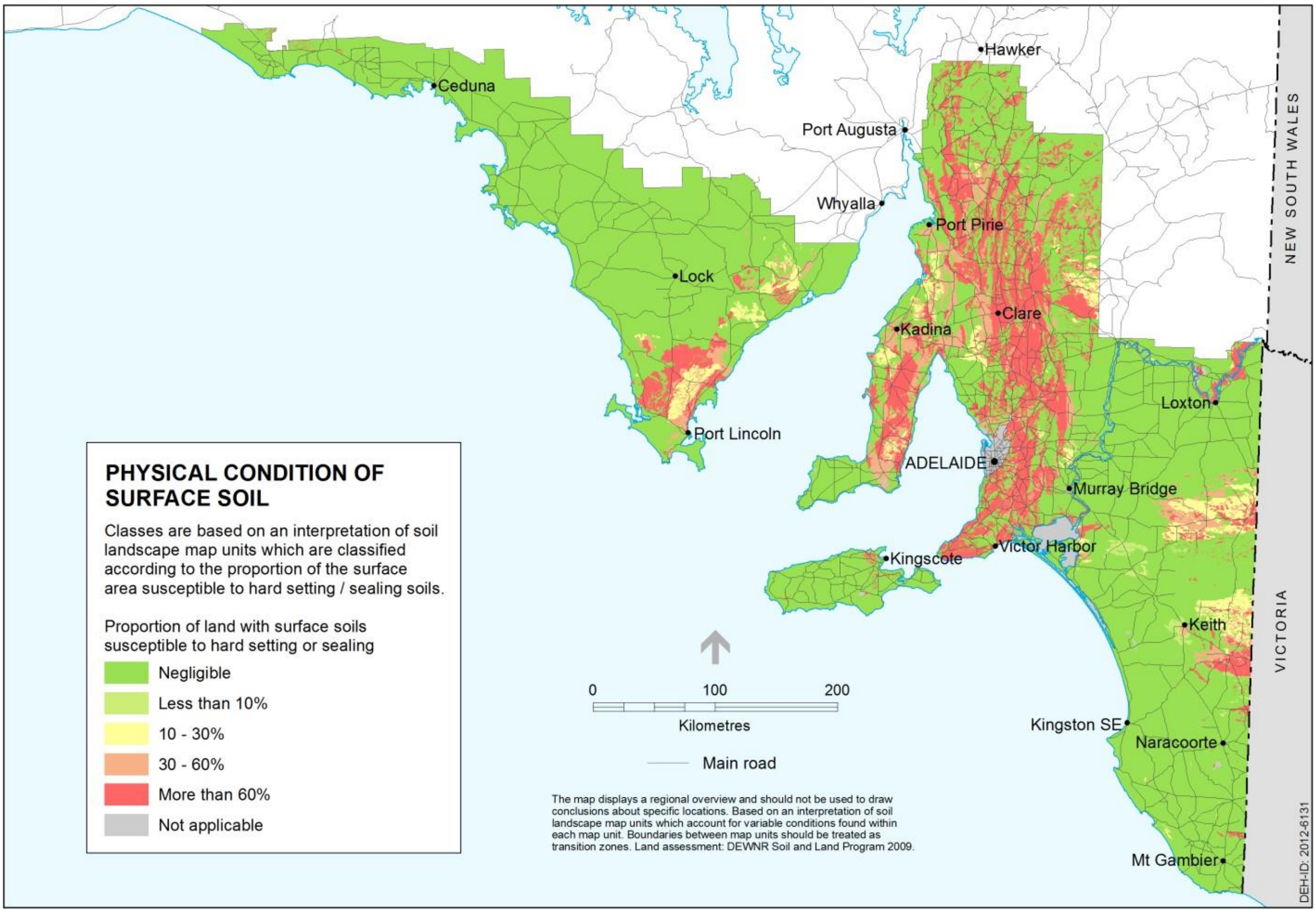

Figure 4.20. Surface soil condition for agricultural soils of South Australia (from the Department of Environment, Water and Natural Resources).
https://data.environment.sa.gov.au/Content/Downloads/SoilAttrib_SA_SurfaceCondition.pdf

Subsoil structure

Poor subsoil structure is commonly attributable to sodic or dispersive clay (often Sodosols), although in soils where there is an abrupt break between the topsoil and subsoil, non-dispersive materials can impede water, air movement and root growth. Poorly structured subsoils at shallow depth present a greater plant production limitation than those which are deeper in the profile. The assessment of subsoil structure is therefore a combination of structure type and depth.

A hardpan is defined as material which is too hard to dig with hand tools, and at shallow depth, influences the effective rootzone of plants and impacts on engineering uses of land. Hardpans (including calcrete, ferricrete and silcrete) are generally relatively young cemented or indurated materials occurring within or below the soil. Calcrete is by far the most common, being widespread on the Eyre and Yorke Peninsulas, Murraylands, the South East and Gulf Plains (Figure 4.21) and in parts of western Victoria. Hard rock is distinguished from hardpan as it tends to become harder with depth, in contrast to hardpans which are generally hardest at the top and become softer with depth. Some hardpans are the result of trafficking and human induced practices as a form of compaction.

Management options for these hardpans include amelioration and mechanical implements such as deep ripping and placement of amelioration materials. There is considerable research in this area especially for grains production systems.

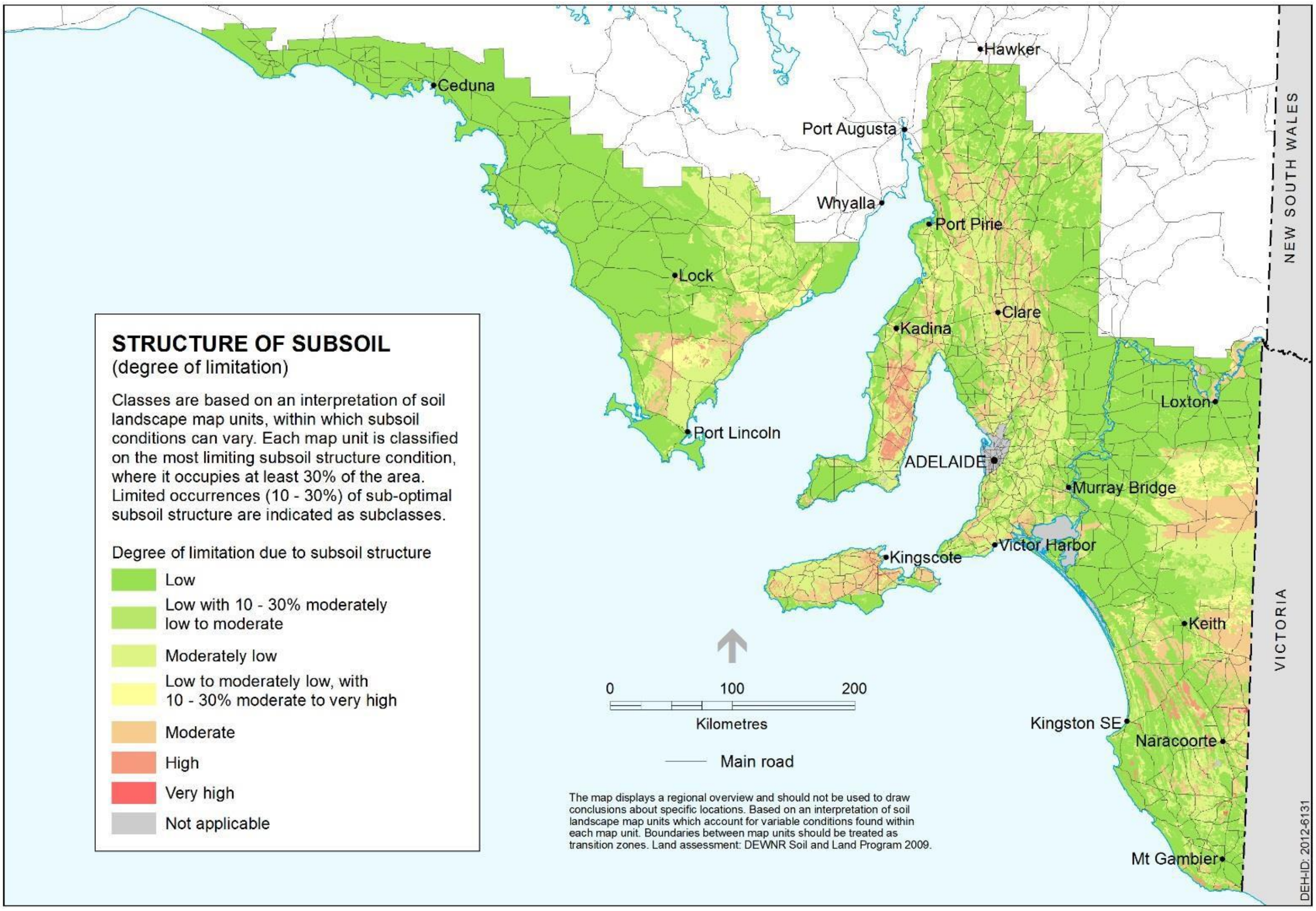

Figure 4.21. Subsoil structure limitations for agricultural soils of South Australia. https://data.environment.sa.gov.au/Content/Downloads/SoilAttrib_SA_SubsoilStructure.pdf

Nutrient Status

Inherent fertility is a relative indicator of the soil's capacity to retain and release nutrients for uptake by plants. Rankings are based on soil properties such as texture, leaching capacity, exchangeable cation characteristics, susceptibility to acidification, and carbonate and ironstone content. Soil fertility is a complex and highly variable property to assess. Soils at the extremes of fertility set the limits of the classification, and all other soils are fitted in between. Self-mulching black cracking clays (Vertosols) are considered the most chemically fertile soils, while highly leached sands are the least fertile.

Poor sands have low inherent fertility. These soils have other constraints that limit yields such as water repellence, low soil water storage, rapid soil permeability, acidic topsoil and subsoil and wind erosion (van Gool 2016). The NLP prioritisation (McKenzie et al. 2017) noted that nutrient decline can occur as a widespread and chronic problem that can threaten viability (e.g. central Queensland cropping lands). Nutrient excesses are often more localised and associated with high input systems (e.g. dairy, sugar cane, intensive livestock production). Priority areas can be readily mapped if land use is used as a proxy but identifying effective interventions and investment opportunities is complex. An example is presented for the agricultural lands of Western Australia (Figure 4.22).

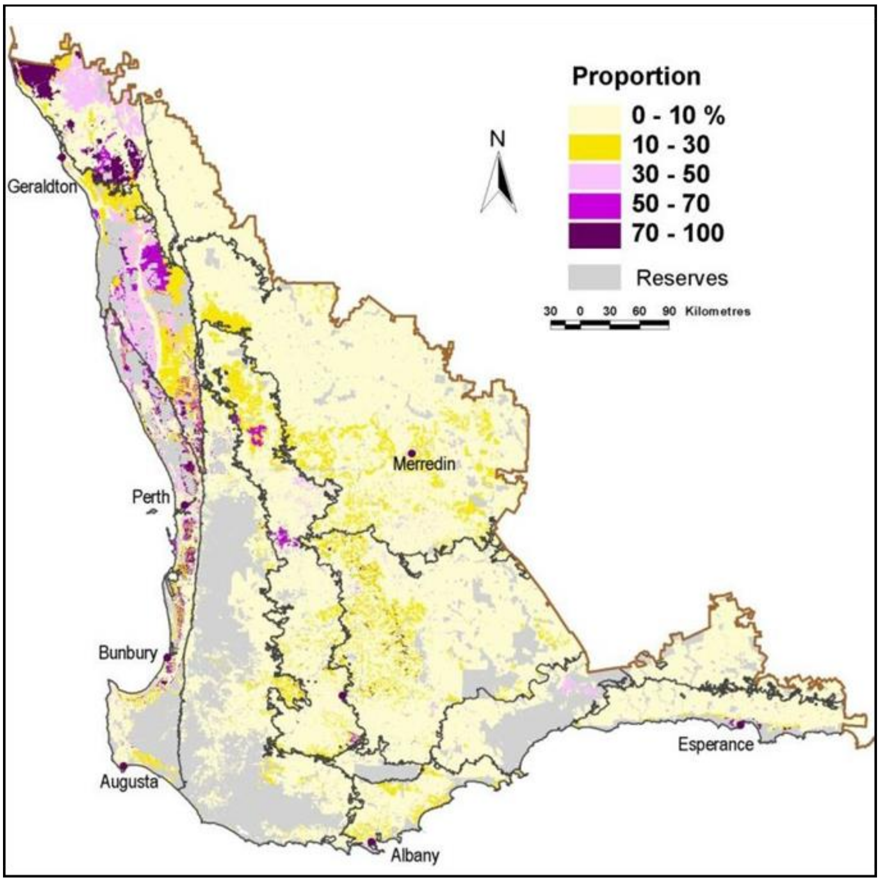

Figure 4.22. Inherent soil fertility ratings for the agricultural zone of Western Australia: from van Gool (2016).

Micronutrient toxicity (e.g. boron, manganese)

Micronutrients (boron, cobalt, copper, chlorine, iron, manganese, molybdenum and zone) are essential plant nutrients but also play critical roles in the health and well-being of livestock. Copper deficiency in cereal crops may lead to shrivelled grain and yield losses. Toxic effects to some micronutrients are more marked in dry seasons when roots penetrate deeper into the soil.

Boron is an example of an essential trace element which occurs naturally in most soils, although at high concentrations it is toxic to many agricultural plants. High concentrations of boron tend to occur where marine sediments have influenced soil formation. Because boron salts are slightly soluble, they are leached out of the rootzone in higher rainfall areas. However, in lower rainfall areas or where impermeable subsoil clay layers prevent leaching, boron concentrations can be high. Excess boron cannot be removed from soil or treated in any way under dryland farming conditions. Deliberate breeding for boron tolerance has produced a range of cultivars which are appropriate for affected soils. An example below notes the higher boron concentrations in northern Victoria (Figure 4.23).

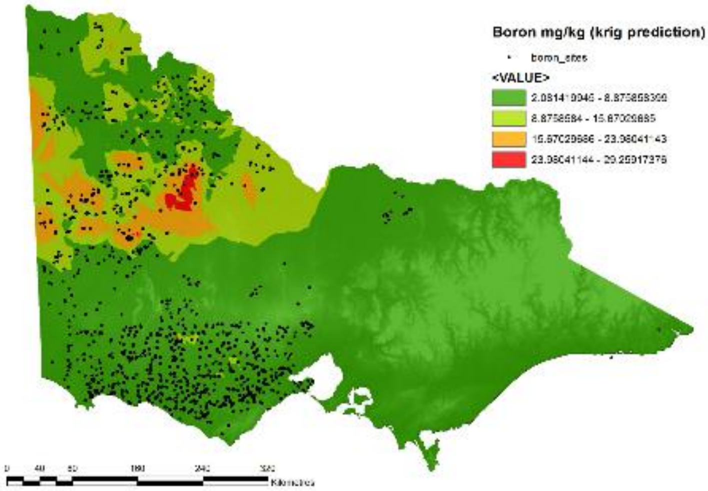

Figure 4.23. Boron concentration in soils of Victoria.

Water Repellence

Water Repellence is caused by hydrophobic organic materials, mainly waxes, contained in plant remains within the soil. The waxes coat the soil particles causing water to bead on the surface. This causes uneven wetting of the upper part of the soil profile, with large masses of soil remaining dry. Patchy plant establishment, uneven and poor growth usually result, increasing susceptibility to water erosion, wind erosion and sand blasting of newly emerged plants, while also decreasing water use efficiency and contributing to increased recharge (elsewhere due to preferential drainage). Water repellence is most common on acid to neutral sands, but calcareous and loamy soils can also be affected, although not as severely. Water repellence is tested by observing the absorption into a soil sample of either water or 2M ethanol. This assessment is based on limited soil testing and extrapolation between similar soils in similar environments, hence indicating the potential (rather than actual) extent of the problem.

Water repellency is a major issue in agricultural zones of Western Australia (Figure 4.24) where it is critically important especially in lower rainfall zones. Repellent soils are commonly associated with other constraints of sandy soils such as low water storage, low fertility, acidity and wind erosion (van Gool 2016). Although water repellence is a widespread issue in WA, affecting agricultural production, the exact severity, extent and overall cost to production is unknown. Yield increases of 100% have been recorded in some trials where the water repellence has been ameliorated, with improvements in soil organic matter and greater nutrient uptake efficiencies (Carter et al. 1998). The average annual opportunity cost of lost agricultural production in the south-west of Western Australia from water repellence is estimated at $251M.

Water repellency is widespread across southern Australia with other impacted areas including south Australia, western Victoria and south-western NSW, affecting some 5 M ha (Tate et al. (1989) in Roper (2004)). The impacts on rangelands are not well understood, especially in southern areas.

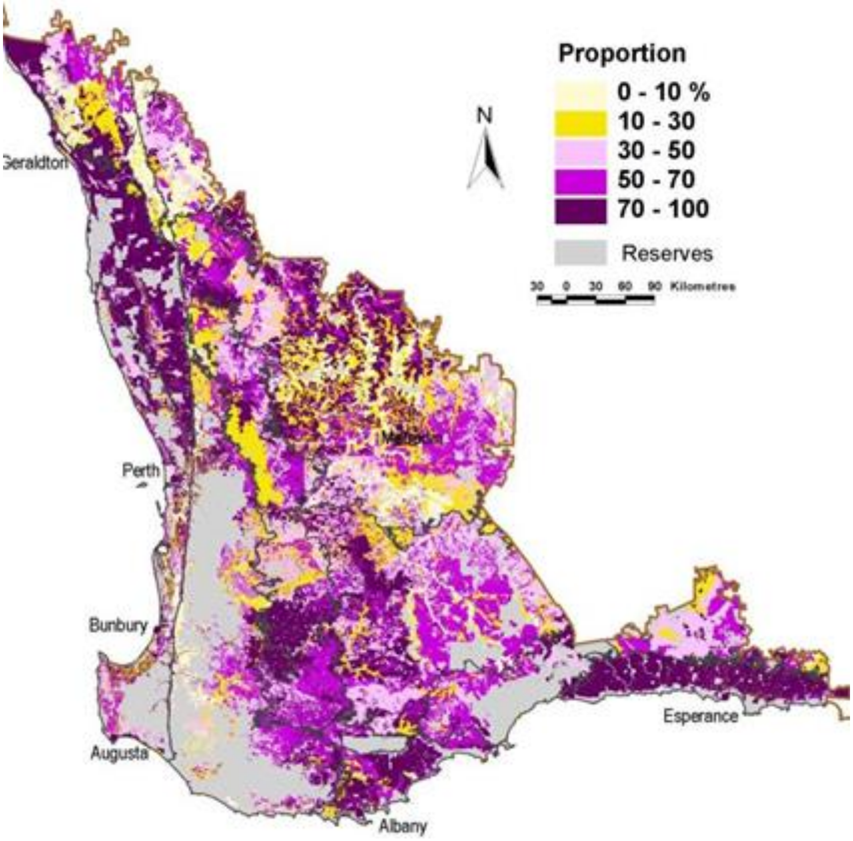

Figure 4.24. Water repellency susceptibility in Western Australia: from van Gool (2016).

Wind erosion

Wind Erosion Potential indicates where wind erosion could be a problem where soil disturbance and weather conditions are conducive (not where wind erosion has been or is currently a problem). The assessment is based on inherent soil and land characteristics such as surface texture, thickness of erodible soil material and topographic features, as well as average annual rainfall (on the basis that higher rainfall areas can generally provide more ground cover). Vegetation and other protective cover occurring at the time of assessment are ignored as these can vary significantly over time, including loss due to bushfire.

Australia has an estimated 110 Mt of dust eroded each year of which most is from the Australian rangelands (Aubault et al. 2015). Wind erosion hazard occurs on exposed land with loose topsoil. Wind erosion is typically associated with sandy soils that often have other major constraints, such as acidity, non-wetting and low soil water storage (van Gool 2016). For prime agricultural soils under grazing, wind erosion can be accelerated where vegetation cover is not maintained above acknowledged thresholds. Continual grazing can impact soil erodibility (reducing soil aggregation in the surface) and impact stability of biological crusts and vegetation. As noted by Aubault et al. (2015), maintaining land condition and adopting low and/or flexible stocking rates can significantly reduce the likelihood of wind erosion.

Wind erosion rates remains a national priority for agriculture. The recent assessment by Zhang et al. (2022) estimated an annual erosion rate of 0.29 Mg/ha/yr for 2001 to 2020 (Figure 4.25). The authors also identified that there were significant variations in wind erosion rates relative to seasonal and monthly differences across Australia (Figure 4.26).

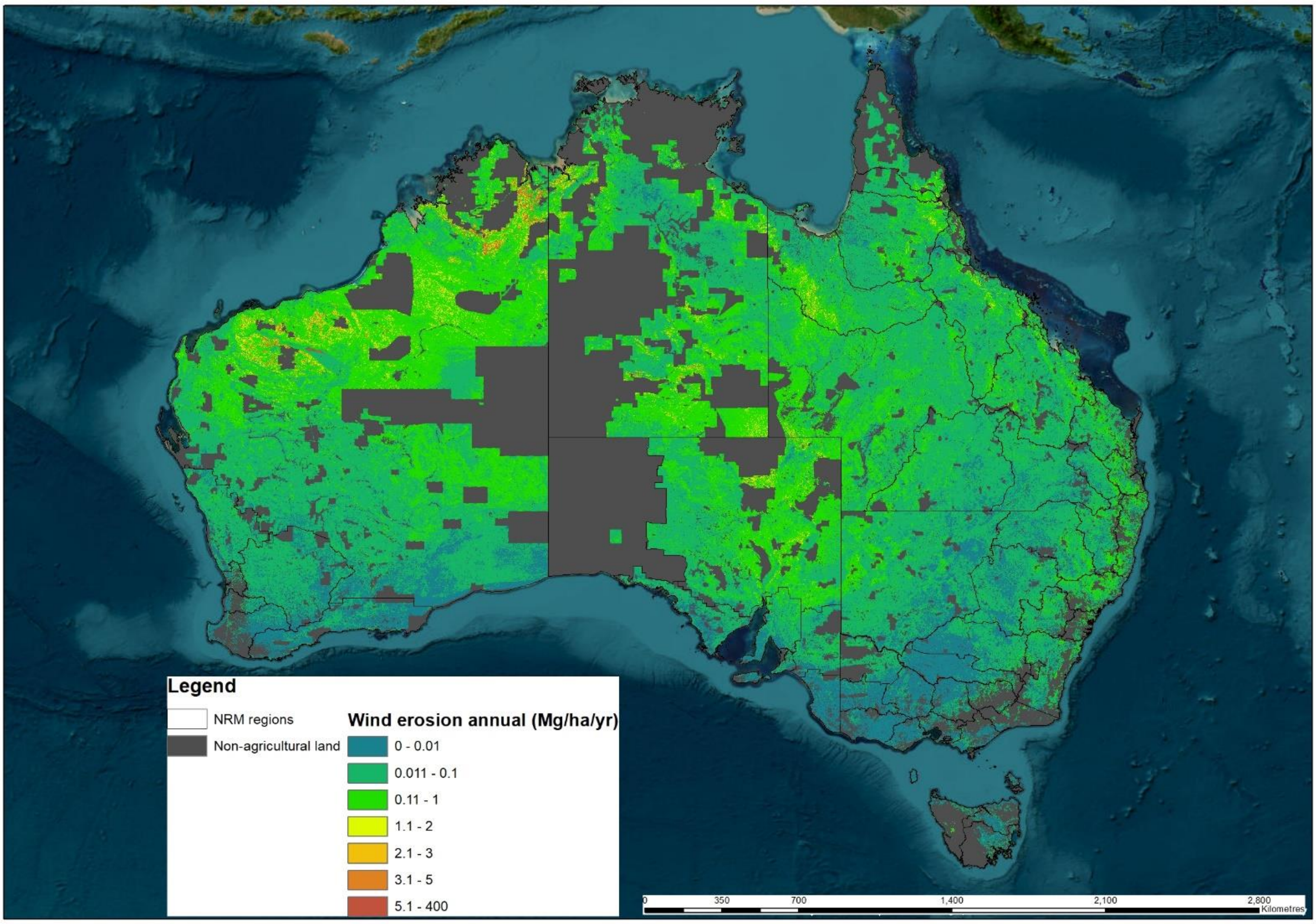

Figure 4.25. Mean annual wind erosion rate (Mg/ha/yr) estimates for 2001 to 2020. Data from Zhang et al. (2022).

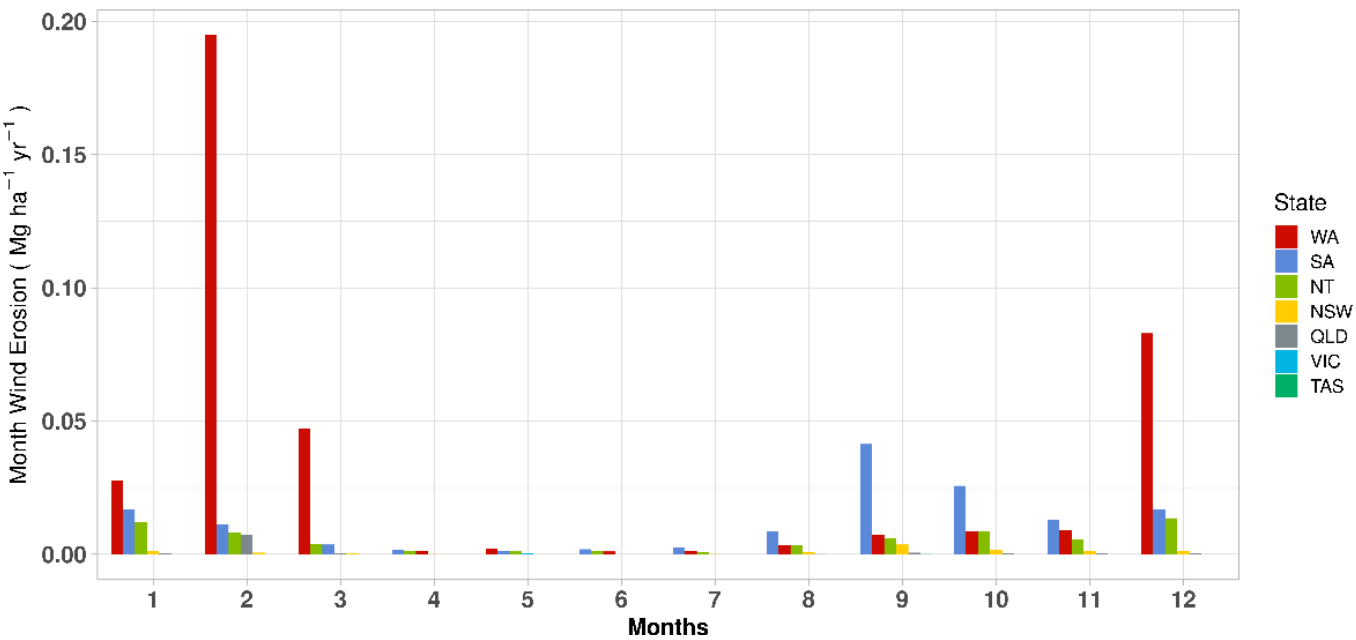

Figure 4.26. Monthly mean wind erosion rate by state/territory for 2001 to 2020: from Zhang et al. (2022).

Water erosion

Water erosion is usually caused by a loss or reduction of vegetative cover. There are different forms of water region – classified as *sheet and rill* and *gully and tunnel* erosion. As summarised in McKenzie et al. (2017), it has been suggested that rates of soil erosion by water should be tolerable at 0.2 t/ha/yr (Bui et al. 2010) with national estimates for sheet and rill erosion of 1.86 t/ha/yr (Teng et al. 2016) and soil formation rates of 0.1 t/ha/yr (Pillans 1997). This suggests that for some regions with shallow topsoils there may be significant agricultural productivity constraints within the next century.

McKenzie et al. (2017) provide a detailed review on hillslope erosion (sheet and rill) and propose management strategies for relevant NRM regions to reduce the area and magnitude of land impacted by erosion. Zhang et al. (2022), using a dynamic model, have estimated water erosion rates across Australia of 0.17 Mg/ha/yr (Figure 4.27) in contrast to 0.69 Mg/ha/yr of Teng et al. (2016). Zhang et al. (2022) also assessed variations in water erosion rates relative to seasonal and monthly differences across Australia (Figure 4.28).

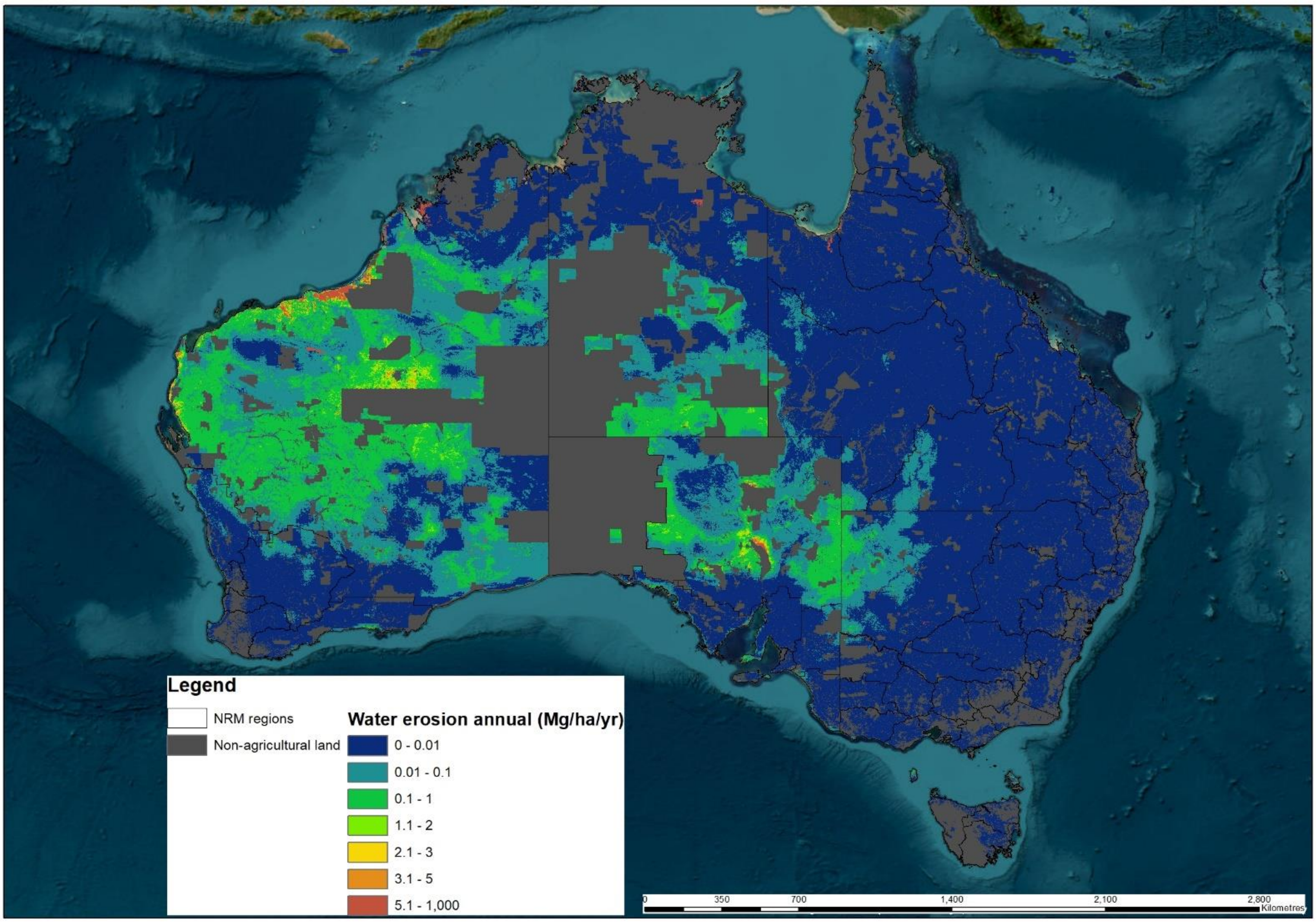

Figure 4.27. Mean annual water erosion rate (Mg/ha/yr) estimates for 2001 to 2020. Data from Zhang et al. (2022).

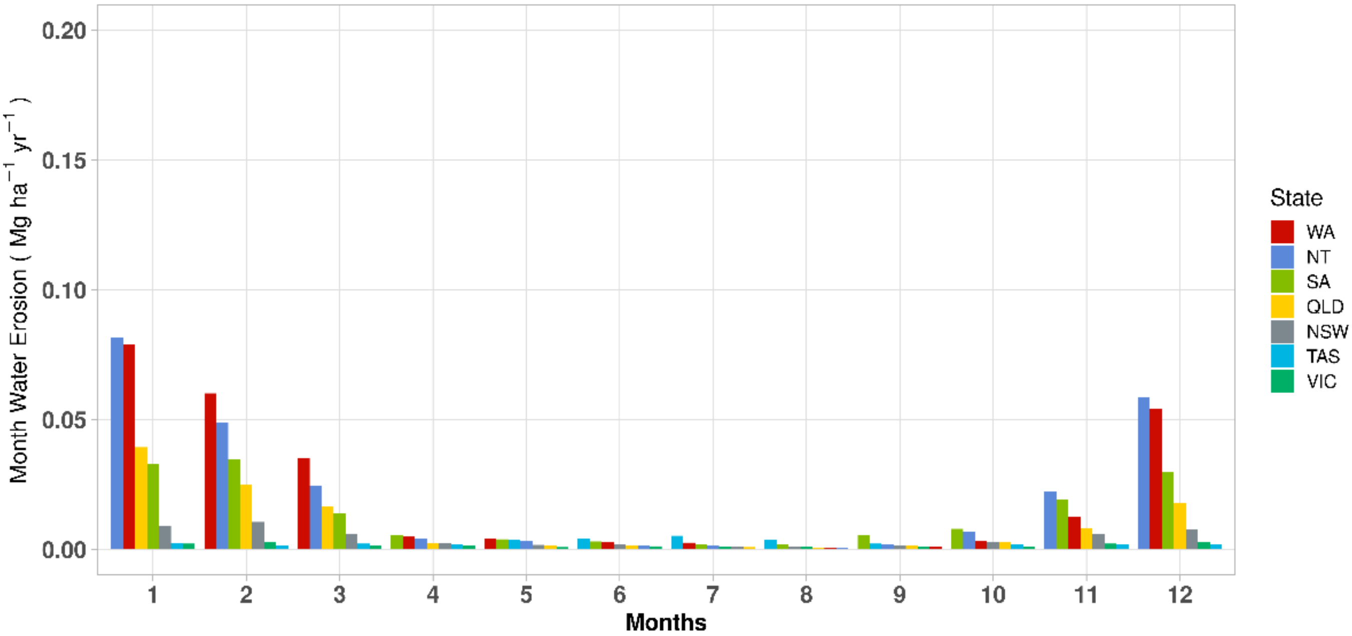

Figure 4.28. Mean monthly water erosion estimates for Australian states/territory: from Zhang et al. (2022).

4.4 Prioritising national soil threats to grazing systems.

This section is based on the assessment by McKenzie et al. (2017) in the setting of national priorities for the National Landcare Program. Soil threats and themes presented in that review include soil acidification, carbon, erosion by water and nutrient imbalances. The focus was on agricultural land with NRM regions ranked as a framework for prioritising investments across these regions. All NRM regions were assessed and ranked for these threats (Table 4.2). Livestock data and information provided by MLA (sheep numbers and cattle numbers at June 2021) have been incorporated and a gross livestock intensity index created for cattle (Figure 4.29) and sheep (Figure 4.30). Other contextual information including annual rainfall and fluxes, evapotranspiration, wind erosion and major soil type for these regions are provided (Table 4.3 and 4.4).

Maps for these threats are also presented (Figure 4.31). There are additional explanatory notes and details on these assessments provided in McKenzie et al. (2017). Additional insights from MLA and the report authors on these maps are provided in Table 4.5.

Table 4.2. Rating class and accompanying description used to assess threat: from McKenzie et al. (2017).

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

Table 4.3. Assessment of priorities for addressing soil acidification, increasing soil carbon, controlling hillslope erosion by water, managing nutrient deficiencies and excesses and wind erosion (from McKenzie et al. 2017) by NRM region. Livestock numbers are from ABS (Agricultural Commodities, Australia–2021-22), cross referenced with AWI (https://www.wool.com/market-intelligence/sheep-numbers-by-state/) and soil types are from the modelled ASC map (Searle, 2021). Definitions of each colour class are provided in Table 4.2.

ID	NRM_REGION	STATE	Area (km^2)	Cattle	Sheep	Acidifi-cation	Carbon	Hillslope erosion	Nutrient decline	Nutrient excess	Wind erosion	No. of soil types	Major soil type
0	Greater Sydney	NSW	12,187	34,695	11,318	Y	Y	Y	G	R	G	12	Kandosol
1	Hunter	NSW	32,972	383,185	191,732	Y	Y	Y	G	R	G	12	Dermosol
2	North Coast	NSW	32,526	380,237	7,950	R	R	R	Y	R	G	13	Dermosol
3	North Coast - Lord Howe Island	NSW	16	0	0	NA	NA	NA	NA	NA	NA		
4	South East NSW	NSW	55,539	38,7743	3,656,989	R	Y	Y	G	Y	G	12	Chromosol
5	Rangelands Region	WA	2,301,737	1,226,061	118,326	G	R	Y	Y	G	R	13	Tenosol
6	South Coast Region	WA	83,953	305,172	2,988,522	R	Y	Y	G	Y	Y	11	Sodosol
7	South West Region	WA	40,107	326,465	3,229,603	R	Y	Y	G	Y	G	13	Sodosol
8	North West NRM Region	TAS	23,064	370,919	60,103	Y	R	Y	Y	G	G	11	Dermosol
9	North NRM Region	TAS	20,124	366,649	1,250,973	Y	R	G	Y	R	G	13	Dermosol
10	South NRM Region	TAS	25,937	42,505	1,060,168	Y	R	G	Y	G	G	13	Dermosol
11	Northern Territory	NT	1,475,958	1,726,982	100	G	G	R	G	G	R	13	Kandosol
12	Alinytjara Wilurara	SA	288,719	0	17,756	G	R	G	G	G	R	9	Arenosols
13	Eyre Peninsula	SA	50,625	9,422	1,423,978	Y	Y	Y	G	Y	R	8	Calcarosol
14	Adelaide and Mount Lofty Ranges (Hills and Fleurieu)[#]	SA	4,639	33,964[#]	286,763[#]	R	R	Y	G	R	Y	12	Chromosol

ID	NRM_REGION	STATE	Area (km^2)	Cattle	Sheep	Acidifi-cation	Carbon	Hillslope erosion	Nutrient decline	Nutrient excess	Wind erosion	No. of soil types	Major soil type
15	Kangaroo Island	SA	4,397	15,114	680,044	R	Y	Y	G	Y	G	12	Sodosol
16	South East (Limestone Coast)	SA	26,872	638,696	3,902,768	R	Y	Y	G	R	Y	11	Tenosol
17	South Australian Murray Darling Basin (Murraylands and Riverland)	SA	48,660	139,998	1,803,396	Y	R	G	Y	Y	R	10	Calcarosol
18	Northern and Yorke	SA	38,184	40,551	1,762,868	R	Y	Y	G	Y	Y	10	Calcarosol
19	Adelaide and Mount Lofty Ranges (Green Adelaide)#	SA	1,281	30,000#	100,000#	R	R	Y	G	R	Y	10	Sodosol
20	Torres Strait	QLD	1,069	0	0	NA	NA	NA	NA	NA	NA	4	Kandosol
21	Central Tablelands	NSW	31,474	319,191	2,386,578	R	Y	Y	G	Y	G	13	Chromosol
22	Central West	NSW	92,280	495,936	4,605,928	R	Y	R	G	Y	G	11	Chromosol
23	Corangamite	VIC	13,364	437,173	1,427,803	R	Y	Y	G	Y	G	10	Sodosol
24	East Gippsland	VIC	21,049	108,436	202,735	Y	Y	G	G	Y	G	12	Dermosol
25	Glenelg Hopkins	VIC	26,754	844,854	5,771,394	R	Y	Y	G	Y	G	12	Chromosol
26	Port Phillip and Western Port	VIC	12,819	239,629	151,365	R	Y	G	G	R	G	11	Dermosol
27	West Gippsland	VIC	17,346	732,627	376,819	R	Y	Y	G	R	G	11	Dermosol
28	Burnett Mary^	QLD	57,919	768,138	2,393^	Y	Y	Y	G	R	G	14	Sodosol
29	Cape York	QLD	125,238	65,741	0	G	G	Y	G	G	G	12	Kandosol

ID	NRM_REGION	STATE	Area (km^2)	Cattle	Sheep	Acidifi-cation	Carbon	Hillslope erosion	Nutrient decline	Nutrient excess	Wind erosion	No. of soil types	Major soil type
30	Co-operative Management Area	QLD	33,818	106,625	0	G	G	Y	G	G	G	11	Kandosol
31	Fitzroy	QLD	165,043	2,523,546	20,202	Y	Y	R	R	R	G	13	Sodosol
32	Burdekin^	QLD	151,874	1,249,795	384^	Y	Y	R	R	R	G	13	Chromosol
33	Northern Gulf	QLD	182,678	781,785	3,791	G	G	Y	G	G	G	14	Kandosol
34	Mackay Whitsunday	QLD	10,027	117,627	545	Y	Y	Y	Y	R	G	12	Sodosol
35	South East Queensland	QLD	24,215	300,226	3,891	Y	Y	Y	G	R	G	13	Dermosol
36	Southern Gulf	QLD	212,374	1,126,772	43,885	G	G	R	G	G	G	11	Vertosol
37	Wet Tropics^	QLD	24,665	138,952	119^	R	Y	Y	G	R	G	14	Dermosol
38	Northern Agricultural Region	WA	74,615	109,670	1,543,611	R	Y	Y	G	Y	R	12	Tenosol
39	Peel-Harvey Region	WA	11,657	104,094	829,000	R	Y	G	G	R	G	11	Chromosol
40	Swan Region	WA	8,872	2,011	1,788	R	Y	G	G	R	G	12	Tenosol
41	Murray	NSW	41,916	375,079	2,761,494	R	R	Y	Y	R	Y	12	Chromosol
42	North West NSW	NSW	83,607	683,009	1,152,746	Y	R	G	Y	Y	G	13	Vertosol
43	Northern Tablelands	NSW	40,093	666,946	1,554,753	R	R	Y	G	Y	G	11	Dermosol
44	Riverina	NSW	67,193	528,651	5,450,775	R	R	G	Y	Y	Y	12	Chromosol
45	Western	NSW	317,545	175,582	2,931,272	G	R	Y	Y	G	R	11	Kandosol
46	Goulburn Broken	VIC	24,069	504,895	1,468,521	R	Y	Y	G	R	G	11	Chromosol
47	Mallee	VIC	39,310	26,497	646,824	Y	R	G	G	Y	R	8	Calcarosol

ID	NRM_REGION	STATE	Area (km^2)	Cattle	Sheep	Acidifi-cation	Carbon	Hillslope erosion	Nutrient decline	Nutrient excess	Wind erosion	No. of soil types	Major soil type
48	North Central	VIC	29,646	239,465	2,697,119	R	Y	Y	G	Y	Y	11	Chromosol
49	North East	VIC	19,800	388,150	358,304	R	Y	Y	G	Y	G	12	Dermosol
50	Wimmera	VIC	23,450	54,926	2,259,790	R	Y	Y	G	Y	Y	10	Sodosol
51	Condamine	QLD	25,126	560,814	41,663	G	R	R	R	Y	G	11	Vertosol
52	Desert Channels	QLD	536,567	1,357,692	795,748	G	G	G	G	G	R	11	Vertosol
53	Maranoa Balonne and Border Rivers	QLD	105,551	1,012,253	641,113	Y	R	Y	R	Y	G	10	Vertosol
54	South West Queensland	QLD	192,499	618,653	463,691	G	R	G	R	G	Y	10	Kandosol
55	Avon River Basin	WA	127,960	58,675	4,003,834	R	Y	Y	G	Y	R	13	Kandosol
56	ACT	ACT	2,359	3,957	31,643	Y	Y	Y	Y	Y	G	10	Chromosol
57	South Australian Arid Lands	SA	536,926	139,271	817,877	G	R	G	Y	G	R	10	Calcarosol

[#] Note the livestock numbers for these NRM regions are estimated owing to differences in NRM region extents between MLA, ABS and Australian government NRMs.

^ The sheep livestock numbers for these regions are from the 2016 livestock numbers from ABS (Agricultural Commodities, Australia–2015-16).

Table 4.4. Livestock intensity (no. of animals per km²), evapotranspiration, annual rainfall, and water erosion estimates from Zhang et al (2022). Note this includes non-agricultural land in estimates.

ID	NRM_REGION	State	Area (km²)	Cattle	Sheep	Cattle intensity	Sheep intensity	Annual total actual evapotranspiration modelled using terrain-scaled water holding capacity (mm)			Average Rainfall – Annual (mm)			Wind erosion (Mg/ha/yr)
								Min	Max	Mean ± SD	Min	Max	Mean ± SD	Mean ± SD
0	Greater Sydney	NSW	12,187	34,695	11,318	2.85	0.93	485	1203	913 ± 106	729	1597	1065 ± 178	0.151 ± 0.445
1	Hunter	NSW	32,972	383,185	191,732	11.62	5.81	500	1303	885 ± 167	575	2033	1002 ± 256	0.127 ± 0.469
2	North Coast	NSW	32,526	380,237	7,950	11.69	0.24	515	1423	1112 ± 81	925	3163	1460 ± 299	0.143 ± 0.230
4	South East NSW	NSW	55,539	38,7743	3,656,989	6.98	65.85	487	1251	767 ± 139	494	2182	915 ± 267	0.067 ± 0.293
5	Rangelands Region	WA	2,301,737	1,226,061	118,326	0.53	0.05	165	1120	347 ± 180	99	1528	325 ± 213	0.310 ± 0.842
6	South Coast Region	WA	83,953	305,172	2,988,522	3.64	35.60	276	774	437 ± 96	256	1303	468 ± 158	0.009 ± 0.034
7	South West Region	WA	40,107	326,465	3,229,603	8.14	80.52	338	800	523 ± 108	339	1368	730 ± 285	0.010 ± 0.099
8	North West NRM Region	TAS	23,064	370,919	60,103	16.08	2.61	377	1002	825 ± 84	725	3421	1961 ± 667	0.116 ± 0.550
9	North NRM Region	TAS	20,124	366,649	1,250,973	18.22	62.16	323	960	698 ± 92	469	2945	997 ± 401	0.023 ± 0.125

ID	NRM_REGION	State	Area (km^2)	Cattle	Sheep	Cattle intensity	Sheep intensity	Annual total actual evapotranspiration modelled using terrain-scaled water holding capacity (mm)			Average Rainfall – Annual (mm)			Wind erosion (Mg/ha/yr)
10	South NRM Region	TAS	25,937	42,505	1,060,168	1.64	40.87	328	960	720 ± 109	445	3090	1313 ± 713	0.046 ± 0.217
11	Northern Territory	NT	1,475,958	1,726,982	100	1.17	0.00	170	1260	520 ± 253	140	1913	565 ± 358	0.256 ± 0.582
12	Alinytjara Wilurara	SA	288,719	0	17,756	0.00	0.06	155	431	217 ± 31	115	664	203 ± 47	0.129 ± 0.467
13	Eyre Peninsula	SA	50,625	9,422	1,423,978	0.19	28.13	245	542	335 ± 54	208	696	353 ± 65	0.021 ± 0.036
14	Adelaide and Mount Lofty Ranges (Hills and Fleurieu) [#]	SA	4,639	33,964	286,763	7.32	61.82	362	763	530 ± 75	323	1084	659 ± 174	0.027 ± 0.046
15	Kangaroo Island	SA	4,397	15,114	680,044	3.44	154.66	414	610	508 ± 30	454	879	624 ± 105	0.008 ± 0.026
16	South East (Limestone Coast)	SA	26,872	638,696	3,902,768	23.77	145.24	373	653	502 ± 54	385	921	570 ± 103	0.004 ± 0.025
17	South Australian Murray Darling Basin (Murraylands and Riverland)	SA	48,660	139,998	1,803,396	2.88	37.06	210	615	292 ± 61	195	825	295 ± 68	0.031 ± 0.042
18	Northern and Yorke	SA	38,184	40,551	1,762,868	1.06	46.17	218	649	387 ± 82	206	805	401 ± 93	0.049 ± 0.087
20	Torres Strait	QLD	1,069	0	0	0.00	0.00	750	1081	938 ± 40	1547	2096	1803 ± 87	0.337 ± 0.668

ID	NRM_REGION	State	Area (km^2)	Cattle	Sheep	Cattle intensity	Sheep intensity	Annual total actual evapotranspiration modelled using terrain-scaled water holding capacity (mm)			Average Rainfall – Annual (mm)			Wind erosion (Mg/ha/yr)
21	Central Tablelands	NSW	31,474	319,191	2,386,578	10.14	75.83	464	1148	730 ± 85	575	1377	801 ± 133	0.053 ± 0.081
22	Central West	NSW	92,280	495,936	4,605,928	5.37	49.91	387	1055	532 ± 92	407	1123	550 ± 100	0.025 ± 0.040
23	Corangamite	VIC	13,364	437,173	1,427,803	32.71	106.84	479	1001	666 ± 87	442	1946	785 ± 254	0.011 ± 0.089
24	East Gippsland	VIC	21,049	108,436	202,735	5.15	9.63	479	1109	798 ± 92	581	2212	1020 ± 282	0.052 ± 0.116
25	Glenelg Hopkins	VIC	26,754	844,854	5,771,394	31.58	215.72	456	918	612 ± 38	497	1279	696 ± 85	0.003 ± 0.010
26	Port Phillip and Western Port	VIC	12,819	239,629	151,365	18.69	11.81	445	1070	718 ± 123	441	1988	876 ± 279	0.020 ± 0.043
27	West Gippsland	VIC	17,346	732,627	376,819	42.24	21.72	518	1075	754 ± 102	582	2023	981 ± 307	0.030 ± 0.121
28	Burnett Mary^	QLD	57,919	768,138	2,393^	13.26	12.09	588	1368	815 ± 174	627	1980	900 ± 230	0.105 ± 0.763
29	Cape York	QLD	125,238	65,741	0	0.52	0.00	547	1408	914 ± 61	973	4298	1449 ± 281	0.107 ± 0.560
30	Co-operative Management Area	QLD	33,818	106,625	0	3.15	0.00	671	1426	895 ± 36	827	2617	1111 ± 128	0.100 ± 0.170
31	Fitzroy	QLD	165,043	2,523,546	20,202	15.29	0.12	518	1413	668 ± 123	541	1813	717 ± 148	0.115 ± 0.526

ID	NRM_REGION	State	Area (km^2)	Cattle	Sheep	Cattle intensity	Sheep intensity	Annual total actual evapotranspiration modelled using terrain-scaled water holding capacity (mm)			Average Rainfall – Annual (mm)			Wind erosion (Mg/ha/yr)
32	Burdekin^	QLD	151,874	1,249,795	384^	8.23	0.00	492	1521	635 ± 142	518	2574	702 ± 208	0.127 ± 0.435
33	Northern Gulf	QLD	182,678	781,785	3,791	4.28	0.02	503	1513	762 ± 108	495	3390	829 ± 178	0.114 ± 0.246
34	Mackay Whitsunday	QLD	10,027	117,627	545	11.73	0.05	783	1517	1211 ± 90	904	2320	1555 ± 210	0.313 ± 1.034
35	South East Queensland	QLD	24,215	300,226	3,891	12.40	0.16	565	1444	979 ± 185	714	3157	1163 ± 318	0.157 ± 0.353
36	Southern Gulf	QLD	212,374	1,126,772	43,885	5.31	0.21	343	952	556 ± 131	360	1293	566 ± 158	0.200 ± 0.503
37	Wet Tropics^	QLD	24,665	138,952	119^	5.63	4.05	682	1655	1196 ± 233	743	7379	2071 ± 1004	0.410 ± 2.365
38	Northern Agricultural Region	WA	74,615	109,670	1,543,611	1.47	20.69	237	603	370 ± 88	246	760	403 ± 109	0.031 ± 0.048
39	Peel-Harvey Region	WA	11,657	104,094	829,000	8.93	71.12	373	710	542 ± 82	399	1240	779 ± 241	0.019 ± 0.061
40	Swan Region	WA	8,872	2,011	1,788	0.23	0.20	402	699	557 ± 44	536	1226	782 ± 134	0.030 ± 0.039
41	Murray	NSW	41,916	375,079	2,761,494	8.95	65.88	293	1130	466 ± 170	331	2066	534 ± 293	0.012 ± 0.038
42	North West NSW	NSW	83,607	683,009	1,152,746	8.17	13.79	413	1174	616 ± 120	424	1344	624 ± 130	0.040 ± 0.066

ID	NRM_REGION	State	Area (km^2)	Cattle	Sheep	Cattle intensity	Sheep intensity	Annual total actual evapotranspiration modelled using terrain-scaled water holding capacity (mm)			Average Rainfall – Annual (mm)			Wind erosion (Mg/ha/yr)
43	Northern Tablelands	NSW	40,093	666,946	1,554,753	16.63	38.78	540	1273	856 ± 106	612	1730	908 ± 161	0.079 ± 0.120
44	Riverina	NSW	67,193	528,651	5,450,775	7.87	81.12	312	1165	491 ± 142	338	1697	552 ± 228	0.021 ± 0.041
45	Western	NSW	317,545	175,582	2,931,272	0.55	9.23	179	489	295 ± 62	172	588	308 ± 66	0.051 ± 0.095
46	Goulburn Broken	VIC	24,069	504,895	1,468,521	20.98	61.01	367	1071	614 ± 149	417	2006	795 ± 349	0.019 ± 0.040
47	Mallee	VIC	39,310	26,497	646,824	0.67	16.45	243	399	311 ± 27	256	427	328 ± 30	0.021 ± 0.026
48	North Central	VIC	29,646	239,465	2,697,119	8.08	90.98	319	889	456 ± 95	344	1361	505 ± 143	0.006 ± 0.010
49	North East	VIC	19,800	388,150	358,304	19.60	18.10	501	1152	788 ± 111	522	2514	1170 ± 389	0.056 ± 0.105
50	Wimmera	VIC	23,450	54,926	2,259,790	2.34	96.37	325	925	451 ± 79	339	1433	495 ± 119	0.006 ± 0.013
51	Condamine	QLD	25,126	560,814	41,663	22.32	1.66	583	1337	657 ± 76	605	1736	696 ± 99	0.039 ± 0.057
52	Desert Channels	QLD	536,567	1,357,692	795,748	2.53	1.48	161	691	319 ± 95	142	738	314 ± 105	0.131 ± 0.197
53	Maranoa Balonne and Border Rivers	QLD	105,551	1,012,253	641,113	9.59	6.07	418	1020	582 ± 65	427	1218	582 ± 74	0.032 ± 0.042

ID	NRM_REGION	State	Area (km^2)	Cattle	Sheep	Cattle intensity	Sheep intensity	Annual total actual evapotranspiration modelled using terrain-scaled water holding capacity (mm)			Average Rainfall – Annual (mm)			Wind erosion (Mg/ha/yr)
54	South West Queensland	QLD	192,499	618,653	463,691	3.21	2.41	225	876	402 ± 91	211	865	406 ± 92	0.057 ± 0.076
55	Avon River Basin	WA	127,960	58,675	4,003,834	0.46	31.29	259	584	328 ± 32	246	808	335 ± 51	0.019 ± 0.019
56	ACT	ACT	2,359	3,957	31,643	1.68	13.41	583	1148	755 ± 113	628	1668	940 ± 249	0.086 ± 0.098
57	South Australian Arid Lands	SA	536,926	139,271	817,877	0.26	1.52	136	606	186 ± 34	124	621	188 ± 41	0.235 ± 0.407

[#] Note the livestock intensity (no. of animals per km^2), evapotranspiration, annual rainfall, and water erosion estimates from Zhang et al (2022) for the Green Adelaide' NRM region is not presented owing to differences in NRM region extents between datasets.

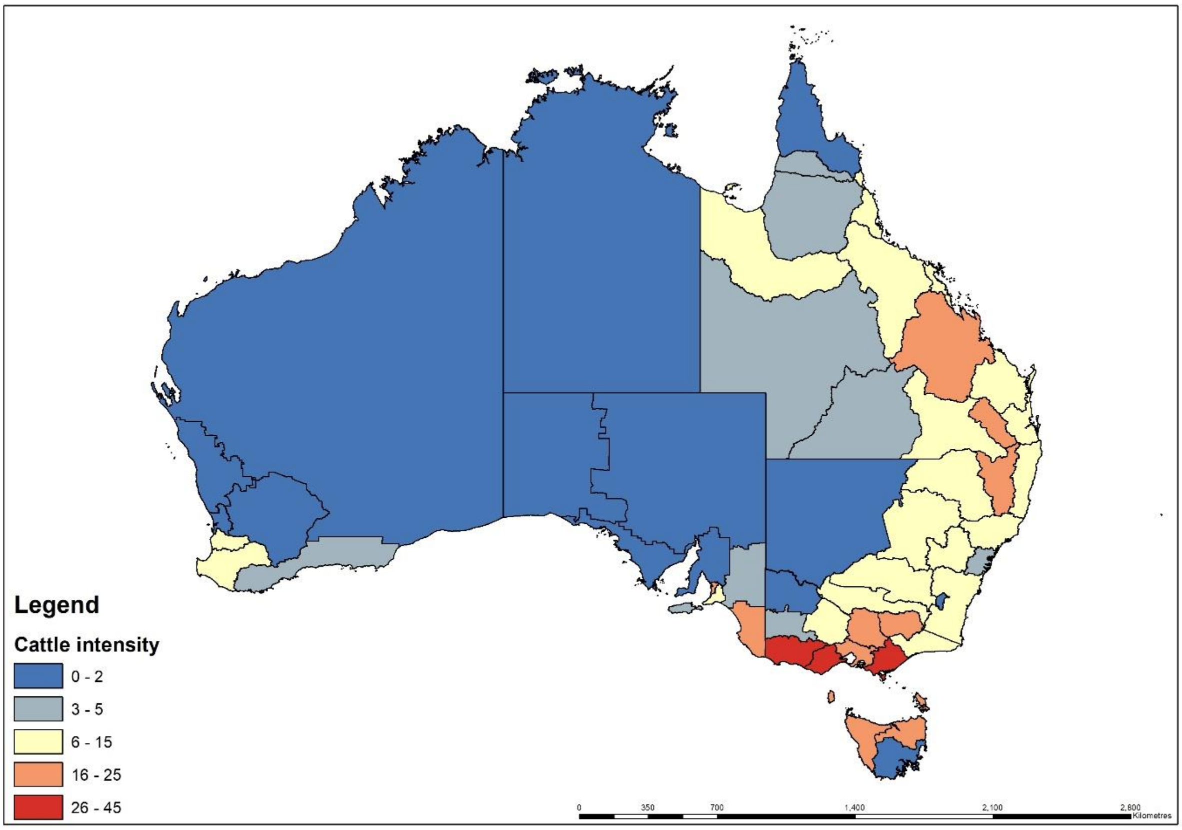

Figure 4.29. Gross cattle livestock intensity (animals/km^2) by NRM region.

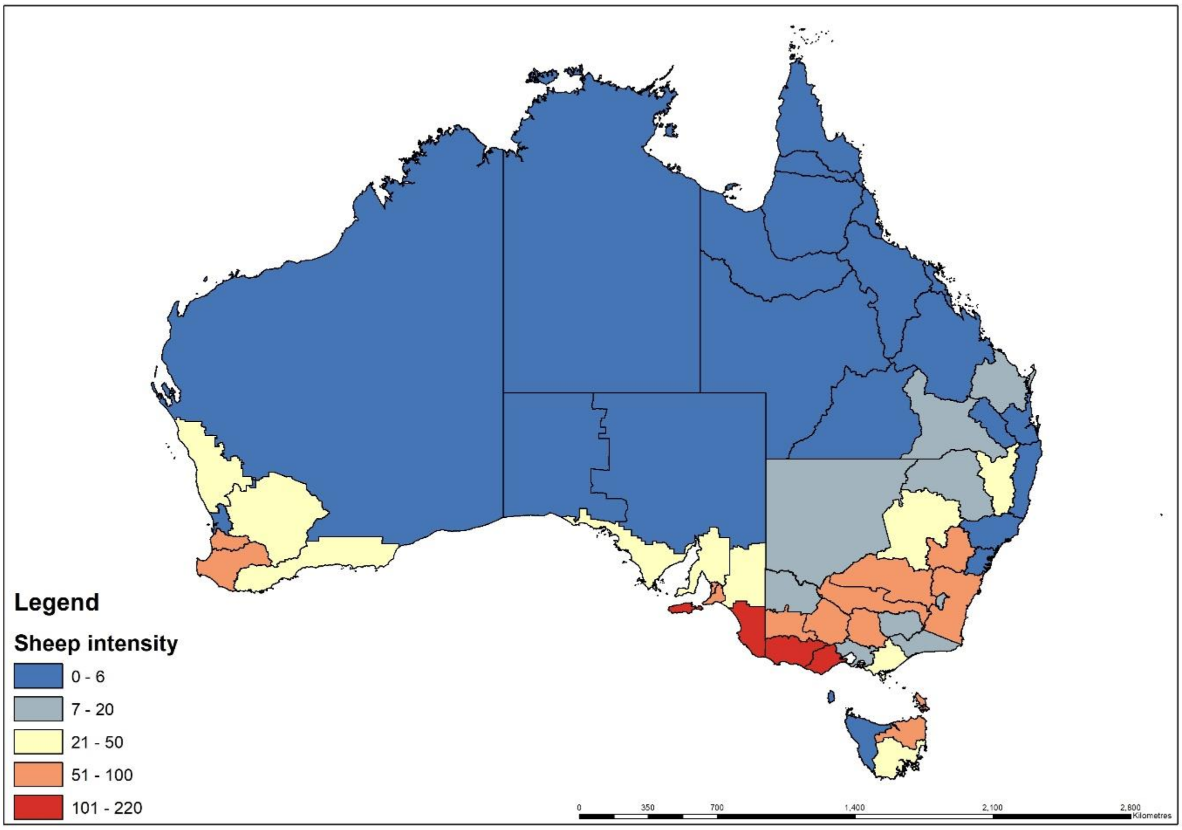

Figure 4.30. Gross sheep livestock intensity (animals/km^2) by NRM region.

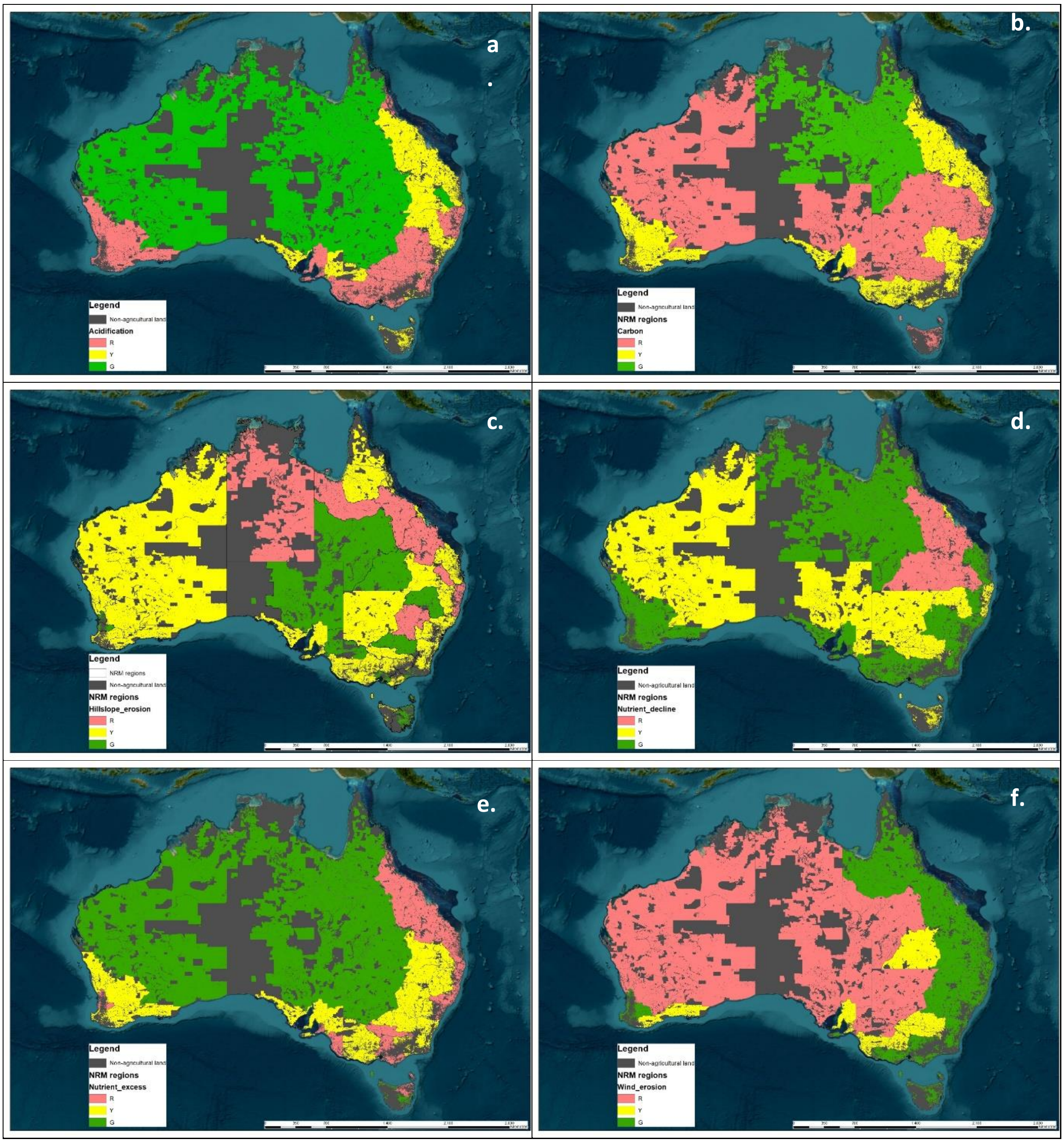

Figure 4.31. Threat rating maps for Australia: **a.** Acidification; **b.** Carbon; **c.** Hillslope erosion; **d.** Nutrient decline; **e.** Nutrient excess; **f.** Wind erosion.

Table 4.5. Insights and comments on the national priority setting maps for soil threats.

Map	Comments on the national priority maps
Acidification	• Acidification correlates with the mixed farming zone and grain production. • The high to medium rainfall zones of South Australia, Victoria, Tasmania, NSW and Queensland and agricultural zone of Western Australia are known for acidification driven by current practices. Extensively any land uses in the agricultural zones are at threat for soil acidification. The rangelands are not at threat from acidity.
Soil carbon	• The carbon map implies potential to improve soil carbon in the temperate/higher rain fall zones where it has declined significantly. This is consistent with studies under the SCaRP program (chapter 6). High stocking rates and low ground cover could be reasons for optimism in rangeland areas to increase or cease a decline in soil organic carbon. • Land transitioning from dryland pastures to cropping will see significant decreases in SOC, maps may not reflect these changes over the last 5-10 years.
Hillslope erosion by water	• Hillslope erosion threats reflect priorities in Queensland and the Northern Territory. The NPP and fractional groundcover maps may provide more insights when combined with water quality and erosion information (see the assessment by Zhang et al. (2022). • Rangeland areas in Western Australia may be some of the highest at risk of water erosion and this may be masked by the large extent of the NRM region.
Nutrient decline	• Nutrient decline in Queensland correlates with Brigalow belt Bio region where there is a high level of cattle production (~50% of the Queensland herd) on sown buffel grass pastures. Nutrient loss due to removal of N+P in beef production- 'N run down' and about 50% decline in beef production over recent years. Buffel grass monoculture has also brought problems of pasture die-back (pasture mealy bug) and weed invasion/less desirable /nutritious species due poor soil fertility. • Studies in southern regions suggest that soil nutrition levels (e.g. phosphorus) are less than ideal for some commodities (e.g. sheep - wool and meat). Paddocks have noted deficiencies in micronutrients (e.g. Boron and Molybdenum) and some macronutrients (Crawford et al. 2020).
Nutrient excess	• Nutrient excess correlates with sugarcane production in coastal Queensland, dairying in the Peel-Harvey catchment and Gippsland (both with very high N inputs). • Agricultural areas all rated R or Y for nutrient excess threat with the rangelands assessed as low threat (G).

Map	Comments on the national priority maps
Wind erosion	• Wind erosion severity in rangelands- impacted likely by overstocking (@ about 1.5-1.7 times above long-term carry capacity)- result of overgrazing, poor ground cover. • The role of biocrust in holding together surface of these fragile/sandy soils? • Map aligns with modelling by Zhang et al. (2022).

4.5 Estimate of costs to Australian grazing systems

An estimated 77%, and increasing, of Australian soils have one or more properties that constrain productivity (Bot et al. 2000 in Dang and Moody 2016). Developing estimates of the costs to Australian agriculture of these constraints involves identifying the production penalty, cause of the penalty, and attributing cost. The uncertainties involved lead to variation in estimates of impacts of soil constraints (Dang and Moody 2016). The estimates of penalties or costs attributed to various constraints provide some context to addressing the limitations (Table 4.6). When used with other information such as soil maps and direct measurements of soil properties, the extent of impacts and appropriate responses for producers may be better understood, though spatial variability is likely to remain a challenge (Ringrose Voase et al. 1997, Trotter et al. 2016, Ulfa et al. 2022). Further, the effect of transient problems such as salinity and chronic problems such as erosion increase the complexity of quantifying penalties. Even with the magnitude and cause of a gap identified, cost will vary with season due to environmental and market factors.

Identification of crop yield gaps in Australia through the Yield Gaps program is well known, where actual yields from local areas are compared to modelled non-nutrient limiting, water-limited potential yields (https://yieldgapaustralia.com.au/maps/). While grazing systems have additional layers of complexity with sward complexity, livestock management, etc., an indicative response may be obtained for forages in the grazing phase in the mixed cropping zone as a starting point. Identifying constrained production is more difficult in the lower and higher rainfall zones outside the cropping belt due to greater variability in rainfall and soil-landscapes. Further identification of poor performance at the farm to paddock scale is potentially possible with the increasing availability of longer timeframes and finer resolution of remotely sensed imagery, though such a process will need development (Dang and Moody 2016, Ulfa et al. 2022).

Notwithstanding the complexities and assumptions underlying the process of quantifying resource and production costs, it is worth developing estimates and strategies to manage the costs. Investment decisions to allay the penalties can then be developed; for instance, Tozer and Leys (2013) estimated that $9M per year would be required for dust mitigation strategies in rural areas to improve the condition of soil on-site and decrease the impacts off-site, addressing chemical constraints for cropping systems holds benefits for pasture phases (Uddin et al. 2022).

Table 4.6. Summary of estimated area and $ or % penalty of soil constraints to Australian agriculture.

Region	Area size	$ Penalty[a]	%Penalty	Source
	At least one constraint			
National	77% of soils			Bot et al. (2000) in Orton et al. (2018)
	Low SOC			
Victoria, high rainfall		$26-85/ha/yr (pasture production)		Meyer et al. 2015
Victoria, low rainfall		$85-105/ha/yr (pasture production)		Meyer et al. 2015
NSW, Wagga Wagga		for 1% point increase in SOC: $116/ha/yr on hillslopes (68% pasture) with low SOC, nil on footslopes and flats with high SOC, $225/ha/yr on dunes (44% pasture) with low SOC		Ringrose-Voase et al. (1997)
	Acidity			
National	50% ag land			McKenzie, Hairsine et al. (2017)
National, wheat cropping belt		$380 M/yr		Orton et al. (2018)
National Beef Sheep All agricultural soil		 $ 95.0 M $ 50.5 M $1584.5 M	 13.2% 16.5% 24.2%	Hajkowicz and Young (2005)
NSW, Northern Tablelands (beef production)			15.0%	Duncan and Mitchell (2003)

NSW, Wagga Wagga		\$11.9/ha/yr per 1% increase in Al% (0-10 cm) on hillslopes (68% pasture) with high acidity		Ringrose-Voase et al. (1997)
	Erosion			
National	110 Mt annually	No established method to value soil loss		Tozer and Leys (2013), Aubault et al. (2015)
National 2009 September 'red dawn'	776 180 km^2, 2.54 M t	\$8.8 m nutrients (at 1994 NPK prices), \$11.4 M CO_2e @ A\$23/t (\$50% discount)		Tozer and Leys (2013)
	Sodicity			
National	2 M ha 17%			Northcote and Skene (1972) Bot et al. (2000) in Orton et al. (2018)
National Cropping soils	12 M ha			Rengasamy (2002)
National Beef Sheep All agricultural soil		 \$ 138.0 M \$ 168.6 M \$1034.6 M	 19.2% 55.2% 15.8%	Hajkowicz and Young (2005)
	Salinity			
National	16% of cropping area likely affected due to watertable rise 67% of cropping area has potential for transient salinity not associated with groundwater and subsoil constraints			Rengasamy (2002)

National: Beef Sheep All agricultural soil		 $ 15.8 M $ 38.9 M $187.0 M	 2.2% 12.7% 2.9%	Hajkowicz and Young (2005)
Western Australia	1.75 M ha			Caccetta et al. (2022)
South Australia	326 000 ha			Barnett (2000)
Victoria	262 000 ha			Clark and Harvey (2008)
New South Wales	120 000 ha			Smith (2000)
Queensland	107 000 ha			ABS (2003)
Tasmania	71 200 ha			Bastick and Walker (2000)
	Nutrient excess/decline			
Northern Australia, productivity of sown pasture		>$500 M/yr (>$17 B over 30 years)	50%	Peck et al. (2011)
NSW, Wagga Wagga		For 1 ppm increase in available P (0-10 cm): $2.79 on footslopes (58% pasture) with moderate P, $24.7/ha/yr on dunes (44% pasture) with low P		Ringrose-Voase et al. (1997)
	Subsoil constraints (chemical, physical)			
National		$1330 M/yr		Rengasamy (2002)
	Water repellency			
Western and southern Australia	5 M ha			Tate et al. (1989) in Roper (2004)

	Waterlogging			
Western Australia		$46 M		(https://www.agric.wa.gov.au/waterlogging/waterlogging-western-australia)
	Compaction			
National Western Australia, crop and pasture production		$850 M/yr $330 M/yr		Walsh (2002) https://www.agric.wa.gov.au/soil-compaction/soil-compaction-overview

[a]dollar costs as reported in the cited sources.

Several observations can be drawn from the impact of soil constraints to Australian agriculture (Table 4.6):

- The dollar values of penalties are as reported in the documents, not standardised to reflect inflation or market prices.
- The benefits of soil organic matter are multifaceted (nutrient cycling, water use efficiency, resilience), though attempts to quantify the benefits has not been widely undertaken. Doing so is worth exploring as awareness grows around the limited scope to increase concentrations outside a natural range in most instances compared to the attention generated by carbon trading.
- The range for some constraints, e.g. acidity (Orton et al. 2018 cf Hajkowicz and Young 2005) may be due to remediation work (liming) already undertaken, and differences in the extent of soils and production system being assessed. This constraint is a natural consequence of agricultural production systems, so liming will be an ongoing cost of production. Some areas are not economic to lime, so the problem will not be addressed entirely. In addition, the process of liming releases CO_2 to the atmosphere, so needs to be accounted for systemically (Conyers et al. 2015).
- The effects of salinity are transient based on climatic conditions, though the presence of substantial salt stores in both humid and dry environments does impose penalties if hydrology cannot be managed during higher rainfall phases.
- Erosion is a long-term chronic problem. While managed better than in earlier decades, water and wind erosion removes the most productive layer of soil, cumulatively depleting resilience and capacity. Difficult to cost, but the most extreme circumstances of gullying or scalding result in a complete loss of productive capacity along with off-site impacts.
- Quantifying the impact of constraints is difficult, often based on assumptions and estimates themselves, and subject financially to market conditions. Quantifying the impacts for grazing enterprises is more complex than for cropping systems due to the extra level of management. An approach based on s similar order of production loss for pastures as for grains is a starting point, though oversimplified due to the potential effects on soil constraints at crucial crop growth stages such as flowering and grain fill.
- Cost penalties indicated by studies (Table 5) may not be greater than the cost of amelioration at the present time. For example, the cost:benefit of lime application in extensive sheep grazing in WA was 0.88 (AACM 1995 in Hajkowicz and Young 2005). Such relative findings are subject to market prices and circumstances that can change, but do not address the resource base or any other issues such as off-site impacts or life-cycle analysis. The more fundamental approach taken by Hajkowicz and Young (2005) of estimating potential gross benefits of addressing the constraint, assuming costless amelioration and notwithstanding assumptions made, provides a basis to inform investment.
- In some cases awareness may of the nature or scale of problems may not exist. In other cases, the penalty may not be seen to outweigh the investment cost (such as the 0.88:1 cost:benefit of salinity noted above). In these cases the problems may be seen as intractable, given current circumstances. As those costs or benefits change so too do the cost:benefit ratios, for example market conditions or including expanding assessment of externalities such as more clearing to increase yield rather than dealing with a constraint, i.e. consideration of natural capital and ecosystem services (Eldridge and Delgado-Baquerizo 2017, Ascui and Cojoianu, 2018).

A summary of constraints in a single line will not capture the extent of constraints but provides a starting point to understand the scale for planning management and investment directions (Table 4.7).

Table 4.7. Summary at a glance of constraints affecting Australian agriculture.

Constraint	Impact
At least one constraint	77% of Australia
Acidity	15-25% penalty
Low SOC	$26-$225/ha/yr[a]
Wind erosion	110 Mt soil annually
Sodicity	17-55% penalty
Salinity	>2600 ha
Nutrient limitations	>$500 M/yr
Compaction	$850 M/yr[b]
Subsoil constraints	$1330 M/yr[c]

Dollar values as published, not adjusted for inflation: [a]Meyer et al 2015, Ringrose-Vaose et al. 1997, [b]Walsh (2002), [c]Rengasamy 2002

4.6 Recommendations

From the assessment of McKenzie et al. (2017), key areas identified for further investigation include:

- insufficient knowledge or uncertainty about implications of current threats to soil function.
- the implications of the large and ongoing increase in the use of N fertiliser.
- intensification of land use in northern Australia requires close attention to the principles of sustainable soil management.
- evidence to suggest that the extent and severity of soil acidification is being underestimated by the national-scale analysis.
- develop specific technical manuals on these threats and opportunities at the district and state/territory level.
- protect organic carbon-rich soils in peatlands, forests and grazing lands.
- 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.
- regular monitoring of soil acidity.
- select an appropriate plant nutrient management system and approach alongside assessing the suitability of the land for a given land use.
- soil and plant-tissue testing, and field assessments should be adopted and used.

- a causal analysis of the record of fractional cover (i.e. bare soil and vegetative cover) is required. It should aim to differentiate the drivers of cover and in particular, the impacts of climate and land management.
- a quantitative social science investigation into the factors that limit the uptake of soil conservation practices.

5 Extreme events

Key points:

- although 80% of research on climate change in livestock systems was focussed on pastures, none was focussed on soil
- vulnerability of pastures will change according to inter-annual variability in weather and climate conditions
- damage from extreme events is often temporary although permanent damage to soils can occur. Recovery is often relatively rapid
- some factors affecting resilience are natural (parent material, slope, rainfall) while others are modifiable (particularly grazing management)

MLA has invested significant resources to extreme events in recent times, particularly in response to extreme rainfall, prolonged dry periods, heat waves and bushfires. Additionally, climate change is likely to increase the frequency of these events causing damage to livestock, infrastructure, pastures and soils. While the gradual increases in temperature are likely to progressively depress pasture yields, the increased climatic variability associated with more frequent extreme climatic events is likely to have a greater impact on agricultural systems (Harrison et al. 2016, Chang-Fung-Martel et al. 2017).

Darbyshire et al. (2022) reviewed the impacts of climate change across sectors over Australia and found that research was skewed towards cropping and biosecurity threats. From a livestock perspective, nearly 80% of research was focussed on pastures with only one focussed on impacts on soil from unplanned fire.

5.1 Vulnerabilities

MLA have conducted significant work on vulnerability of livestock and grazing systems to extreme events. However, while some of this work has been on pastures, there has been limited attention to soils. Vulnerabilities take on many forms. For example, high temperatures in feedlots make cattle vulnerable to the extent that they may not recover their previous level of productivity. In rangeland systems, Godde et al. (2020) found that vegetation trends and inter-annual variability were likely to make livestock systems more vulnerable in many countries including Australia. Marshall et al. (2018) also found that vulnerability could be minimised within the livestock industry if producers could enhance their adaptive capacity. With respect to soils, Marshall et al. (2018) stated that vulnerability could be reduced by a focus on carbon sequestration, but more research was required on adaptation rather than mitigation. However, a focus on increasing soil carbon is not just a mitigation strategy: soils with increased soil carbon improves the soil through its ability to aggregate soil particles and increase the store of essential nutrients. This improvement in turn increases the resilience of a soil to extreme events.

Soils are vulnerable to degradation from extreme events and the impacts can be temporary or permanent. Loss of soil through erosion can cause a permanent decline in the productivity of a soil whereas some physical, chemical, and biological impacts can be temporary, making recovery possible. Recovery can, however, take time and can be expensive. Identifying vulnerabilities and the actions needed to reduce or prevent them is important.

Bushfires are a natural agent of disturbance often resulting in multifactorial damaging impacts. Heat from unplanned fire has capacity to sterilise soil, kill pasture seeds, remove soil nutrients, and temporarily decimate the soil microbiome (Purdie et al. unpublished).

5.2 Recovery

Recovery from extreme events can take time and money and is a burden on the wellbeing of livestock enterprises. However, sometimes, natural factors are important in the speed of recovery as well. Ideal growing factors can speed recovery and (Yao et al.) found that the determining factor in a soil's recovery from drought was soil moisture levels. Likewise, recovery from fires is dependent on natural conditions and (Pereira et al. 2018) found that post-fire management can trigger or reduce soil degradation. The impacts of flooding look to be more complex, with anaerobic conditions and temperature changes triggering physical, chemical and biological changes. Besides drought, flooding is one of the most damaging abiotic stresses which affects 17 million km^2 annually (Alaoui et al. 2018). In all extreme events, favourable weather conditions for recovery seem to be essential in determining the rate of recovery. However, modifiable factors such as SOC levels, groundcover and good soil structure will hasten this recovery.

Recovery from bushfires seems fairly rapid and the impact on soils appears temporary provided erosion does not occur. Impacts on the soil microbiome are not well understood and a major unintended impact was the appearance of previously unseen weeds on fire impacted areas (Purdie et al. unpublished)

5.3 Resilience

Soil resilience refers to the intrinsic ability of a soil to recover from degradation and return to a new equilibrium similar to the antecedent state (Blanco-Canqui and Lal 2008). Resilience of soil to extreme events is likely to centre around improving the 'bank' of soil qualities so that in extreme events, they won't run down to such an extent that there will be permanent damage or loss of production. Resilience could also take the form of enabling farmers to diversify their production systems (Howden et al. 2008). Resilience of a soil is dependent on many factors, some inherent and some which are changeable. (Greenland et al. 1997) describe a suite of processes, factors and causes of soil degradation and soil resilience (Figure 5.1).

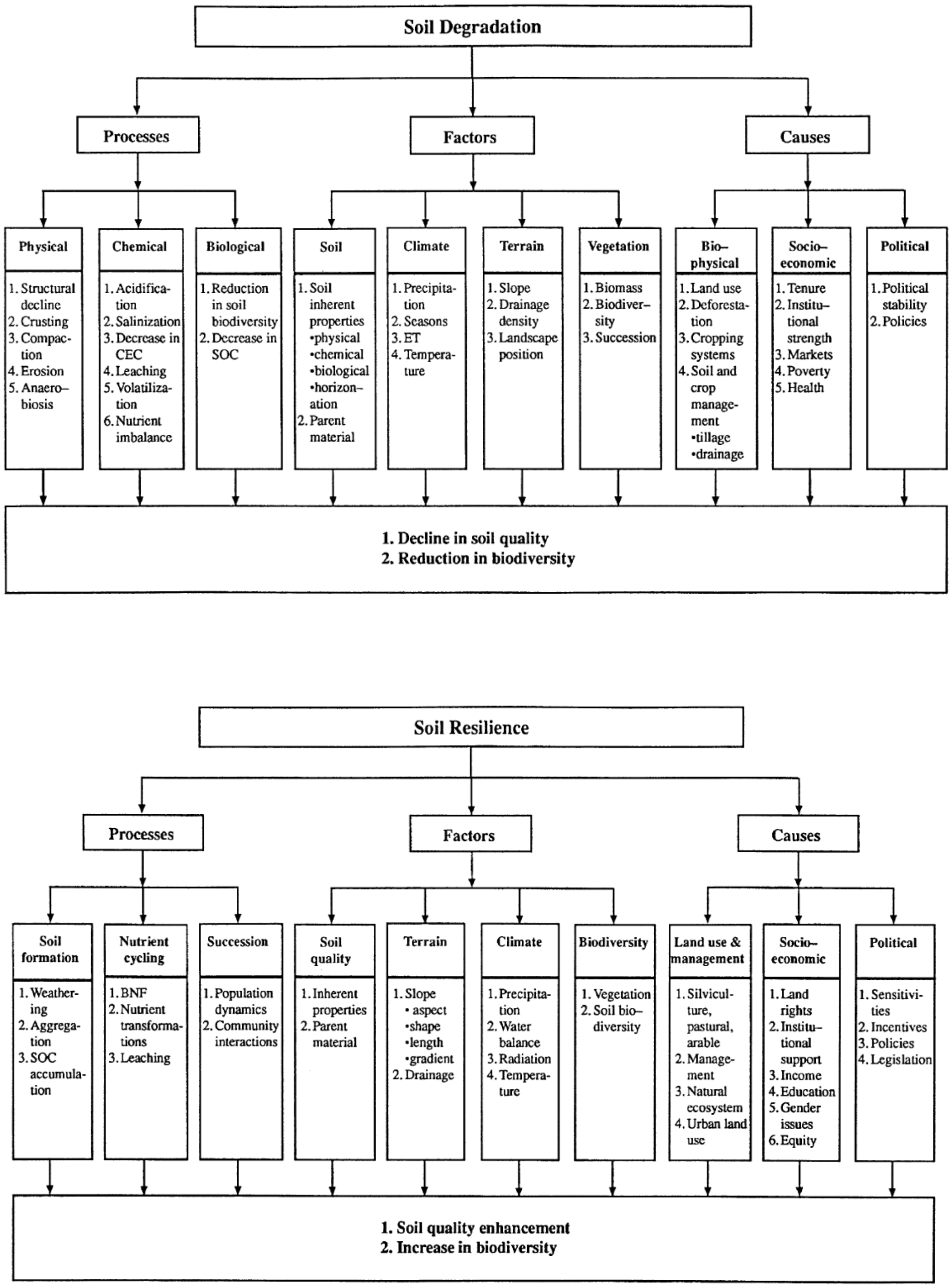

Figure 5.1: Processes, factors and causes of soil degradation and soil resilience (Greenland et al. 1997)

It is a useful distinction that the suite of processes factors and causes contributing to soil degradation is not the same suite of factors contributing to resilience and notable that many factors contributing to both degradation and resilience are inherent soil, landscape and climatic factors which are generally not modifiable. Soil and land management is listed as a biophysical cause of soil degradation while there are a suite of land use and management factors causing soil resilience.

Managing soils to increase soil carbon not only provides temporary pathways to mitigate the impacts of climate change, but also provides a pathway for soils to become more resilient to extreme events such as drought, floods and fire.

5.4 Recommendations

- Vulnerabilities can be inherent to the landscape and climate and an effort should be made to identify what modifiable factors can influence these vulnerabilities.
- Recovery is often relatively rapid, further work should concentrate on modifiable factors and inherent factors need to be recognised.
- Soil resilience is preferable, dependent on inherent factors and will vary according to soil type, landscape and climatic conditions. Increasing soil carbon is likely to be a major influencer on soil resilience.

6 Capacity for carbon storage

Key Points:

- soil organic carbon is part of soil organic matter
- organic matter is a vital component of soil for production and resilience
- soil organic matter/carbon is strongly influenced by environmental factors, with management being a minor factor
- interest in SOC for trading requires accurate measurement (or modelling) and a long-term commitment
- the capacity to increase SOM is influenced by environmental variables, soil properties, and the nature of the organic material
- real benefits of managing SOM/SOC for soil health exist for agriculture outside trading

6.1 Overview

Soil organic carbon is present in the soil as part of organic matter. This material, derived from plants, is distinct from litter or roots, and has entered a process of decomposition by soil organisms. The decomposition process cycles the carbon and other components e.g. nutrients, hydrogen, oxygen, having been composed by plants (Lehmann and Kleber 2015). Thus, we can consider the stock of carbon in the soil, and the flux through it. The stock of SOC is generally considered to be 57% of SOM, though varies with the stage of decomposition and is probably closer to 50% (Pribyl 2010). We generally discuss SOC because that is the measure determined in the laboratory and can be compared to any other stock of C – in vegetation, the ocean or atmosphere. Carbon stock is of interest for the physical benefits it provides to soil – e.g. structural stability, temperature moderation, food source for organisms. Increasingly stock is of interest related to a potential abatement sink for atmospheric CO_2 and related policy and market stakeholders. Flux is of primary interest through the nutrient cycling back to plants, and as related to the residence time or degree of permanence for those policy and market stakeholders.

The distribution of SOC stocks is strongly influenced by the balance of organic matter inputs (plant growth) and outputs (decomposition). As such, SOC distribution broadly reflects rainfall and temperature as drivers of plant growth (Figure 1.1). Land management has a comparatively minor influence on SOC levels, and the effects can be overestimated due to erosion (Chappell et al. 2011, Badgery et al. 2014, Li et al. 2014). Broad pools of organic matter, designated as pools of organic carbon, describe the general stability in soils (Román Dobarco, Wadoux et al. 2022). These pools fall into particulate organic C (POC), which is labile and cycles rapidly through biological processes. More stable are minerally occluded forms, MAOC. This pool is an updated interpretation of humus or HUM, and useful to appreciate that the pool is not necessarily large microbially recalcitrant molecules (Lehmann and Kleber 2015). The third pool is pyrogenic OC (PyOC), commonly charcoal, previously considered as recalcitrant OC (ROC). This rephrasing from ROC is important to appreciate that PyOC is not necessarily a long-term store of SOC (Zimmerman et al. 2012, Lutfalla et al. 2017). These pools provide a useful framework to consider the cycling of nutrients, the activity of soil biology, and the relative longevity of OM in soil.

The national SCaRP project provided a snapshot of the effect on soil carbon stocks of different land management systems across Australia a decade ago (Baldock, Macdonald et al. 2013). Subsequent syntheses drew larger inferences about the broader trends and relationships between soil carbon and environmental and management factors (e.g. Rabbi et al. 2014, Rabbi et al. 2015), finding that climate and soil properties limit any positive effects of land use reversion on carbon storage. Since SCaRP, (Gray et al. 2022) modelled current C stocks and sequestration potential, Wang et al. (2018) estimated SOC stocks for the rangelands, while (Wang, Gray et al. 2022) presented possible changes C stocks under different climate scenarios. Those modelling and mapping exercises provide a valuable basis to understand possible regional SOC dynamics, though ensuring quality with the particular frameworks used, the availability of supporting data, and review of reliability are important (Biggs et al. 2022).

Figure 1.1 Modelled total soil organic carbon content, 0-5 cm (Viscarra Rossel, Chen et al. 2014).

6.2 Opportunities

Soil carbon research continues as a common theme across several topics:

- the capacity of soil to store C.
- the potential for CO_2e abatement and of an income stream from soil carbon sequestration and trading markets.
- developing measurement or modelling techniques which aim to estimate soil C stocks more cost-effectively than traditional measurement.
- the dynamics of soil carbon and the fertility, resilience, and productivity benefits that organic matter cycling provides.

Definitions

SOM – material less than 2 mm derived from organisms (plant, animal).

SOC – the carbon as part of the SOM. Brought in through photosynthesis from atmospheric CO_2.

POC –particulate organic carbon. Labile material prone to rapid decomposition.

MaOC – mineral associated organic C. Similar to the previously termed HUM, 'humic' organic carbon. Partially decomposed, considered to be more stable material.

PyOC – pyrogenic organic carbon. Previously referred to as ROC, resistant organic carbon. Predominantly charcoal residues.

CO_2 – carbon dioxide. Atmospheric reservoir for photosynthesis, and greenhouse gas.

CO_2e – CO_2 equivalent. Unit to compare the greenhouse warming potential of other gases such as methane (CH_4), nitrous oxide (N_2O) for accounting or trading purposes.

C stock – the amount of OC in the soil. SOC% multiplied by bulk density.

C flux – cycling of C through the soil from and to other pools.

Equivalent soil mass – the amount of soil used to compare between SOC stocks to account for differences in bulk density and gravel content. Note: correct sampling and bulk density is required.

The potential concentration of C in soil is understood to have an upper ceiling or envelope within which it reasonably fluctuates according to climatic conditions (Briske et al. 2013, Wiesmeier et al. 2019). The notion of the envelope is one of the balance between organic matter inputs and outputs via mineralisation, setting aside the losses due to erosion (Webb et al. 2012, Webb et al. 2013, Yang et al. 2018, Yang et al. 2023). Different environments and different soils have different ranges, though the concept holds internationally. These fluctuations are primarily driven by climate, so high inputs over good seasons can be depleted by mineralisation as soil organisms continue to cycle once the inputs (plant growth) slows. For example, Badgery et al. (2020) found that slow increases in SOC over 12 years in permanent pastures and cropping systems in central-west NSW were wholly depleted in three years of dry conditions, with the cropping systems having marginally lower levels than 16 years prior. Indeed, White and Davidson (2020) reported that the CFI Carbon Mapping Tool (2015) showed no potential to sequester SOC throughout most of Australia, and where potential does exist it is low (0.07 to 0.59 t CO_2e/ha/yr).

It is not that there is no potential to increase soil C. Some examples of opportunities include increasing from a low base, improving the stability of sequestered C by physical or chemical means, understanding processes refinements in management details, and lifting the ceiling:

- increases in SOC are possible, often with some management change to increase inputs or decrease output rate, where the SOC level can recover from a depleted state. Such increases are possible across the range of environments and soil types particularly where there is enough clay to help stabilisation (Khandakar et al. 2017, Mitchell et al. 2021), and some schemes to encourage sequestration may take advantage of these circumstances (Badgery et al. 2021). Most potential to increase SOC is broadly those soils that have been depleted, have moderate textures of loam or heavier, are in areas of 600 mm rainfall or greater, and where plant perenniality and production can be increased.
- retention of new SOM in more stable forms occurs where an adequate of nutrients in the mineralisation process and can indeed decrease the mineralisation of SOM already present in the soil (Kirkby et al. 2011, van Groenigen, van Kessel et al. 2017, Coonan et al. 2020).
- opportunities also exist where not just soil or grazing can be managed, but factors such as trees, litter and biocrusts that provide suitable microenvironments (Orgill et al. 2017).
- diversity of plant species can contribute a wider range of organic material that can slow decomposition rates and be associated with higher levels of SOC (Wilson and Lonergan 2013, Wang et al. 2017).
- most work to date has focussed on SOC in the upper 30 cm due to practicality, cost, and that covering the main area of activity of inputs and cycling. More recently, attention is turning to the possibilities of increasing SOM at depth, with potentially slower decomposition and more retention surfaces. The majority of that work has been done in cropping systems, and while increases in SOC have been observed (Harper and Tibbett 2013, Wilson and Lonergan 2013, Wu et al. 2014, Hobley et al. 2016, Minasny et al. 2017, Osanai et al. 2021, Button et al. 2022), such effects may only be short-term (Hulugalle et al. 2013) or negative (Fontaine et al. 2007).
- there are instances where the ceiling of soil C can be increased such as the addition of biochar (Weng et al. 2022), not just by the addition of C material as biochar but stabilising SOM. The priming effect though can be negative (enhancing decomposition of SOM) as well as positive (Joseph et al. 2021).

Any of the above opportunities may be explored in isolation or together, and understanding the potential is important. What may be achievable and where, what policy instruments or incentives may assist adoption, are part of that understanding (Amelung, Bossio et al. 2020). Development of measurement techniques provides scope in this exercise to efficiently identify potential areas where soil C can be increased, such as depleted soils, suitable soil types, yield gaps, trade-offs (e.g. Wang et al. 2018, Thaler et al. 2019, Žížala et al. 2019). A moderating factor too of the potential to increase SOC is that future climate scenarios place limits on the potential (Rabbi et al. 2015, Wiesmeier et al. 2019, Wang et al. 2022).

Given potential exists to manage and increase SOC levels, the social context behind any change to land management needs to be considered (Corbeels et al. 2019, Amin et al. 2023). Changes to management practices for the purpose of increasing SOC can be at the opportunity cost of production, even if temporary, so establishing a business case or a value to the co-benefits becomes important (White et al. 2018). Not many examples have been developed, but the co-benefits to soil health and condition from increasing SOM, especially from a low base, can be substantial (Ringrose-Voase et al. 1997, Meyer et al. 2015).

In the context of taking up opportunities for increasing SOC, it is important for all industries to have confidence in the integrity of policy and market instruments. It is important to not disregard the production benefits of having a 'good' level of SOM, because delving into trading invites economic comparisons to other options, and intense scrutiny of which abatement and offset options are most cost and practically effective (White and Davidson 2020, Simmons et al. 2021). This integrity is especially important for the red meat industry due to the standing emission of methane from livestock, and an area in which MLA is active (White and Davidson 2020, Glasson et al. 2022).

6.3 Gaps

With the opportunities available to increasing or managing SOC comes uncertainty around what can actually be achieved, and how to resolve apparent inconsistencies. There are several gaps in the research that MLA could support research:

- management options – compared to cropping soils, the effect of management in grazing systems in not clear due to limited data availability and large spatial variability of SOC (Wiesmeier et al. 2019).
- priming – the circumstances determining if priming is positive or negative on both labile C (Coonan et al. 2020, Joseph et al. 2021, Román Dobarco et al. 2022) and amelioration of hostile conditions (Grover et al. 2021). This is currently a particular limitation because soil testing is not commonly undertaken by graziers.
- compare and refine the modelling techniques used to assess current and potential sequestration regionally (e.g. Wang et al. 2018, Filippi et al. 2021, Gray et al. 2022, Wang et al. 2022) and nationally (e.g. McKenzie et al. 2017) to better appreciate potential storage and implications under different scenarios (Figure 6.2).
- technological development can assist in scaling investigations, for example with remote sensing applications (Sorenson et al. 2022) or new measurement/estimation techniques for soil samples (Ravansari et al. 2021).
- understanding medium to long-term cycles is important to assess changes through time. Comparative studies can be limited by circumstance, so the accumulation and monitoring of sites through time should be supported (Badgery et al. 2020, Badgery et al. 2021).

- use the information generated from research and monitoring to develop and prioritise management plans to maintain productivity and soil condition for the long term (Koch et al. 2015, Yang et al. 2023).
- the processes of potential SOC accumulation need to be extended to grazing systems. Areas for further research include soil organic matter transformations at depth, potential residence timeframes, enhancement of root growth into subsoils, scaling up the potential storage, the requirement for nutrients as part of the organic matter, and the potential effect of climate change on any of these factors (Button et al. 2022) (Figure 6.3).
- establish co-benefits of management decisions that may increase SOM levels e.g. improved productivity, better rainfall use efficiency, natural capital value.

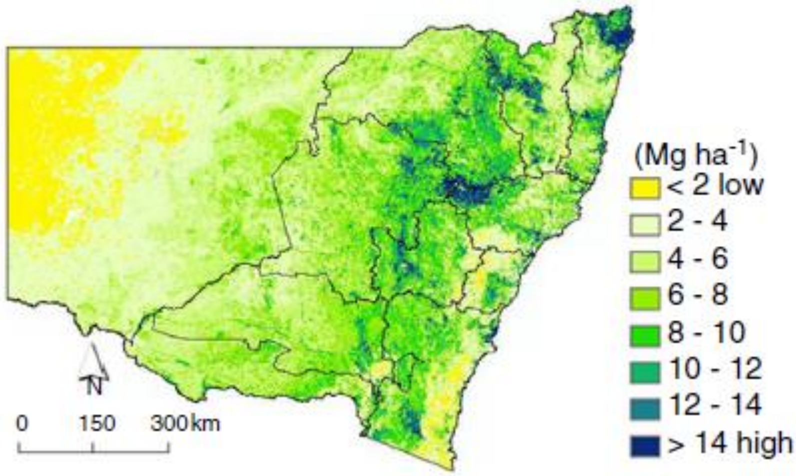

Figure 6.2. Potential increase in C stock under an extra 10% long-term vegetation ((Fig 4c in Gray, Wang et al. 2022)).

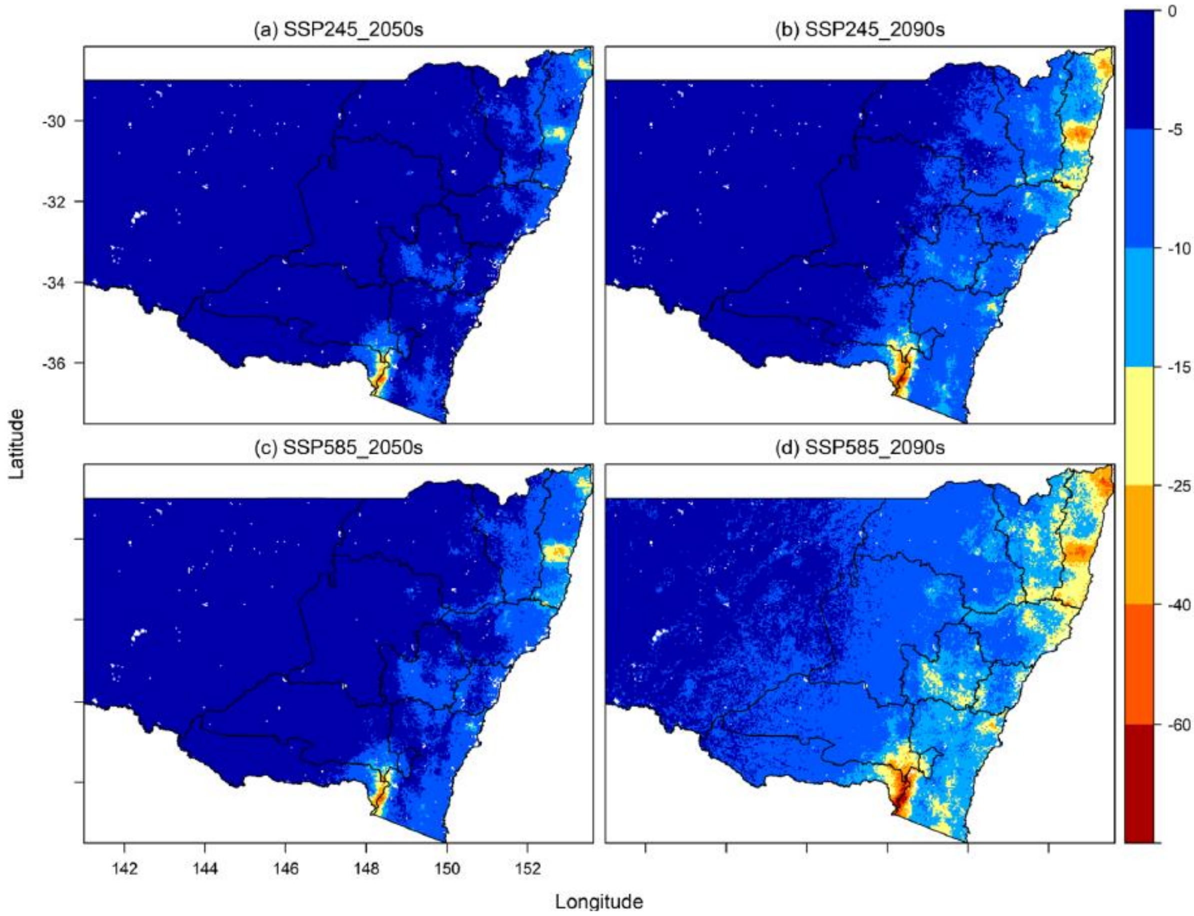

Figure 6.3. Modelled mean change in SOC stocks (t ha^{-1}) (i.e. decreases) projected for the 2050s and 2090s under different emission scenarios (SSP245, 'middle of the road', and SSP585, high emissions) compared to the baseline (1990–2019) (Fig 5 in Wang, Gray et al. 2022).

6.4 Recommendations

- Support long-term trials to assess C and nutrient dynamics over seasonal cycles to track the dynamic process in soil, including effect of priming, CNPS fertility, fractions/lability.
- Assess the capacity to increase SOC in depleted soils, recognising that depleted soils are often eroded, which leaves a poorer topsoil material that is harder to manage productively.
- Monitor soil status with correct methodologies, and use the information to actively manage for the long-term security of soil.
- Establish more 'business cases' where the profit benefit of 'good' levels of SOM/SOC (providing stability and soil functioning) can be quantified.
- Understand and promote the message that cycling is important and desirable for producers–functioning soils, nutrient cycling, active soil biology.
- Promote a rigorous system for SOC verification as the basis for any trading.

7 Natural Capital and biodiversity

Key points:

- of all the sectors of the economy, agriculture is the most dependent on natural capital. It is also one of the sectors with the greatest impacts on natural capital
- natural capital accounting focusses on the natural capital assets owned or controlled by the business – e.g. a farming property – and, just like conventional accounting, aims to collate relevant information on the state of those assets and the value of flows of benefits derived from those assets
- natural capital risk assessment focusses on any natural capital that the business impacts or depends on, regardless of ownership or control, and the consequences (risks and opportunities) for the business arising from these impacts and dependencies
- there are significant natural capital risks and opportunities for farms. Some of these opportunities may come with productivity trade-offs

7.1 What is natural capital?

Natural capital is the stock of the world’s renewable and non-renewable natural assets (natural resources and ecosystems), that yield flows of natural inputs (e.g. minerals, water and energy) and ecosystem services (e.g. biomass provisioning or pollination services) that provide benefits to people.

Historically, many of the benefits provided by nature have been ignored – taken for granted because they are perceived to be ‘free’, or priced only at the cost of their extraction, rather than their cost of replacement. This has contributed to unsustainable consumption and environmental degradation. For example, land degradation has reduced productivity across 23% of the world’s land area and 25% of all species are already threatened with extinction (IPBES, 2019).

There is now growing understanding that the economy is embedded within the environment, and that we need to manage our natural capital with at least the same diligence we devote to manufactured or financial capital. The threats posed by the loss of natural capital are significant. More than half of the world’s economic output has been estimated to be moderately or highly dependent on nature, and therefore vulnerable to its loss (World Economic Forum and PwC, 2020). This recently led the World Economic Forum to identify biodiversity loss as one of the top three risks to the global economy over the next ten years (World Economic Forum, 2020).

Soil is a vitally important natural capital asset, playing a critical role in the functioning of ecosystems, underpinning their ability to provide ecosystem services such as biomass provisioning, flood control, water purification and climate regulation. Soil is rapidly degrading at a global scale (Yang et al. 2020) and approximately 75% of Australian agricultural soils can already be regarded as being in sub-optimal condition, reducing their potential productivity (Orgill et al., 2018).

7.2 Natural capital and agriculture

Of all the sectors of the economy, agriculture is the most dependent on natural capital (NCFA and UN Environment World Conservation Monitoring Centre 2018). Agriculture is also one of the sectors with the greatest impacts on natural capital. Livestock production in particular has been singled out as “one of the top two or three most significant contributors to the most serious environmental problems, at every scale from local to global” (Steinfeld et al. 2006). Livestock grazing, plus feed crop production, occupies 30% of the ice-free land surface of the planet, accounts for 8% of global human water use and is probably the largest source of water pollution, as well as a major driver of deforestation and land degradation, biodiversity loss, and climate change (Steinfeld et al. 2006). It follows, therefore, that better management of natural capital in agriculture has the potential both to enhance the sector’s economic sustainability (by mitigating threats to critical natural capital dependencies) and to improve its environmental sustainability (by mitigating natural capital impacts).

At the level of individual businesses, there is emerging consensus that two different perspectives on natural capital are relevant for both operational management decision-making, and reporting (whether to supply chains, industry bodies, communities, lenders or investors). **Natural capital accounting** focusses on the natural capital assets owned or controlled by the business – e.g. a farming property – and, just like conventional accounting, aims to collate relevant information on the state of those assets and the value of flows of benefits derived from those assets. The United Nations System of Environmental-Economic Accounting (SEEA) framework provides a high-level standard for natural capital accounting at the national level (United Nations et al. 2014, United Nations 2021) that firms are now beginning to adapt for corporate natural capital accounting (Eftec et al. 2015, Forestry England 2019, Forico 2021).

Natural capital risk assessment, on the other hand, focusses on any natural capital that the business impacts or depends on, regardless of ownership or control, and the consequences (risks and opportunities) for the business arising from these impacts and dependencies. High-level guidance includes the Natural Capital Protocol (Natural Capital Coalition, 2016) and the Taskforce on Nature-related Financial Disclosures (TNFD) Nature-related Risk & Opportunity Management and Disclosure Framework (TNFD 2022). Specific guidance has also been developed for natural capital risk assessment in agriculture (Ascui and Cojoianu 2019b); and there is a growing literature on how to operationalise natural capital risk assessment (Allianz 2018, Cojoianu and Ascui 2018, NCFA and PwC 2018, NCFA and UN Environment World Conservation Monitoring Centre 2018, Ascui and Cojoianu 2019a, 2020, World Economic Forum and PwC 2020, Ascui et al. 2021, CISL, 2021, Smith et al. 2021, WWF, 2021). Finalised versions of draft nature-related and sustainability-related disclosure standards are expected to be issued by the International Sustainability Standards Board (ISSB) and the TNFD in 2023 (ISSB 2022, TNFD 2022), and leading agricultural companies such as AACo are already preparing for future TNFD-aligned natural capital risk and opportunity disclosures (AACo 2022).

7.3 Natural capital risks and opportunities for Australian livestock production

High-level materiality assessments of natural capital risks for Australian beef and sheep production (Ascui and Cojoianu 2019a, Ascui et al. 2021, Ascui 2023a, 2023b) have highlighted that these industries are exposed to a combination of significant impact and dependency risks. Typically, the most highly material natural capital dependency risks are related to water availability, water quality, temperature, extreme weather, soil quality, fertiliser use (mainly for Southern beef production and sheep production), weeds, and pests and diseases. The most highly material natural capital impact risks are associated with water quality (in sensitive catchments), fire (mainly for Northern beef production), contamination and waste, biodiversity, weeds, pests and diseases, and greenhouse gas emissions. These assessments did not include the impacts or dependencies associated with irrigated production, feedlots, or the production of non-pasture feed and supplements.

The flip side of these risks is that there are significant opportunities to improve both economic and environmental performance through improved management of these impacts and dependencies. Opportunities also exist in product differentiation and participation in new markets, such as carbon credits and biodiversity offsets. Elements of natural capital risk management are already embedded in best practice farm management practices and codified in industry sustainability frameworks (MLA 2021, 2022, Sheep Sustainability Framework, 2022), and as such, can be expected to increasingly inform expectations from supply chains and consumers. Agricultural lenders and investors are increasingly interested in understanding agricultural businesses' natural capital management so that they can price their financial contributions accordingly (Henry 2016). Over time, this is expected to lead to increased availability and/or lower cost of capital for investments in more sustainable agriculture.

Where opportunities for the red meat industry do exist, trade-offs between production and some aspects of biodiversity can also occur. Clearly, clearing of native vegetation for agriculture has a substantial direct effect on several attributes of natural capital. Once operational, ongoing management of developed land is critical to maintain natural capital and the ecosystem services to agriculture (Eldridge and Delgado-Baquerizo 2017). Examples of opportunities to balance production include effective management of grazing intensity that increase perennial ground cover and plant diversity yet can come at the cost of decreasing invertebrate diversity, providing an example of trade-offs between natural capital and production (Waters et al. 2017). Soil compaction due to heavy grazing by livestock in rangelands can decrease the activity of soil organisms (Neilly and Schwarzkopf 2018) and decrease infiltration and seedling recruitment (Neilly et al. 2016). While much of the area of alpine soils is in national parks, the short growing season for recovery means the services they provide to the ecology, hydrology and potential C storage of the region are vulnerable to disruption (Wilson et al. 2022). By comparison, the historical context is important for grazing, in that problems caused by past practices may be recovered with judicious management decisions, e.g. scalded soils or landscape function may be ameliorated through stock management (McDonald et al. 2018).

Substantial opportunities in natural capital exist for agricultural businesses and systems. Offsetting greenhouse gas emissions through soil carbon sequestration is one area garnering significant attention (White and Davidson 2020, White et al. 2021). Other refinements to production systems include decreasing the methane footprint of livestock production with temperate pasture mixes suited to soil types and conditions (Badgery et al. 2023). Increasing or accounting for SOC or other practices such as managing creek lines and farm dams, enhancing native remnant or revegetation, or other landscape features like rocky outcrops also provide avenues to increase production and natural capital value on-farm (Williams 2017, Richards and Vollebergh 2018, Dobes et al. 2021, Lindenmayer et al. 2022). Focussing on ecological restoration without compromising agricultural production, recent analysis has calculated 30% of the pre-European extent of most Australian native vegetation groups in every bioregion could be restored and conserved (Mappin et al. 2022). This analysis found the improvements would be achievable without compromising food production and with benefits to soil health.

7.4 Gaps

It is vital that the systems and processes developed and used to manage natural capital be robust. By way of example, the attention paid to the potential for income streams from soil C trading, and indeed confirmed atmospheric C sequestration, may overlook the integrity of C trading systems. Confidence in the trading and offsets systems in soil carbon were investigated by Oldfield et al. (2022), though questions remain.

The opportunities given above still contain sometimes conflicting or competing demands of agricultural production with natural capital. Establishing a natural capital system will be central to resolving those conflicts and prioritising management options. Doing so will necessarily involve value judgements, so Ascui and Cojoianu (2019) call for urgent research in both critical and empirical social science research to ensure that natural capital is managed diligently in what they see as the relatively short time before that natural capital is irrevocably depreciated. For the red meat industry, systematic approaches to assessing natural capital have been proposed for the sheep (Ascui et al. 2021) and beef (Ascui and Cojoianu 2019) industries. These approaches were developed as a risk profile for the finance industry, though principles still apply to the farm level. The proposed approaches use practicable indicators to assess dependency risks. However, challenges remain in respect of establishing risk thresholds for most of the indicators and quantifying the possible impacts of falling below those thresholds. With resolution to those challenges, further challenges to implement a system include the complexity and interconnectedness of natural capital attributes, the availability and cost of suitable data, and analytical capacity.

7.5 Recommendations

We are not yet able to give specific recommendations for producers in this developing area of study and application. We would however draw attention to several points raised in this review:

- Acknowledge the dependency of agriculture among all industries on natural ecosystems and resources – soil, biodiversity, ecosystems – increasingly referred to as natural capital.
- Commit to better management of natural capital in agriculture for the potential economic and environmental sustainability.
- Analyse the opportunities presented through the TNFD nature-related risk and opportunity framework, particularly recent local publications for sheep (Ascui et al. 2021) and beef (Ascui and Cojoianu 2019) industries.
- Take advantage of the forthcoming nature-related and sustainability-related disclosure standards from the ISSB and the TNFD in 2023, and leverage throughout the industry the lead taken by AACo to prepare natural capital risk and opportunity disclosures.
- Assess, engage with research, and promote the potential to reinforce the industry's sustainability through incorporating natural capital management of the key indicators of soil, biodiversity and ecosystems.
- Ensure robust natural capital accounting and risk assessment systems are implemented.

8 Role of soils in reporting on supply chains

Key points:

- there are many international, European, and Australian soil initiatives which have the potential to impact or be used in future market access agreements and supply chain identification
- currently, the Australian red meat industry only aligns with the United Nations Sustainable Development Goals
- MLA is able to influence the red meat industry in adopting more of these initiatives and facilitating adoption at a farm, regional and industry scale.

8.1 International soil initiatives

There are several reporting systems used internationally to monitor and assess the health of soils. These include:

8.1.1 The Global Reporting Initiative (GRI)

The Global Reporting Initiative (GRI) is a framework which provides guidelines and indicators for organisations to report on their economic, environmental, and social performance. It was established in 1997 by the United Nations Environment Programme (UNEP) and the Coalition for Environmentally Responsible Economies (CERES) to encourage companies and organisations to be more transparent about their sustainability impacts and to promote sustainable development and is widely used by businesses, governments, and other organisations around the world to assess and communicate their sustainability performance to stakeholders. The framework includes a set of standardized sustainability indicators and disclosures that organisations can use to report their sustainability performance and is updated periodically to reflect new developments and stakeholder feedback. The GRI is widely recognized as a leading standard for sustainability reporting, and its reporting framework has helped to promote transparency, accountability, and sustainable development across a range of industries and sectors.

8.1.2 The United Nations Sustainable Development Goals

The United Nations Sustainable Development Goals (SDGs) are a set of 17 goals designed to guide and coordinate international development efforts between 2015 and 2030. They were adopted by all United Nations Member States in 2015 as part of the 2030 Agenda for Sustainable Development. The 17 SDGs are:

1. No Poverty
2. Zero Hunger
3. Good Health and Well-being
4. Quality Education
5. Gender Equality
6. Clean Water and Sanitation
7. Affordable and Clean Energy
8. Decent Work and Economic Growth

9. Industry, Innovation and Infrastructure
10. Reduced Inequalities
11. Sustainable Cities and Communities
12. Responsible Consumption and Production
13. Climate Action
14. Life Below Water
15. Life On Land
16. Peace, Justice and Strong Institutions
17. Partnerships for the Goals

The Australian Beef Sustainability Frameworks aligns with SDGs 2, 5–12–15, and 17 (see section 8.3.1). The Australian Sheep Sustainability Framework has a stated alignment with SDG 2 – Zero hunger (see section 8.3.2)

From a soil perspective, there is perhaps better alignment with the Life on Land goal, (SDG 15) which aims to protect, restore and promote the sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, halt and reverse land degradation, and halt biodiversity loss. It has some specific targets which could align well with MLA research, viz: *Enhancing ecosystem resilience, adaptation to climate change, and promoting sustainable agriculture and agroforestry practices.*

8.1.3 The Sustainable Agriculture Initiative (SAI) Platform:

The Sustainable Agriculture Initiative (SAI) Platform is an initiative that aims to promote sustainable agriculture practices worldwide. The SAI Platform was established in 2002 by a group of food and beverage companies, in collaboration with the United Nations Environment Programme (UNEP) and the Food and Agriculture Organisation (FAO) of the United Nations. The platform aims to align stakeholders from across the food and agriculture supply chain, including farmers, processors, retailers, NGOs, and academics, to develop and promote sustainable agriculture practices. The Sustainable Agriculture Initiative has an Australian branch which is a member-based organisation claiming to promote and implement sustainable agricultural solutions across the supply chain.

The platform has indicators covering a range of sustainability issues, including soil health, water use, biodiversity conservation, greenhouse gas emissions, and social impacts. It also provides guidance and support to its members to help them implement sustainable agriculture practices and improve their sustainability performance.

Soil health is an important aspect of sustainability in agriculture, and the Sustainable Agriculture Initiative (SAI) Platform incorporates soil health into its sustainability framework. The SAI Platform's sustainability indicators cover a range of soil-related issues, including soil management, soil conservation, and soil fertility.

The SAI Platform's soil-related indicators (Kuneman and Fellis 2014) include:

- soil organic matter (% organic matter in the top 30cm).
- soil erosion expressed as a score between 0 and 14.
- soil acidity expressed as pH in water.

8.1.4 The Global Soil Partnership (GSP)

The Global Soil Partnership (GSP) is a global initiative launched by the Food and Agriculture Organisation (FAO) of the United Nations in 2011 to promote sustainable soil management and conservation. It brings together national governments, non-government organisations, the private sector, research institutions, and other stakeholders to develop and implement programs and policies to protect and sustainably manage soils around the world.

The GSP is guided by a steering committee that oversees its work and is supported by a secretariat based at the FAO headquarters in Rome. It collaborates with a range of partners, including national and regional soil initiatives, to achieve its goals. Australia is a member of the GSP and actively participates in its activities and programs. Other Australian partners include CSIRO, the Soil CRC and various universities. Australia has a National Soil Research, Development and Extension Strategy, which is aligned with the objectives of the GSP. The strategy is overseen by the Australian Soil Network, currently co-chaired by the NSW Department of Primary Industries and the GRDC.

8.1.5 The World Business Council for Sustainable Development (WBCSD)

The World Business Council for Sustainable Development (WBCSD) is a global CEO-led organisation that brings together businesses, governments, and other stakeholders to promote sustainable development. It was founded in 1995 and is based in Geneva, Switzerland. It focuses on three key areas: energy and climate, circular economy, and sustainable cities and mobility. It is made up of over 200 member companies from a range of sectors, including energy, agriculture, chemicals, and consumer goods. Its members commit to working towards sustainability goals and collaborate on projects and initiatives to drive progress towards these goals. The WBCSD also works with governments, NGOs, and other stakeholders to promote sustainable development.

Initiatives and programs created by the WBCSD include:

- the Livestock Environmental Assessment and Performance (LEAP) Partnership
- the Sustainable Agriculture Landscapes (SAL) initiative, and
- the Circular Bioeconomy Alliance (CBA) which includes sustainable livestock production and the use of livestock waste for energy and other purposes.

8.1.6 The Global G.A.P. Standard

The Global G.A.P. (Good Agricultural Practice) Standard is a set of voluntary, third-party certification standards for agricultural production systems. It covers a range of agricultural products, including livestock and sets out requirements for farm management, environmental and social sustainability, food safety and quality, and animal welfare. It also includes specific requirements for different production systems, such as integrated pest management, irrigation, and fertilization.

To become certified under the Global G.A.P. Standard, farms must undergo an audit by an independent certification body. The certification process involves an assessment of the farm's compliance with the Standard's requirements, as well as an evaluation of its management systems and documentation.

8.1.7 ISO 14001

ISO 14001 is a recognized standard for environmental management systems (EMS). It was developed by the International Organisation for Standardization (ISO). To become certified under ISO 14001, an organisation must develop and implement an EMS that meets the requirements of the standard. This includes setting environmental objectives and targets, establishing processes to monitor and measure environmental performance, and regularly reviewing and improving the EMS. There is a potential for individual farms, co-operatives or the entire livestock industry to create ISO 14001 certification.

The standard provides a framework for livestock producers to identify and manage their environmental impacts, comply with applicable environmental regulations, and continually improve their environmental performance. It can identify and manage impacts on soil health, comply with applicable regulations related to soil protection, and continually improve their environmental performance with regard to soil health. Under an ISO 14001 certification system, the livestock industry could:

- identify and assess soil-related risks and impacts associated with farming practices, such as soil erosion, soil degradation, and soil contamination.
- develop and implement soil management plans and procedures to reduce soil-related impacts and improve soil health, such as improving soil organic matter, and minimising the use of chemical inputs.
- establish and monitor soil health metrics, such as soil organic matter content, soil nutrient levels, and soil structure.
- engage with stakeholders, such as MLA, local communities, environmental organisations, and regulatory agencies, to build trust and address concerns related to soil health impacts.

8.2 European soil initiatives

While Europe is committed to international initiatives, it also has some specifically European initiatives which should be considered if trying to enter European markets.

8.2.1 The Common Agricultural Policy (CAP) of the European Union

The Common Agricultural Policy (CAP) is a European Union policy that provides financial and other support to European farmers and rural communities. One of the key objectives of the CAP is to promote sustainable farming practices that protect the environment and support rural development. Soil health is an important aspect of this objective, and the CAP includes a number of measures to promote soil health.

Under the CAP, farmers can receive financial support for adopting sustainable land management practices that promote soil health. It also includes regulations aimed at protecting soil health. For example, the CAP requires farmers to comply with minimum standards for soil conservation and management, including measures to prevent soil erosion, maintain soil fertility, and avoid soil contamination. It also includes monitoring and reporting requirements related to soil health. Member states are required to report on soil erosion and organic matter content, and to develop national action plans for soil conservation and management.

These practices can also increase the cost of production for European farmers, which can make it more difficult for them to compete with lower-priced imports from countries with less stringent environmental regulations. Consequently, the barriers for exporting into European countries are likely to increase, resulting in increased compliance requirements from Australian farmers.

8.2.2 The EU Soil Framework Directive

The EU Soil Framework Directive is legislation enacted by the European Union in 2006. The directive aims to establish a framework for the protection of soil, water, and carbon storage, among other functions. Under the Directive, member states are required to identify and map their soil resources and to establish measures to protect and manage these resources. Member states must also develop national soil monitoring programs to assess soil quality and identify threats to soil health. In addition, the directive requires member states to establish a soil information system to provide information and support decision-making related to soil management.

By establishing common principles and objectives for soil protection and management, the directive aims to ensure that the soil resources in the EU are used in a sustainable manner. It also promotes the sharing of information and best practices related to soil management. Like the CAP, there is a likelihood that the standards adopted in the EU Soil Framework Directive could become a reporting and data quality standard demanded of countries trying to export into the EU.

8.2.3 The European Livestock and Meat Tracing System (ELMTS)

The European Livestock and Meat Tracing System (ELMTS) is a system introduced in 2010 and used by the European Union (EU) to:

- trace the movement of livestock and meat products within the EU, and
- enhance food safety and improve traceability throughout the meat supply chain.

The ELMTS has close similarities with Australia’s National Livestock Identification System so Australia is likely to be able to comply. However, this increased traceability is likely to increase demands on individual farms for environmental stewardship, potentially leading to environmental reporting requirements for farms.

8.3 Australian Red Meat Initiatives

8.3.1 The Australian Beef Sustainability Framework.

The Australian Beef Sustainability Framework (Anon 2022a) is a transparent framework tracking best practice in the beef industry. It has identified 24 priority issues under four themes (Figure 8.1).

Figure 8.1: Australian Beef Sustainability Framework priorities (Anon 2022a).

While soil health is a stated priority under environmental stewardship, soils also have a role in the best animal care theme (particularly in regard to nutrient deficiencies) and economic resilience where soil knowledge is essential to climate change resilience, productivity and profitability. Reporting on soil management may also contribute to market access and soils will also play an essential role in GHG emissions and carbon capture.

The Beef Sustainability Framework addresses a number of the United Nations Sustainable Development goals: 2 (zero hunger), 5 (gender equality), 6 (clean water and sanitation), 7 (affordable and clean energy), 8 (decent work and economic growth), 9 (industry, innovation and infrastructure), 10 (reduced inequalities), 12 (responsible consumption and production), 13 (climate action), 14 (life below water), 15 (life on land), and 17 (partnerships for the goals).

8.3.2 The Sheep Sustainability Framework

The Sheep Sustainability Framework was launched in April 2021 (Anon 2022b). It reports data on industry progress against key sustainability priorities across the Australian sheep industry's domestic value chain. To progress the sustainability framework, the Sheep Sustainability Framework Strategic Plan 2022-2024 (Anon 2022c) was released in 2022. The framework has 21 priorities grouped under nine focus areas which sit in four themes (Figure 8.2).

Theme	Focus Area	Priority
Caring for our sheep		
	1. Animal care and handling	1.1 Reduce, refine and replace painful husbandry practices
		1.2 Implement best practice sheep management
		1.3 Ensure humane processing and on-farm euthanasia
	2. Animal health	2.1 Prevent and manage disease
Enhancing the environment and climate		
	3. Environment	3.1 Improve natural resource management
		3.2 Responsible environmental practices
		3.3 Encourage biodiversity
	4. Climate change	4.1 Reduce net greenhouse gas emissions
		4.2 Adapt to a changing climate, including extreme weather events
Looking after our people, our customers and the community		
	5. Health and safety	5.1 Improve industry safety culture
		5.2 Improve our people's health
	6. Capacity building	6.1 Support and grow workforce
		6.2 Encourage workforce diversity
	7. Contribution to community	7.1 Enhance community trust
		7.2 Deliver products that customers demand
Ensuring a financially resilient industry		
	8. Profitability, productivity and investment	8.1 Maintain or increase industry profitability
		8.2 Maintain or increase contribution to the Australian economy
		8.3 Increase productivity
		8.4 Encourage innovation
	9. Market access	9.1 Ensure positive market positioning and access
		9.2 Guarantee product integrity and safety

Figure 8.2: Themes, focus areas and priorities of the Australian sheep Sustainability Framework (Anon 2022b)

Soil is not explicitly mentioned in any of the priorities; however, it is described in the Environment and Climate Change focus areas. Soil issues could also be included in the animal care and handling, Profitability, productivity and investment, and market access focus areas.

The Sheep Sustainability Framework aligns with Goal 2 of the United Nations Sustainable Development Goals – Zero hunger, which states: *"By 2030, ensure sustainable food production systems and implement resilient agricultural practices that increase productivity and production, that help maintain ecosystems, that strengthen capacity for adaptation to climate change, extreme weather, drought, flooding and other disasters and that progressively improve land and soil quality".*

8.3.3 Red Meat 2030

Red Meat 2030 (Red Meat Advisory Council 2019) was developed to support the industry to respond to risks and harness opportunities as they emerge. Red Meat 2030 has a vision of *"doubling the* *value of red meat sales as the trusted source of the highest quality protein".* The priorities are pictured below (Figure 8.3):

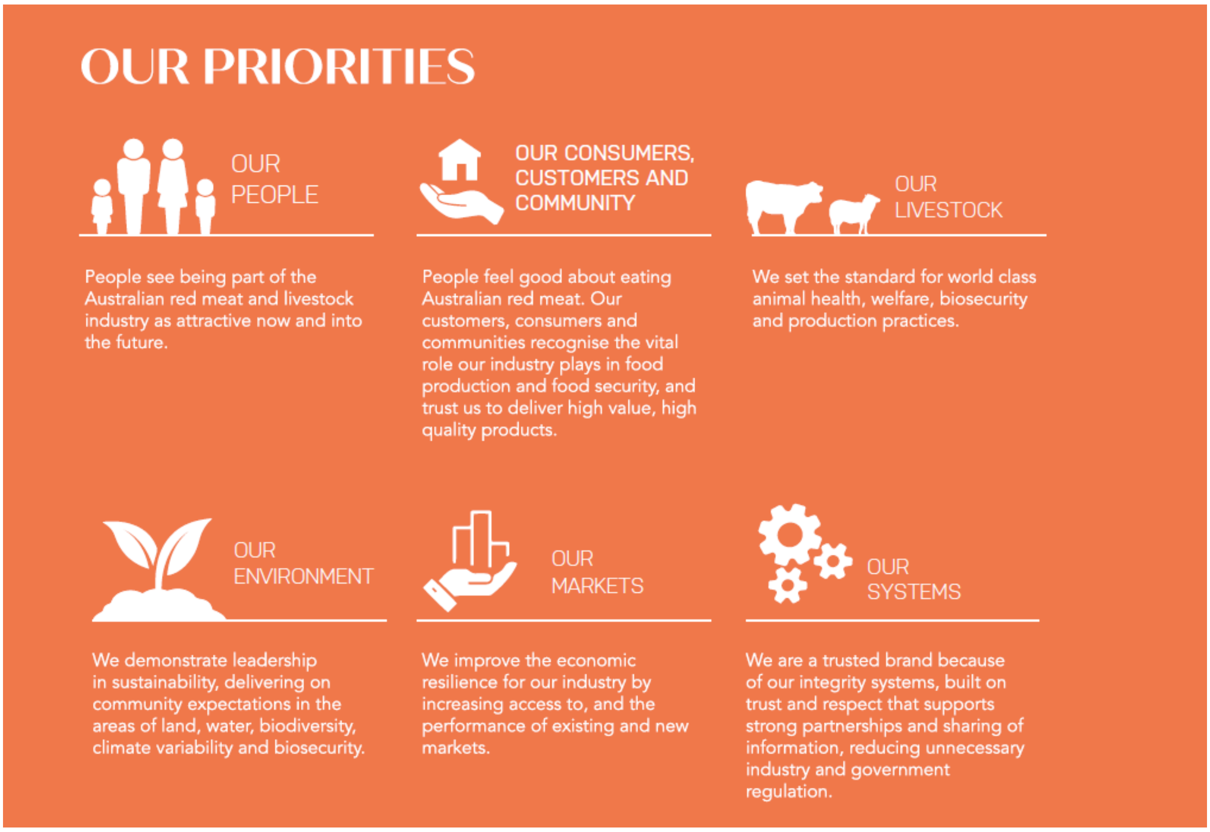

Figure 8.3: Red Meat 2030 priorities (Red Meat Advisory Council 2019)

While soil is not mentioned in the description of the six priorities, within the document, soil is mentioned in both "Our livestock" and "Our environment" objectives when providing more detail, meaning that soil is important from both a productivity and sustainability perspective in Red Meat 2030.

8.4 Australian Soil Initiatives

8.4.1 The National Soil Research, Development and Extension (RDE) Strategy.

The National Soil RDE Strategy is a 20 year strategy with a vision of 'securing Australia's soil for profitable soils and healthy landscapes' was released in 2014. It was developed under the National Primary Industries Research, Development and Extension Framework. The stated goals of the strategy are to:

- improve effectiveness of co-investment to generate and apply new knowledge.
- improve quality, availability and access to soil data and information.
- improve communication and exchange of soil knowledge.
- adopt a national approach to building future skills and capacity.
- collaborate on development and use of physical infrastructure.

The Australian Soil Network (ASN) is a collaboration between government, industry and research organisations that aims to promote the sustainable management and use of Australia's soils through the implementation of the Soil RDE Strategy.

8.4.2 The National Soil Strategy

The Australian National Soil Strategy sets out how Australia will value, manage and improve its soil for the next 20 years. It was released in May 2021. It is overseen by the National Soil Strategy Implementation Steering Committee who are overseeing the development of the National Soil Action Plan (to be released in 2023) which has significant investment into soil health. The stated goals of the National Soil Strategy are:

- prioritise soil health.
- empower soil innovation and stewards.
- strengthen soil knowledge and capability.

The National Soil Package is a $214.9 million funding package including $196.9 million in new funds over four years to implement the National Soil Strategy. The National Soil Strategy also has close links with the National Soil Advocate.

8.4.3 Case Study: The better cotton initiative and cotton traceability

The Better Cotton Initiative (BCI) is a program designed to promote the sustainable production of cotton in Australia. The initiative was established in 2015 and is managed by Cotton Australia, the peak industry body for Australia's cotton industry.

The BCI aims to improve the sustainability of cotton production by promoting the adoption of best management practices related to soil health, water use, pest and disease control, and other aspects of crop management. To qualify for BCI, Australia's cotton growers must reach full certification in the industry's myBMP (Best Management Practices) program which involves meeting over 300 criteria for full certification. The initiative also provides support for growers to implement these practices, including training and technical assistance.

The BCI aims to improve the sustainability of cotton production in Australia and increase the market demand for sustainable cotton products. The initiative also helps to support the long-term viability of Australia's cotton industry by promoting sustainable and productive farming practices.

In the 2019 season:

- an estimated 157 Australian cotton farms opted in to BCI, all holding full certification in the myBMP (Best Management Practices) program.
- an estimated 57,421 hectares of Australian cotton were produced as Better Cotton, equating to 19.6% of total area.
- an estimated 102,723 tonnes of Better Cotton lint was produced in Australia (https://australiancotton.com.au/supply_chain/how-much-better-cotton-bci-is-grown-in-australia).

The Australian Cotton Industry has also worked hard to improve cotton traceability. To carry the Australian Cotton Mark, there are minimum traceability requirements, enabling a consumer to identify which farm and which paddock the cotton a garment is made of came from (Figure 8.4). Cotton Australia places the onus around traceability of Australian cotton on the brands and retailers making the claim, and also requires traceability evidence as part of the Application to Use the Australian Cotton Mark. The figure below shows the minimum traceability required to use the Australian cotton mark.

Australian Cotton Mark Traceability Checklist

MINIMUM TRACEABILITY REQUIREMENTS

This checklist is for textiles suppliers in relation to orders made from Australian cotton that must be kept physically separated through the supply chain from the production of yarn, to fabric and finished products.

Please ensure ALL of this documentation is provided in order to meet the minimum traceability requirements of the use of the Australian cotton marks(s).

Spinning Mill

- ☐ Signed and dated declaration *(template provided by Cotton Australia)*
- ☐ Australian Cotton Bale numbers used to make yarn *(provided with cotton shipment)*
- ☐ Certificate of Origin *(provided with cotton shipment)*
- ☐ Purchase Order OR Invoice to show transaction between cotton merchant/shipper and spinning mill

Fabric Mill

- ☐ Signed and dated declaration *(template provided by Cotton Australia)*
- ☐ Yarn Purchase Order OR Invoice to show transaction between fabric and spinning mill.

Cut and Sew Factory

- ☐ Signed and dated declaration *(template provided by Cotton Australia)*
- ☐ Fabric Purchase Order OR Invoice

All of this evidence must be provided before an application will be approved.

☑ Documents must be correctly signed and dated and submitted in English

☑ Please check documents meet these requirements BEFORE submitting them

Figure 8.4: The Australian Cotton Mar traceability Checklist (Australian_Cotton_Minimum_Traceability_Requirements-1.pdf (australiancotton.com.au) accessed 26 May 2023)

8.5 Recommendations

- Identify potential international, European and other soil reporting systems which may be used in quality frameworks in future reporting scenarios.
- Create an enduring dialogue with the Red Meat Advisory Council to inform and influence how these reporting systems align with the Sheep and Beef Sustainability Frameworks, and Red Meat 2030.
- Investigate a reporting framework for the red meat industry to align with soil and other environmental reporting issues.

9 Monitoring, extension, and adoption

Key Points:

- only 25-30% of producers participate in soil testing, and this has remained stable for last 20 years
- key reason for soil testing is pH and fertiliser assessments
- many producers report using observation rather than laboratory analysis to assess soil health
- how soil health is monitored depends on the scale. At the national and regional scale there is often a focus on extent of land degradation. At the local scale, specific soil indicators are used
- score card assessments are useful tools to compare local changes to soil indicators in the same paddock over time or assess the soil health capacity compared to a good local reference soil
- there is a vast quantity of soil extension information available across many platforms (print, online, training courses, workshops, YouTube) offered by industry, government, technical associations and CRCs, including the MLA Healthy Soil Hub
- increasing producers' access to, and use of soil information increases direct engagement of producers, especially when interactive platforms assess the capacity or benchmark their soil result
- the Understanding Producer Adoption (UPA) framework combines key learning from the 3 case studies

9.1 Monitoring

Lobry de Bruyn and Andrews (2016) reviewed how producers use soil information for soil health management. They found that in the last two decades, the level of producer participation in soil testing has remained steady across Australia and USA with only 25-30% undertaking soil analysis. Assessing fertiliser requirement and pH are the key reasons identified for soil sampling. However, many producers use observation instead of laboratory testing to assess soil health. Whilst observation is valuable, there may not be sufficient information to know what changes to make to improve soil condition and health.

At the national and regional scale, soil health is often measured by the extent of land degradation (erosion, acidity, carbon) than by subtle variations in soil properties which are more relevant at the local scale. Without monitoring of these key soil health indicators, it is difficult to determine trend changes and likelihood of deterioration is possible.

9.1.1 Soil health scorecards – are they useful?

A soil health card is a field tool for assessing soil health and identifying the underlying issues. Often developed with soil conservation in mind by industry, extension agents and producers they are used to provide local assessment of soil health and provide valuable talking points at field days. With our interest in monitoring changes to soil properties over time, score cards are used by governments to assess the current and historical trends in time in relation to soil management practices (Guo 2021).

As discussed in Section 3.2.1, there is difficulty in creating a soil health index as different soils, climate and regions will require different indicators to be applicable to the system and a weighting system would need to be developed to ensure the index is comparable at larger than regional scales. However, a score card is very useful at the local scale to compare change in indicators over time or soil health capacity compared to a good reference soil.

A number of score card assessments have been developed and are shown in Table .

Table 9.1. Examples of soil health or management manuals or scorecards outside of MLA

Body	Name	Module	Link	Year
Australian				
NSW DPI	SoilPak	Dryland farmers on red soil of Central WNSW	SOILpak - dryland farmers on the red soil of Central Western NSW	1998
Terrain NRM	Soil Health	Tropical Soils: A guide to soil health	Soil Health: Supporting Rural Industries in the Wet Tropics (terrain.org.au)	2022
Soil Quality Australia	Soil Quality Australia	Benchmarks	https://www.soilquality.org.au/.	2014
Agriculture Bureau of SA	Better Soils		Better Soils Modules Index (soilwater.com.au)	1997
International				
Cornell University	Cornell Soil Health		Manual | Cornell Soil Health	2016
United States Department of Agriculture USDA	Soil health assessment	Soil quality indicator sheets	https://www.nrcs.usda.gov/conservation-basics/natural-resource-concerns/soils/soil-health/soil-health-assessment	2015
NZ Graham Shepherd	Visual Soil Assessment	Pastures - Part 1 Pastures - Part 2	pasture_vol1_2011.pdf (fao.org) 03-Folder.indd (fao.org)	2011 2011

Healthy Soils – Soil Health for Productive Landscapes Tools and systems for assessing soil health \| VRO \| Agriculture Victoria evaluated a number of soil health and decision support tools including the USDA and the NSW Northern Rivers Soil Health Card and is a good source of information for further reading.

9.1.2 Common Soil Health Indicators

As discussed in 3.2.1 Soil Health and Sustainability, there are many analytical tests and observational assessments that can be used to assess soil health. The difficulty can be in choosing the most appropriate test for the soil type, soil constraint and the management system.

Table 9.2 compiles soil assessments based on work by Lehmann et al. (2020), Guo (2021), Vogel et al. (2019) and the scoping report “Soil indicators for livestock grazing systems performance”. This provides a summary of key soil health indicators, their relevance and confidence in the assessment to provide reliable measures and good interpretation over time, and what soil function the indicator is measuring.

Tables 9.2 details tests or observations and the in-field or laboratory methods that can be used to assess soil categories of interest. Those in bold are the simplest or commonly used indicator. Tables 9.4 and 9.5 determine assessments based on the soil constraint of interest.

Table 9.2. Tests and observations that can be used as soil health indicators identifying their relevance (Lehmann et al. 2020), confidence (Guo 2021) and measure of soil function.

						Soil function				
		Test or Assessment	**Laboratory or In-field**	**Relevance (Lehmann et al 2020)**	**Tier (Guo 2021)**	**Biomass production**	**Nutrient cycling**	**Water storage**	**Biodiversity**	**GHG Mitigation**
Physical Measures	Site and Soil Description	Temperature, Slope	I							
	Morphological characteristics	Soil colour, topsoil and rooting depth	I							
		Mineralogy	L							
	Soil capacity	Texture	I, L	r	1					
	Soil structure and stability	Structure, aggregate stability, slaking/dispersion	I, L	i, s, r	2					
	Soil porosity	Bulk density	I, L	i, s, e, r	1					
	Soil Strength	Penetration resistance	I	i, s, e, r						
	Water movement and storage	Water infiltration, conductivity	I, L	i, s, r	1					
Chemical Measures	Soil reaction	pH, Salinity (EC)	I, L	i, s, e, r	1					
	Macronutrients	Available and Total N, P, K, S	L	i, s, e, r	1					
	Carbon	OCwb,	L	i, s, e, r	1					
		Total C	L	i, s, e, r	2					
	Micronutrients	Trace elements	L		1					
	Base cations	Ca, Mg, Na, K, Al	L							
	Soil capacity	Cation exchange capacity	L	i, s, e, r	1					
	Soil stability	Sodicity	I, L	i, s, e, r	2					
Biological Measures	Nutrient release	Enzyme activity	L	i, s	2					
		Potentially mineralisable N and C	L	i, s, r	1					
	Microbial activity	Soil respiration	I, L	i, s						
		Cotton strip test	I	i						
	Microbial biomass and community	Microbial biomass	L	s, r	3					
		Microbial diversity	L	i, s, e, r	3					
		Microbial composition	L		3					
	Rhizobial symbiosis	Nodule counts and distribution	I, L		2					
	Macrofauna community and abundance	Earthworms, insects, spiders, springtails etc	I	i, s, r						
Proxy measures	Productivity	Biomass / yield	I	i, s, e, r	1					
		Fractional cover	L		3					
	Weed	Plant indicators	I	i, s, e						
	Disease	Pathogens	I, L	i						
	Pest	Pests	I, L	i						

Table 9.2 abbreviations

Lehmann et al. 2020 Soil health indicators are:

- *informative/interpretational (i) – inference of management*
- *sensitive (s) – rapid and large changes consistent*
- *effective/practical (e) – easy, reliable, cheap, quick*
- *relevant/conceptual (r) – related to soil function*

Texture and soil depth do not change readily and are not managed. They are also considered capability indicators.

Guo 2021 defined tiers of soil health indicators as:

- *Tier 1 – effective soil health indicator, regionally defined, known thresholds, responsive to land use management*
- *Tier 2 – relevant to soil health, ranges and thresholds known for some regions, improvement strategies can be suggested, require further research and validation*
- *Tier 3 – potential to be a soil health indicator, research required before confidence in measurement and interpretation*

Vogel et al. 2019 identified soil attributes that are affected by inherent soil and site characteristics (orange) and management practices (green).

Categories based on the scoping report "Soil indicators for livestock grazing systems performance" developed for MLA.

Table 9.3. Assessments to determine soil health. Those in bold are recommended 'simple' assessments.

	Category	Test or Assessment	In field	Laboratory
Physical Measures	Site and Soil Description	Temperature		BOM
		Slope	Visual	
	Morphological characteristics	**Soil colour**	Visual (Munsell)	
		Mineralogy		X-ray diffraction
		Topsoil depth	Visual (measure)	
		Horizon depth	Visual (measure)	
	Soil capacity	**Texture**	Hand ribbon	Particle size analysis
	Soil structure and stability	**Soil structure**	Visual: friable, hard, restrictions?	
		Aggregate stability		Wet sieving
		Slaking / dispersion	Visual (Emerson Dispersion)	
	Soil porosity	Bulk density	Intact core (weight/volume)	
		Pore size distribution	Visual (fuse wire)	Mercury porosimetry
	Soil Strength	**Penetration resistance**	Penetrometer, heavy gauge wire	
	Water movement and storage	**Water infiltration rate**	PVC ring and timer	
		Available water holding capacity	Estimated from texture and horizon depth, Soil moisture probes	
		Saturated hydraulic conductivity		Pressure plates

	Category	Test or Assessment	In field	Laboratory
Chemical Measures	Soil reaction	**pH**	Field pH kits Rhizobial nodulation	pH water or CaCl2
		Salinity (EC)		EC 1:5
	Macronutrients	Total N, P **Available N, P, K**		Leco Colwell, Olsen, Bray
	Organic carbon	**OC** **TOC/TC** OC fractions (labile and stable)		Walkley Black Leco and acid pre-treatment if carbonate present Potassium permanganate, TOC
	Micronutrients	Trace elements		
	Base cations	Ca, Mg, Na, K, Al		
	Soil capacity	Cation exchange capacity		Sum of base cations
	Soil stability	**Sodicity**	Slaking /dispersion	Exchangeable sodium percentage
Biological Measures	Nutrient release	Enzyme activity Potentially mineralisable N/C		e.g. dehydrogenase, cellulase, chitinase, amylase, phosphatase & phytases
	Microbial activity	**Soil respiration** **Cotton strip test**		
	Microbial biomass and community	Microbial biomass Microbial diversity Microbial composition		
	Rhizobial symbiosis	Nodule counts and distribution	If legumes present, look for and record nodules	
	Macrofauna community and abundance	Earthworms, insects, spiders, springtails etc	Record what and how many are present	
Proxy measures	Productivity	**Biomass/yield** Fractional cover	Healthy, growing, colour	Remote mapping or models NDVI etc
	Weed	**Plant indicators**	Species present	
	Livestock	**Productivity**	Kg liveweight/ha (can also be reported on a kg/ha/100mm)	
	Disease	Pathogens		
	Pest	Pests		

Table 9.4. Suggested assessment for the key constraints identified in Section 4.4 McKenzie *et al.* (2017)

Constraint	Laboratory	In-field	Proxy
Acidity	pH CaCl2	Field pH test kit Nodulation in legumes	Indicators plants, sorrel etc
Sodicity	Exchangeable sodium percentage	Emerson Dispersion	
Salinity	EC 1:5, EC saturation extract		Indicator plants
Carbon	OC or total OC Active – potassium permanganate		
Nutrient decline	Macro and micro-nutrients		
Nutrient excess	Macro and micro-nutrients		
Wind erosion		Soil depth, visual change	Remote mapping or models
Water erosion		Soil depth, visual change	Remote mapping or models

Table 2.5. Common assessments based on soil constraint of interest.

Constraint	How to measure
Chemical limitations for function	pH, salinity, boron, sodicity, Ca:Mg ratio
Physical limitations for function	bulk density, soil strength, structure assessment, visual pans/cementation, water infiltration rate
Soil texture, rootzone depth	In-field assessment
Biological diversity	Microscopic abundance, DNA/PLFA assessment, Fungal:Bacterial
Biological activity	Basal respiration
Nutrient storage	Soil texture, cation exchange capacity (CEC), mineralogy
Water storage	Texture, rootzone depth, bulk density, slope, coarse fragments, water infiltration, structure assessment
Soil OC persistence	C fractions, TOC/Labile C
Nutrient cycling	Chemical analysis, CEC, Available and/or total N & P
Biomass productivity	Dry matter or yield t/ha
Livestock productivity	kg liveweight/ha (can also be reported on a kg/ha/100mm)

9.2 Extension

Effective extension of soil research builds the capacity of landholders to manage soils productively and sustainably (Andersson and Orgill 2019).

9.2.1 Australian extension information outside of MLA

There is a vast quantity of soil extension information available across many platforms (print, online, training courses, workshops, YouTube) offered by industry, government, technical associations and CRCs (Table). The Soil CRC technical report 'Supporting farmer decision making for soil stewardship and profitability' for Program 1 provides a more detailed inventory and reports a solid investment from Australian governments and research institutions but note that many are not updated, no longer used or may not be available (Soil CRC 2018).

Table 9.6. Examples of Australian extension material or programs outside of MLA

Body	Program name	Module	Link
MLA/GRDC	Evergraze	Soil and fertility management	On-Farm Options – Soil and Fertility Management | EverGraze More livestock from perennials
AWI/MLA	Making More from Sheep	Healthy Soils Module	MODULE 6: Healthy Soils (makingmorefromsheep.com.au)
Soil Science Australia	Soil education and online resources	All modules	General Soil Information Sources - Soil Science Australia
University of New England	Welcome to living soils	All modules, biology focus	UNE: Living Soils
NSW DPI	Soil management guides	All modules	Soil management guides (nsw.gov.au)

9.2.2 Australian extension information provided by MLA

MLA invested in Making better fertiliser decisions for grazed pastures in Australia and More beef from pastures both now 15-20 years old.

MLA has the Healthy Soils Hub which collates relevant soils information for grazing livestock in a variety of options including factsheets, online training (The toolbox), videos, posters and reports enabling producers to select the style that best suits their learning style. The information is credible, reliable and importantly easy to find. Additionally, other MLA programs include soil management or health components and include (see Appendix 2 for links):

- profitable Grazing Systems Pay Dirt and Pay Dirt North modules,
- EDGE network Grazing Fundamentals and Grazing Land Management packages,
- more Beef from Pastures Pasture growth – 2.3 Build and maintain soil nutrients to improve soil fertility and health in all pasture zones module,
- e-learning through the toolbox healthy soils and pastures and CN30 programs Carbon 101, Measuring your own emissions and Carbon sense.

There is a vast quantity of soil management information available across Australia and Internationally. Whilst traditional field days and training courses are still one of the keys sources of information, in this busy and large country, it can be difficult to get information to all the areas where it is needed. There are good soil resources online, but the selection of appropriate information can be challenging and sometimes overwhelming.

Online platforms that offer an interactive way of examining soil data and interpreting it for various users may help engagement, such as the Soil Quality website (https://www.soilquality.org.au/) that enables producers to compare their own soil testing data to that held on the website. Increasing producers' access to, and use of soil information means more direct engagement of producers and is done very well with the Healthy Soils Hub.

The benefits of improving soil health may prove to be persuasive for practice change, but a range of financial, environmental, social, and personal motivators also play a role in achieving it (Lobry de Bruyn and Andrews 2016).

9.3 Adoption

However, the provision of high-quality information is only the start of the decision-making process. Adoption or implementation of improved soil management practices on-farm has been relatively slow (Higgins et al. 2021) and can require strong economic, environmental, market or regulatory drivers (Luke et al. 2021).

9.3.1 Case Study: MLA: Review of innovative approaches to support adoption and practice change

The MLA Producer Adoption Reference Group recommended a global adoption review of innovative approaches to support adoption and practice change which could be applied to the red meat sector in Australia. The project was conducted by University of Melbourne and commenced in May 2021. Three design concepts were selected for development into proposed activities:

1. Understanding target audiences and contextual factors in adoption through behavioural insights (producer segmentation and tailoring of approaches).
2. Supporting producer peer-to-peer learning and producer leadership in program design (co-design/ co-innovation/producer action groups).
3. Strengthening the capacity of the advisory sector (advisor mentoring and training).

Four activities were proposed for implementation:

a. engaging with 'hard to reach' producers in the Australian southern rangelands,
b. designing a collaborative program to support wide adoption of pain relief in animal management,
c. applying a 'Living Labs' approach in R&D regional consultation processes, and
d. supporting producer driven 'Farmer Action Groups' as part of strategic partnerships.

Key learnings are to be integrated into existing adoption products to further increase engagement and impact. The novel proposed activities outlined above, are to be pursued through the development of new products and processes and by embedding the proposed activities into MLA's adoption framework.

9.3.2 Case Study: Soil CRC Project: Why Soils management practices are adopted.

https://soilcrc.com.au/wp-content/uploads/2022/04/FINAL_REPORT_1.2.002_HIGGINS_FINAL-1.pdf

in 2019, the Soil CRC funded a project dedicated to understanding adoption of soil management practices across different geographical contexts and farming systems. The key recommendations from the project were published in 2021 and are outlined below.

1. That investment bodies support farmer groups when developing workshops that provide farmers with skills in soil data management and interpretation. The workshops should be developed in consultation with local agronomists, advisors and other trusted change intermediaries such as accredited soil practitioners.
2. That investment bodies integrate into the project application process:
    - a requirement that all research involving adoption implications details how the Framework for Understanding and Assessing Adoptability of Soil Management Innovations (https://soilcrc.com.au/wp-content/uploads/2019/02/SOILCRC_FS_1.2.001.T1_FINAL_NoBleed.pdf) will be integrated within research projects.
    - a requirement for documented evidence from end users that the outcomes and products from the research are likely to be relevant to locally defined soil management challenges and priorities and suited to the local geographical and farming systems context.
3. That investment bodies collaborate with policy makers, farmer groups and soil researchers to develop a strategy that defines best practice soil management standards and outlines different options for rewarding farmers who meet those standards.
4. That investment bodies develop a strategy for resourcing and evaluation of farmer group soil improvement extension initiatives. The strategy should be developed in consultation with farming system groups and extension and adoption experts.

9.3.3 Case Study: Lessons Learnt through the Soil Health Partnership

The Soil Health Partnership (https://www.soilhealthpartnership.org/) was a farmer-driven, on-farm initiative to monitor and improve soil health to increase adoptions of soil health practices in the USA. The case study has summarised key findings from On-farm soil health evaluations: Challenges and opportunities (Karlen et al. 2017). Several transferrable lessons were learnt during the program.

1. **On-farm research will be neither inexpensive nor will it be as precise and controlled as most research scientists would like.** Inherent variability, on-farm management and of course weather affects what is grown above ground and hence impacts chemical, physical and biological soil indicators. Repeated sampling, analysing, interpretation and extension of the results all add up.
2. **On-farm research network will require a dedicated, multi-person infrastructure.** There will need to be ‘field manager/s’ who will be the front line contacts for participating farmers, operation manager/s for logistics and data manager/s to ensure the information is collected and collated who are the conduit between the field manager/s and the scientists or funding

body directing the research. Finance and human resource support will be needed if the network is large.

3. **A diverse science advisory council is crucial to ensure scientific rigor and valid experimental questions are being answered.** Can provide support if participants would like to trial different management or products to the main practices. A well-respected science advisory team also lends credibility to the overall project and can be influential in sustaining current funding sources and attracting new ones to sustain the treatment comparisons needed to quantify long-term soil management effects.
4. **The implementation phase, for multistate projects in particular, will be much slower than expected.** Especially true if recruitment of key personnel is required, site selection, experimental design, sampling, data collection and analysis often take longer than planned in the first year of multi-year projects.
5. **Multistate, on-farm projects must have a well-developed, efficient, and effective communication infrastructure.** This is critical at all stages of the project but most importantly at the start of the project with communication between farmers, field managers and the directors of the research to ensure site establishment and sampling go to plan and once information starts to come out of the analysis it is critical to get clear messages to all involved especially farmers so changes in management may be considered and trialled on new places.
6. **Ensure funding or a repository secured to maintain availability of resources**. Since writing the publication in 2017, program funding was ceased so there is now an issue of archiving data and continued access of developed resources.

9.4 Understand Producer Adoption Framework

The Understand Producer Adoption (UPA) framework is a combination of key learnings from the three case studies from MLA, Soil CRC and Soil Health Partnership (Figure 9.1).

UNDERSTAND

Understand target audience and external factors in adoption

Clarity that on-farm research is expensive and not as precise or controlled as many scientists would like

Activities

Project applications follow the Soil CRC Framework for Understanding and Assessing Adoptability of Soil Management Innovations

Document outcomes and products from research are likely to be relevant to locally defined soil management challenges and priorities and suited to the geographical and farming system

Diverse science advisory committee to ensure scientific rigour and locally relevant soil challenges are addressed

PRODUCER

Support producer peer to peer learning

Include producer leadership in program design

Provision of repository for soil information

Activities

Apply a Living Labs approach to regional consultation and project design

Support producer driven 'Action Groups' as part of strategic partnerships

Engage with 'hard to reach' producers in Australian southern rangelands

Provide producers with skills in soils data management and interpretation

Healthy Soils hub can host relevant project information and ensure funding is secured into the future, so information is not lost

ADOPTION

Strengthen the capacity of the advisory sector

Ensure clear and effective communication between MLA, advisors and farmers

Activities

Involvement of advisors, local agronomists and trusted change intermediaries in workshop development

In conjunction with farming system groups, extension and adoption experts, MLA develops a strategy for resourcing and evaluation of farmer group soil improvement extension initiatives

Provision of dedicated, multi-person infrastructure for large soil monitoring programs to ensure clear communication between researchers, advisors and farmers and flow of information goes to everyone

Figure 9.1. Understand Producer Adoption Framework

Information originating from MLA, Soil CRC and Soil Health Partnership

9.5 Recommendations

- There is a need for collated soil datasets to create local reference site comparisons and if sufficient data is available the creation of soil benchmark data to enable producers to assess where their soils fit compared to others.
- Monitoring of high value soil indicators are needed to aid in determining trends in soil properties and health of the system.
- A need for soil health assessment to include observational indicators to enable a blend of traditional testing with digital technology.
- Provision of good local soil management information to help producers choose the practice most suited to their region, soil and business framework.
- Funding secured to ensure soil resource material is relevant, reviewed, updated and available over time not just when the project is run.
- Continue to review and add relevant soil information to the Healthy Soils Hub. As much as possible make the content interactive especially when a producer's soil indicators can be benchmarked against other results, similar to that on the Soil Quality website.
- The Understanding Producer Adoption (UPA) framework can be used to align the key learning from the three adoption case studies.

10 Remote sensing

Key points:

- remote sensing has a relatively limited number of technologies for generating data: optical sensors (hyperspectral and multispectral sensors); RADAR sensors and LiDAR sensors.
- all information developed relies on correlations developed through research to provide usable data. There is rarely a direct soil measurement to ground truth remote sensing.
- most soil properties derived from remote sensing require bare soil to generate the information.
- improvements in technology, resolution and accuracy all contribute to improved information generated from remote sensing.

Remote sensing, as opposed to proximal sensing, refers to the collection of data from a distance, typically using sensors mounted on aircraft or satellites. Remote sensing can cover large areas quickly and efficiently, making it ideal for studying broad-scale phenomena such as climate change, land use change, and ecosystem dynamics. Proximal sensing, on the other hand, involves the collection of data at a much closer range. Proximal sensors are typically handheld or mounted on a vehicle and are used to collect data on specific points or areas of interest.

Interest in the potential for remote sensing of soils has been gleaned ever since the first commercial satellite (LANDSAT-1) was placed in orbit in 1972 (Ben-Dor 2002). While a wealth of information can be obtained from satellite imagery, converting this information into useful knowledge can be a challenge. Remote sensing can be very useful for obtaining large amounts of spatial information, particularly in regard to variations within and between areas. Remote sensing is useful in interpolating data, particularly from extensive landscapes and hard to get to places, which means it provides a lot of potential for grazing lands. However, this information is usually only as good as the ground truthing that accompanies it. It can provide a significant boost towards soil mapping.

This short review of remote sensing has concentrated on remote sensing for soil information. Consequently, information on other potentially useful attributes such as pasture quality and density, have not been included. The information below on remote sensing technologies and products is largely taken from Wulf et al. (2014)

10.1 Remote Sensing Technologies

There are several remote sensing technologies which are currently being used. It is important to note that these technologies provide remotely sensed information. Identifying correlations of this information with soil properties can be a difficult process and claims where these correlations exceed the potential of the remote sensing technology are common.

10.1.1 Optical Sensors

There are a number of optical sensors important in remote sensing. All of them depend on the ability to detect the spectral reflectance of the soil in order to identify particular properties.

Hyperspectral imaging (also known as imaging spectroscopy) captures many images simultaneously in many spectral bands (wavelengths) so that a reflectance spectrum from each pixel can be obtained. It is most useful at the very near infra-red and the short wave infra-red wavelengths. Multispectral imagery has the potential to be affected by atmospheric conditions such as gas composition and water vapour. Most hyperspectral imaging is airborne although there are some satellite prototypes.

Multispectral imaging sensors record data in fewer bands, resulting in coarser spectral resolution compared to hyperspectral imaging. However, it offers significant advantages over hyperspectral imaging because technologies to accurately record multispectral images from satellites has been developed. Multispectral imaging also includes spectral bands in the thermal infra-red bands, allowing surface temperature and surface thermal emissions to be estimated.

10.1.2 RADAR Sensors

RADAR (RAdio Detection And Ranging) sensors use microwave radiation to collect data on terrain and soil moisture. RADAR sensors are commonly active microwave systems (most commonly Synthetic Aperture Radar). RADAR sensors have the advantage of working in most weather conditions (they can work independently of rain or fog) and have relatively good precision in ascertaining soil moisture. Passive microwave systems deliver information at relatively poor resolution (pixel sizes of around 50km squared) and are useful at detecting changes at country and global scales. There is some use for this technology being used to estimate regional soil moisture levels for extreme events such as floods, droughts and heat waves.

10.1.3 LiDAR sensors

LiDAR (Light Detection and Ranging) is used to generate accurate digital elevation models. LiDAR provides very accurate distance estimation by bouncing laser pulses from specific points to the ground. A major limitation for LIDAR is the presence vegetation. Satellite LiDAR systems can also be impacted by atmospheric conditions.

10.2 Soil attributes and properties estimated from remote sensing.

The technologies above allow many soil properties to be estimated. However, it should be noted that in most cases, remote sensing needs to estimate these attributes from bare soil.

Mineralogy: Mineral composition of surface soils and rock outcrops can be reliably determined from their remote sensing spectral signature. Airborne imaging is more suited to this than satellite imagery since high spectral resolution is required to identify the “spectral fingerprint” of the mineralogical composition.

Soil Texture: Soil texture is estimated from differentiating between clay-rich and quartz-rich soils. This is best done using airborne hyperspectral analysis and the results can be influenced by organic matter.

Soil Moisture: Relatively accurate soil moisture levels in the soil surface (0-3 centimetres) are available by using RADAR technology. However, the precision provides data at around 1km square pixels, making it useful for detecting changes in soil moisture over time. Limited success has been made using hyperspectral imagery and surface energy balance models which estimate evapotranspiration and are showing promise for estimating root zone soil moisture. More advanced models are progressing this to soil-vegetation-atmosphere transfer models.

Soil Organic Carbon: Soil colour from the visible spectrum is the principal indicator used to estimate soil carbon and the changes due to other factors are important to take into account. Most remote sensing for soil carbon has been calibrated on small plot ($1m^2$) trials. Using spectrally based indices to estimate content of lignin, starch and cellulose are showing good relationships for remote sensing over extensive areas. This is currently showing promise for airborne imagery but satellite imagery with its' reduced spectral resolution still needs considerably more work to calibrate. As may be expected (Biggs et al. 2022), more recent work is demonstrating some promising but more commonly only low to moderate accuracy for estimating SOC using digital soil models that include remote sensing inputs (Wang et al. 2018, Zhang et al. 2019, Sorenson et al. 2022, Wang and Zhou 2023). Estimating carbon levels in areas of increased vegetation will also be challenging, as will comparing areas which generate increased vegetation levels over time.

Iron content: In some parts of the world, iron content is seen as an indicator of fertility and sediment age. Whether this applies to the vast red soils of inland Australia is questionable. Both soil colour and some reflectance features have been used to estimate surface iron content.

Soil Salinity: In soils with arid and semi-arid climates, the amount of rainfall is sometimes insufficient to allow the build-up of salt to percolate through the soil. Since most (not all) arid zones are a significant distance from the sea, the amount of salt deposited on them is relatively low. Soil salinity has been estimated through RADAR technology, although the technology measures moisture as well as electrical conductivity, making calibration difficult. Salinity can also only be detected in the surface, and much of the salinity is in the sub-surface, making this technology limited in its use.

Soil degradation and contamination: Surface roughness and water content can be estimated to identify eroded areas. Additionally, post-fire soils provide an opportunity to measure many bare-soil characteristics. Considerable success has been experienced identifying water repellent soils in fore affected areas, which often correlate to erosion prone soils. Imaging spectroscopy can be used to detect contamination, but this has only been done in cases of significant contamination such as the bursting of mine spoil dams.

Soil nutrients: In recent years, increased interest has been focussed on soil nutrients. However, despite some claims, remote sensing does not appear to be able to deliver useful information at a useful scale for soil nutrients. Interest on soil nutrients and many other metrics useful at the sub-paddock scale are being investigated more seriously using proximal sensors, either collected while the tractor is making a pass or during other operations (Conway et al. 2023).

Proximal sensors: Sensors in, on or near the soil surface can provide extra information, different types of sensors and the ability to provide layered and deeper information. Electromagnetic induction has long been researched and provides useful information on salinity, sodicity and soil moisture providing it is adequately calibrated. Other proximal sensors include magnetometers, seismic reflection, ground penetrating radar and gamma ray spectrometry (Wulf et al. 2014). Since there is a need to drive proximal sensors around the paddock, they are useful at finding variation between and within paddocks, but the labour and expense required for larger scale enterprises is unlikely to be useful except for in defined local areas. There are some proximal sensors which provide useful information on soils, but many are still in development. Care also needs to be taken to ensure that results provided in well controlled laboratory or field conditions transfer effectively to paddock and farm scale in real-world conditions (Ge et al. 2011). In proven technologies, proximal sensing can be a more cost effective approach than grid sampling and better at getting spatial variability.

10.3 Conclusions

Remote sensing uses a relatively small box of tools to obtain information: spectroscopy using optical sensors, RADAR and LiDAR. Despite the limitations in what can be measured, the information derived from remote sensing is considerable, however, much of this information is associated with correlations which can change with environmental conditions and landscape. While some remote sensing will only be useful for estimating global changes in the near future, a significant number of measurements are providing useful correlations for estimating information at the farm, paddock and sub-paddock scale. Hyperspectral imagery is most commonly obtained aerially while reliable measurements from multispectral imagery, LiDAR and RADAR are able to be obtained via satellite. While there is very useful information being generated through remote sensing, the origins of the available data need to be considered when looking at the claimed information these can generate. Proximal sensing has the capability to feed into smaller scales, providing useful information on variability within and between paddocks. Future work for the livestock industry should identify large scale variations in the rangelands and consider combining remote and proximal sensing for more intensive areas.

10.4 Recommendations

- Undertake an extensive review of available technologies for remote and proximal sensing and identify a suite of readily available technologies to provide useful soil information.
- Understand the limitations, as well as the potential of various proximal and remote sensing tools.
- Clearly articulate soil information which needs bare soil to obtain information from to those which can identify correlations from groundcover.
- Don't develop technologies. The road from technical or laboratory potential to field capability is long and bumpy and there is a lag of more than five years (often longer) from identifying remote or proximal sensing technologies to producing useful information. Let these technologies be developed to a relatively advanced stage before adapting them for the red meat industry.

11 Conclusions

A thorough review of MLA projects over the past 10 years and a comparison with work conducted over the past 10 years showed that the MLA priorities aligned fairly closely with priorities in peer reviewed journals. The MLA Strategic Plan aligns with Australian Government Science and Research priorities, Rural R, D, &E priorities and the Red Meat 2030 Plan. Although the Strategic Plan itself only mentions soils in respect to enabling new sources of revenue, the dependency of the grazing industry on soil quality is more extensively mentioned in the Australian Government priorities and the Red Meat 2030 Plan. While there is no need to more explicitly mention soils in the strategic plan, there is a need to ensure that soils do not get lumped into an environmental basket, as they are important from productivity, market access and grazing systems.

We found significant differences in priorities between the intensive/mixed farming zones and the rangelands. Intensive and mixed farming zones need to soil test more and incorporate those soil tests into management decisions. Benchmarking soil nutrition rates will be important for maximising production, minimising environmental impacts and reporting to demonstrate environmental sustainability. Soil carbon needs to be looked at closely. Claims by alternative management groups seem to be largely unfounded in terms of their ability to increase soil carbon although improved pastures have greater potential to increase carbon. Identifying why farmers need to increase soil carbon is important, as is their decision whether to trade that carbon or use it to move to carbon neutrality. In the rangelands, erosion is a major issue worthy of further investigation.

The impact of extreme events on soil have not been investigated in any detail and more research could be conducted on this issue. In particular, identifying which processes cause permanent degradation versus those that cause temporary degradation which recover rapidly are worthy of investigation. Aiming for soil resilience to withstand extreme events rather than recovering and repairing soils after extreme events would be preferable. Determining what can be done to reduce degradation and to increase resilience will be complex, varying depending on landscape and management factors – identifying those soils easily managed to become resilient is important.

Soil organic carbon will continue to be an important factor in all grazing soils in the foreseeable future, but it is important to realise that utilising soil carbon for emissions offsets cannot continue indefinitely. Soil carbon fractionation, deep soil carbon and improved modelling techniques could all be pursued.

Current natural capital work implies that for grazing enterprises to improve natural capital, they may have to sacrifice productivity and profitability. This may not be the case. Management systems which use innovative ways to improve both natural capital and productivity should be prioritised. In cases where declining natural capital is likely to impact market access, this may need to be taken into account when developing new systems and reporting on natural capital.

In terms of reporting on supply chains, there are many international, European, and Australian soil initiatives which have the potential to impact or be used in future market access agreements and supply chain identification. Currently, the Australian red meat industry only aligns with the United Nations Sustainable Development Goals and there is potential to align with others. MLA is able to influence the red meat industry in adopting more of these initiatives and facilitating adoption at a farm, regional and industry scale.

Although the provision of soil extension services has declined markedly in recent times, there is a vast quantity of soil extension information available across many platforms (print, online, training courses, workshops, YouTube) offered by industry, government, technical associations and CRCs.

The MLA Healthy Soil Hub is an excellent existing resource. Increasing farmers' access to, and use of soil information increases direct engagement of farmers especially when interactive platforms assess the capacity or benchmark their soil result.

Remote sensing uses a relatively small box of tools to obtain information: spectroscopy using optical sensors, RADAR and LiDAR. Despite the limitations in what can be measured, the information derived from remote sensing is considerable. While there is very useful information being generated through remote sensing, the origins of the available data need to be considered when looking at the claimed information these can generate. Future work for the livestock industry should identify large scale variations in the rangelands and consider combining remote and proximal sensing for more intensive areas.

12 References

AACo (2022) *Evolving together to benefit future generations: Sustainability Report 2022.pdf*. AACo.
Alaoui, A., M. Rogger, S. Peth and G. Bloschl (2018). "Does soil compaction increase floods? A review." Journal of Hydrology **557**: 631-642.
Allen, D. E., M. J. Pringle, S. Bray, T. J. Hall, P. O. O'Reagain, D. Phelps, D. H. Cobon, P. M. Bloesch and R. C. Dalal (2013). "What determines soil organic carbon stocks in the grazing lands of north-eastern Australia?" Soil Research **51**(8): 695-706.
Allianz (2018) *Measuring and Managing Environmental Exposure: A business sector analysis of natural capital risk*. Munich: Allianz.
Amelung, W., D. Bossio, W. de Vries, I. Kögel-Knabner, J. Lehmann, R. Amundson, R. Bol, C. Collins, R. Lal, J. Leifeld, B. Minasny, G. Pan, K. Paustian, C. Rumpel, J. Sanderman, J. W. van Groenigen, S. Mooney, B. van Wesemael, M. Wander and A. Chabbi (2020). "Towards a global-scale soil climate mitigation strategy." Nature Communications **11**(1): 5427.
Amin, M. N., L. Lobry de Bruyn, M. S. Hossain, A. Lawson and B. Wilson (2023). "The social-ecological system of farmers' current soil carbon management in Australian grazing lands." Environmental Management.
Andersson, K. and S. E. Orgill (2019). "Soil extension needs to be a continuum of learning; soil workshop reflections 10 years on." Soil Use and Management **35**.
Andersson, K. O., M. K. Tighe, C. N. Guppy, P. J. Milham, T. I. McLaren, C. R. Schefe and E. Lombi (2016). "XANES demonstrates the release of calcium phosphates from alkaline Vertisols to moderately acidified solution." Environmental Science & Technology **50**(8): 4229-4237.
Anon (2020). MLA Strategic Plan 2025. Meat and Livestock Australia Limited, North Sydney.
Anon (2022a). Australian Beef Sustainability Framework Annual Update 2022, Meat and Livestock Australia Limited, North Sydney.
Anon (2022b). Sheep Sustainability Framework Annual Report 2022. Sheep Producers Australia and Wool Producers Australia, North Sydney.
Anon (2022c). Sheep Sustainability Framework Strategic Plan FY2022-FY2024. Sheep Sustainability Framework, North Sydney.
Ascui, F. (2023a) *Natural Capital Risk Materiality Assessment – Beef Industry*. Hobart: CSIRO.
Ascui, F. (2023b) *Natural Capital Risk Materiality Assessment – Sheep Industry*. Hobart: CSIRO.
Ascui, F., A. Ball, L. Kahn and J. Rowe (2021). "Is operationalising natural capital risk assessment practicable?" Ecosystem Services **52**: 101364.
Ascui, F. and T. F. Cojoianu (2019a) 'Implementing natural capital credit risk assessment in agricultural lending', *Business Strategy and the Environment*, 28(6), pp. 1234–1249. Available at: https://doi.org/10.1002/bse.2313.
Ascui, F. and T. F. Cojoianu (2019). "Implementing natural capital credit risk assessment in agricultural lending." Business Strategy and the Environment **28**(6): 1234-1249.
Ascui, F. and T. F. Cojoianu (2019b) *Natural Capital Credit Risk Assessment in Agricultural Lending: An Approach Based on the Natural Capital Protocol*. Oxford: Natural Capital Finance Alliance.
Ascui, F. and T. F. Cojoianu (2020) 'Natural Capital Credit Risk Assessment', in M. Jun, B. Caldecott, and U. Volz (eds) *Case Studies of Environmental Risk Analysis Methodologies*. Paris: Network for Greening the Financial System, pp. 121–144. Available at: https://www.ngfs.net/en/case-studies-environmental-risk-analysis-methodologies.
Ashton, L. J. and N. J. McKenzie (2001). Conversion of the Atlas of Australian Soils to the Australian Soil Classification, CSIRO Land and Water (unpublished).
Aubault, H., N. P. Webb, C. L. Strong, G. H. McTainsh, J. F. Leys and J. C. Scanlan (2015). "Grazing impacts on the susceptibility of rangelands to wind erosion: The effects of stocking rate, stocking strategy and land condition." Aeolian Research **17**: 89-99.
Australian Bureau of Statistics (2003). Salinity in Queensland. 1387.3 – Queensland in Review, 2003. https://www.abs.gov.au/Ausstats/abs@.nsf/39433889d406eeb9ca2570610019e9a5/2383FDC616E8BAA0CA256E92007F9065?opendocument.

Badgery, W., G. Li, A. Simmons, J. Wood, R. Smith, D. Peck, L. Ingram, Z. Durmic, A. Cowie, A. Humphries, P. Hutton, E. Winslow, P. Vercoe and R. Eckard (2023). "Reducing enteric methane of ruminants in Australian grazing systems – a review of the role for temperate legumes and herbs." Crop and Pasture Science: -.

Badgery, W., B. Murphy, A. Cowie, S. Orgill, A. Rawson, A. Simmons and J. Crean (2021). "Soil carbon market-based instrument pilot – the sequestration of soil organic carbon for the purpose of obtaining carbon credits." Soil Research **59**(1): 12-23.

Badgery, W. B., G. D. Millar, K. Broadfoot, D. L. Michalk, P. Cranney, D. Mitchell and R. van de Ven (2017). "Increased production and cover in a variable native pasture following intensive grazing management." Animal Production Science **57**(9): 1812-1823.

Badgery, W. B., J. M. Mwendwa, M. R. Anwar, A. T. Simmons, K. M. Broadfoot, M. Rohan and B. P. Singh (2020). "Unexpected increases in soil carbon eventually fell in low rainfall farming systems." Journal of Environmental Management **261**: 110192.

Badgery, W. B., A. T. Simmons, B. W. Murphy, A. Rawson, K. O. Andersson and V. E. Lonergan (2014). "The influence of land use and management on soil carbon levels for crop-pasture systems in Central New South Wales, Australia." Agriculture, Ecosystems & Environment **196**(0): 147-157.

Baldock, J., L. Macdonald and J. Sanderman (2013). "Foreword to 'Soil Carbon in Australia's Agricultural Lands'." Soil Research **51**(8): i-ii.

Barnett, S.R (2000). Extent and Impacts of Dryland Salinity in South Australia. Report for the National Land and Water Resources Audit, Adelaide, Department for Water Resources.

Bartley, R., B. N. Abbott, A. Ghahramani, A. Ali, R. Kerr, C. H. Roth and A. Kinsey-Henderson (2023). "Do regenerative grazing management practices improve vegetation and soil health in grazed rangelands? Preliminary insights from a space-for-time study in the Great Barrier Reef catchments, Australia." Rangeland Journal.

Bastick, C.H. and M. G. Walker (2000). Extent and impacts of Dryland Salinity in Tasmania. Department of Primary Industries, Water and Environment.

Ben-Dor, E. (2002). Quantitative remote sensing of soil properties. Advances in Agronomy, Academic Press. **75:** 173-243.

Biggs, A. J. W., M. Crawford, J. Burgess, D. Smith, K. Andrews and M. Sugars (2022). "Digital soil mapping in Australia. Can it achieve its goals?" Soil Research **61**: 1-8.

Blanco-Canqui, H. and R. Lal (2008). Soil Resilience and Conservation. Principles of Soil Conservation and Management. H. Blanco-Canqui and R. Lal. Dordrecht, Springer Netherlands**:** 425-447.

Boschma, S. P., S. R. Murphy and S. Harden (2017). "Growth rate and nutritive value of sown tropical perennial grasses in a variable summer-dominant rainfall environment, Australia." Grass and Forage Science **72**(2): 234-247.

Bowen, M. K., F. Chudleigh, R. M. Dixon, M. T. Sullivan, T. Schatz and T. Oxley (2020). "The economics of phosphorus supplementation of beef cattle grazing northern Australian rangelands." Animal Production Science **60**(5): 683-693.

Brennan, R. F., B. Penrose and R. W. Bell (2019). "Micronutrients limiting pasture production in Australia." Crop and Pasture Science **70**(12): 1053-1064.

Briske, D. D., B. T. Bestelmeyer and J. R. Brown (2014). "Savory's unsubstantiated claims should not be confused with multipaddock grazing." Rangelands **36**(1): 39-42.

Briske, D. D., B. T. Bestelmeyer, J. R. Brown, S. D. Fuhlendorf and H. W. Polley (2013). "The Savory method can not green deserts or reverse climate change." Rangelands **35**(5): 72-74, 73.

Briske, D. D., N. F. Sayre, L. Huntsinger, M. Fernandez-Gimenez, B. Budd and J. D. Derner (2011). "Origin, persistence, and resolution of the rotational grazing debate: Integrating human dimensions into rangeland research." Rangeland Ecology & Management **64**(4): 325-334.

Bui, E., G. Hancock, A. Chappell and L. Gregory (2010). Evaluation of tolerable erosion rates and time to critical topsoil loss in Australia. Canberra, CSIRO.

Button, E. S., J. Pett-Ridge, D. V. Murphy, Y. Kuzyakov, D. R. Chadwick and D. L. Jones (2022). "Deep-C storage: Biological, chemical and physical strategies to enhance carbon stocks in agricultural subsoils." Soil Biology and Biochemistry **170**: 108697.

Byrnes, R. C., D. J. Eastburn, K. W. Tate and L. M. Roche (2018). "A Global Meta-Analysis of Grazing Impacts on Soil Health Indicators." J Environ Qual **47**(4): 758-765.

Caccetta, P. A., J. Simons, S. Furby, N. Wright and R. George (2022). Mapping salt-affected land in the South-West of Western Australia using satellite remote sensing,, CSIRO, Australia.
Carter, D. J., E. Walker and R. J. Gilkes (1998). Claying of water repellent soils: Effects on hydrophobicity, organic matter and nutrient uptake. 16th World Congress of Soil Science. Symposium 41. Reg. No. 2619, . Montpellier, France.
Chang-Fung-Martel, J., M. T. Harrison, R. Rawnsley, A. P. Smith and H. Meinke (2017). "The impact of extreme climatic events on pasture-based dairy systems: a review." Crop and Pasture Science **68**(12): 1158-1169.
Chappell, A., R. A. Viscarra Rossel and R. Loughran (2011). "Spatial uncertainty of ^{137}Cs-derived net (1950s–1990) soil redistribution for Australia." Journal of Geophysical Research: Earth Surface **116**(F4).
Chappell, A., N. P. Webb, J. F. Leys, C. M. Waters, S. Orgill and M. J. Eyres (2019). "Minimising soil organic carbon erosion by wind is critical for land degradation neutrality." Environmental Science & Policy **93**: 43-52.
CISL (2021) *Handbook for nature-related financial risks: key concepts and a framework for identification*. Cambridge, UK: University of Cambridge Institute for Sustainability Leadership.
Clark, R. and W. Harvey (2008). Dryland salinity in Victoria in 2007. An analysis of data from the soil salinity database and Victorian discharge monitoring network. Department of Primary Industries, Bendigo.
Cojoianu, T.F. and F. Ascui (2018) ‘Developing an evidence base for assessing natural capital risks and dependencies in lending to Australian wheat farms’, *Journal of Sustainable Finance & Investment*, 8(2), pp. 95–113. Available at: https://doi.org/10.1080/20430795.2017.1375776.
Colwell, J. D. (1971). "Estimations of sampling intensities for the characterization of soil within experiment sites." Australian Journal of Experimental Agriculture **11**(52): 541-545.
Condon, J., H. Burns and G. Li (2021). "The extent, significance and amelioration of subsurface acidity in southern New South Wales, Australia." Soil Research 59(1): 1-11.
Conway, L. S., K. A. Sudduth, N. R. Kitchen and S. H. Anderson (2023). "Repeatability of commercially available visible and near infrared proximal soil sensors." Precision Agriculture.
Coonan, E., C. Kirkby, J. Kirkegaard, M. Amidy, C. Strong and A. Richardson (2020). "Microorganisms and nutrient stoichiometry as mediators of soil organic matter dynamics." Nutrient Cycling in Agroecosystems **117**.
Corbeels, M., R. Cardinael, K. Naudin, H. Guibert and E. Torquebiau (2019). "The 4 per 1000 goal and soil carbon storage under agroforestry and conservation agriculture systems in sub-Saharan Africa." Soil and Tillage Research **188**: 16-26.
Crawford, D. M., B. Mitchard and W. R. Burton (2020). "Recent trends in soil fertility across the farms of East Gippsland." Soil Research **58**(6): 561-575.
CSIRO and BoM (2018). State of the Climate 2018.
Darbyshire, R. O., S. B. Johnson, M. R. Anwar, F. Ataollahi, D. Burch, C. Champion, M. A. Coleman, J. Lawson, S. E. McDonald, M. Miller, J. Mo, M. Timms, D. Sun, B. Wang and J. Pardoe (2022). "Climate change and Australia’s primary industries: factors hampering an effective and coordinated response." International Journal of Biometeorology **66**(6): 1045-1056.
Department of Primary Industries and Regional Development (2020). Status of the Western Australian pastoral rangelands 2020: condition, trend and risk. South Perth, WA, DPIRD.
Dixon, R. M., S. T. Anderson, L. J. Kidd and M. T. Fletcher (2020). "Management of phosphorus nutrition of beef cattle grazing seasonally dry rangelands: a review." Animal Production Science **60**(7): 863-879.
Dobes, L., M. Crane, T. Higgins, A. I. J. M. Van Dijk and D. B. Lindenmayer (2021). "Increased livestock weight gain from improved water quality in farm dams: A cost-benefit analysis." PLOS ONE **16**(8): e0256089.
Donkor, N. T., J. V. Gedir, R. J. Hudson, E. W. Bork, D. S. Chanasyk and M. A. Naeth (2002). "Impacts of grazing systems on soil compaction and pasture production in Alberta." Canadian Journal of Soil Science **82**(1): 1-8.
Donohue, R. J., R. A. Lawes, G. Mata, D. Gobbett and J. Ouzman (2018). "Towards a national, remote-sensing-based model for predicting field-scale crop yield." Field Crops Research **227**: 79-90.
Doyle, R. B. and F. M. Habraken (1993). "The distribution of sodic soils in Tasmania." Soil Research **31**(6): 931-947.

Edmeades, D. C. (2002). "The effects of liquid fertilisers derived from natural products on crop, pasture, and animal production: A review." Australian Journal of Agricultural Research **53**(8): 965-976.
Edmeades, D. C. (2011). Pseudo-science: a threat to agriculture? Grassland farmers - opportunities, threats and realaties. G. Lodge, W. Wheatley and J. Scott. Bathurst, Grassland Society of NSW**:** 38-47.
Eftec, RSPB, and PwC (2015) *Developing Corporate Natural Capital Accounts: Final Report*. London: Department for the Environment, Food and Rural Affairs.
Eldridge, D. J. and M. Delgado-Baquerizo (2017). "Continental-scale impacts of livestock grazing on ecosystem supporting and regulating services." Land Degradation & Development **28**(4): 1473-1481.
Fazel, A., B. M. S. Abdul Rashid and T. Taybeh (2012). Monitoring Land Suitability for Mixed Livestock Grazing Using Geographic Information System (GIS). Application of Geographic Information Systems. A. Bhuiyan Monwar. Rijeka, IntechOpen**:** Ch. 13.
Fierer, N., S. A. Wood and C. P. Bueno de Mesquita (2021). "How microbes can, and cannot, be used to assess soil health." Soil Biology and Biochemistry **153**: 108111.
Filippi, P., S. R. Cattle, M. J. Pringle and T. F. A. Bishop (2021). "Space-time monitoring of soil organic carbon content across a semi-arid region of Australia." Geoderma Regional 24: e00367.
Fontaine, S., S. Barot, P. Barré, N. Bdioui, B. Mary and C. Rumpel (2007). "Stability of organic carbon in deep soil layers controlled by fresh carbon supply." Nature 450(7167): 277-280.
Forestry England (2019) *Natural Capital Account 2018-19*. Bristol: Forestry England.
Ford, G. W., J. J. Martin, P. Rengasamy, S. C. Boucher and A. Ellington (1993). "SOIL SODICITY IN VICTORIA." Australian Journal of Soil Research **31**(6): 869-909.
Forico (2021) *Natural Capital Report 2021*. Kings Meadows: Forico.
Fraser, G. W. and G. S. Stone (2016). "The effect of soil and pasture attributes on rangeland infiltration rates in northern Australia." The Rangeland Journal **38**(3): 245-259.
Ge, Y., J. A. Thomasson and R. Sui (2011). "Remote sensing of soil properties in precision agriculture: A review." Frontiers of Earth Science **5**(3): 229-238.
Glasson, C. R. K., R. D. Kinley, R. de Nys, N. King, S. L. Adams, M. A. Packer, J. Svenson, C. T. Eason and M. Magnusson (2022). "Benefits and risks of including the bromoform containing seaweed Asparagopsis in feed for the reduction of methane production from ruminants." Algal Research **64**: 102673.
Godde, C. M., R. B. Boone, A. J. Ash, K. Waha, L. L. Sloat, P. K. Thornton and M. Herrero (2020). "Global rangeland production systems and livelihoods at threat under climate change and variability." Environmental Research Letters **15**(4): 044021.
Gosnell, H., S. Charnley and P. Stanley (2020). "Climate change mitigation as a co-benefit of regenerative ranching: insights from Australia and the United States." Interface Focus **10**(5).
Gourley, C., D. Weaver and J. Kraak (2019). A guidance document for agronomic best practice soil sampling in Australia. 'Cells to Satellites'. Proceedings of the 2019 Agronomy Australia Conference. J. Pratley. Wagga Wagga, Australian Society of Agronomy.
Gourley, C. J. P. and D. M. Weaver (2019). A guide for fit for purpose soil sampling. Canberra, Australia.
Gourley, C. J. P., D. M. Weaver, R. J. Simpson, S. R. Aarons, M. M. Hannah and K. I. Peverill (2019). "The development and application of functions describing pasture yield responses to phosphorus, potassium and sulfur in Australia using meta-data analysis and derived soil-test calibration relationships." Crop and Pasture Science **70**: 1065-1079.
Gray, J. M., B. Wang, C. M. Waters, S. E. Orgill, A. L. Cowie and E. L. Ng (2022). "Digital mapping of soil carbon sequestration potential with enhanced vegetation cover over New South Wales, Australia." Soil Use and Management **38**(1): 229-247.
Greenland, D. J., P. J. Gregory, P. H. Nye and R. Lal (1997). "Degradation and resilience of soils." Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences **352**(1356): 997-1010.
Grover, S. P., C. R. Butterly, X. Wang, D. B. Gleeson, L. M. Macdonald and C. Tang (2021). "Liming and priming: the long-term impact of pH amelioration on mineralisation may negate carbon sequestration gains." Soil Security **3**: 100007.
Grundy, M. J., R. A. V. Rossel, R. D. Searle, P. L. Wilson, C. Chen and L. J. Gregory (2015). "Soil and Landscape Grid of Australia." Soil Research **53**(8): 835-844.
Guo, M. (2021). "Soil Health Assessment and Management: Recent Development in Science and Practices." Soil Systems **5**(4): 61.

Hacker, R. B. and S. E. McDonald (2021). "Prospects for sustainable use of the pastoral areas of Australia's southern rangelands: a synthesis." The Rangeland Journal **43**(4): 185-209.
Hannam, R. J. (2013). Soil Biology Review and project prioritisation for the feedbase investment plan. Australia, Meat and Livestock Australia**:** 111.
Harper, R. J. and M. Tibbett (2013). "The hidden organic carbon in deep mineral soils." Plant and Soil **368**(1-2): 641-648.
Harrison, M. T., B. R. Cullen and R. P. Rawnsley (2016). "Modelling the sensitivity of agricultural systems to climate change and extreme climatic events." Agricultural Systems **148**: 135-148.
Hayes, R. C., I. Ara, W. B. Badgery, R. A. Culvenor, R. E. Haling, C. A. Harris, G. D. Li, M. R. Norton, S. E. Orgill, B. Penrose and R. W. Smith (2019). "Prospects for improving perennial legume persistence in mixed grazed pastures of south-eastern Australia, with particular reference to white clover." Crop and Pasture Science **70**: 1141-1162.
Hayes, R. C., M. Rohan, G. D. Li, S. E. Orgill, G. J. Poile, A. A. Oates and M. K. Conyers (2022). "The nature of spatial variability of four soil chemical properties and the implications for soil sampling." Journal of Soils and Sediments **22**: 3006-3017.
Henry, K. (2016) *Dr Ken Henry AC Speech – Advancing Australia's Natural Capital*. Available at: http://news.nab.com.au/dr-ken-henry-ac-speech-advancing-australias-natural-capital/ (Accessed: 19 October 2016).
Hermans, S. M., H. L. Buckley, B. S. Case, F. Curran-Cournane, M. Taylor and G. Lear (2020). "Using soil bacterial communities to predict physico-chemical variables and soil quality." Microbiome **8**(1): 79.
Higgins, V., C. Allan, M. Bryant, P. Leith, G. Cockfield and P. Cooke (2021). Understanding adoptability of techniques and practices for improved soil management. Final technical report, Project 1.2.002. Newcastle.
Hobley, E. U., J. Baldock and B. Wilson (2016). "Environmental and human influences on organic carbon fractions down the soil profile." Agriculture, Ecosystems & Environment **223**: 152-166.
Howden, S. M., S. J. Crimp and C. J. Stokes (2008). "Climate change and Australian livestock systems: impacts, research and policy issues." Australian Journal of Experimental Agriculture **48**(7): 780-788.
Hulugalle, N. R., T. B. Weaver, L. A. Finlay and V. Heimoana (2013). "Soil organic carbon concentrations and storage in irrigated cotton cropping systems sown on permanent beds in a Vertosol with restricted subsoil drainage." Crop and Pasture Science 64(8): 799-805.
IPBES (2019) *Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*. Edited by S. Díaz et al. Bonn, Germany: IPBES Secretariat.
ISSB (2022) *Exposure Draft IFRS S1 General Requirements for Disclosure of Sustainability-related Financial Information*. London: International Accounting Standards Board. Available at: https://www.ifrs.org/content/dam/ifrs/project/general-sustainability-related-disclosures/exposure-draft-ifrs-s1-general-requirements-for-disclosure-of-sustainability-related-financial-information.pdf (Accessed: 7 September 2022).
Isbell, R. F. (1996). The Australian soil classification. Collingwood, VIC, Australia, CSIRO Australia.
Isbell, R. F. (2002). The Australian Soil Classification. Revised Edition. Melbourne, CSIRO Publishing.
Isbell, R. F. and National Committee on Soil and Terrain (Australia) (2021). The Australian Soil Classification. Third Edition. Melbourne, CSIRO Publishing.
Jamali, H., G. Nachimuthu, B. Palmer, D. Hodgson, A. Hundt, C. Nunn, M. Braunack (2021) Soil compaction in a new light: Know the cost of doing nothing – a cotton case study. Soil & Tillage Research **213**: 105158.
Johnston, P. W., G. M. McKeon and K. A. Day (1996). "Objective `safe' grazing capacities for south-west Queensland Australia: Development of a model for individual properties." The Rangeland Journal **18**(2): 244-258.
Joseph, S., A. L. Cowie, L. Van Zwieten, N. Bolan, A. Budai, W. Buss, M. L. Cayuela, E. R. Graber, J. A. Ippolito, Y. Kuzyakov, Y. Luo, Y. S. Ok, K. N. Palansooriya, J. Shepherd, S. Stephens, Z. Weng and J. Lehmann (2021). "How biochar works, and when it doesn't: A review of mechanisms controlling soil and plant responses to biochar." GCB Bioenergy **13**:1731-1764.
Karlen, D. L., N. J. Goeser, K. S. Veum and M. A. Yost (2017). "On-farm soil health evaluations: Challenges and opportunities." Journal of Soil and Water Conservation **72**(2): 26A-31A.

Khandakar, T., C. Guppy, M. Tighe, S. M. F. Rabbi and H. Daniel (2017). "Increased carbon stabilization in australian ferrosol with high carbon saturation deficit." Communications in Soil Science and Plant Analysis **48**(15): 1772-1780.
Kirkby, C., J. Kirkegaard, A. Richardson, L. Wade, C. Blanchard and G. Batten (2011). "Stable soil organic matter: A comparison of C:N:P:S ratios in Australian and other world soils." Geoderma **163**: 197-208.
Koch, A., A. Chappell, M. Eyres and E. Scott (2015). "Monitor soil degradation or triage for soil security? An Australian challenge." Sustainability **7**(5): 4870-4892.
Koci, J., R. C. Sidle, A. E. Kinsey-Henderson, R. Bartley, S. N. Wilkinson, A. A. Hawdon, B. Jarihani, C. H. Roth and L. Hogarth (2020). "Effect of reduced grazing pressure on sediment and nutrient yields in savanna rangeland streams draining to the Great Barrier Reef." Journal of Hydrology **582**.
Kopittke, P. M. and N. W. Menzies (2007). "A review of the use of the basic cation saturation ratio and the “ideal” soil." Soil Science Society of America Journal **71**(2): 259-265.
Lai, L. and S. Kumar (2020). "A global meta-analysis of livestock grazing impacts on soil properties." PLoS One **15**(8): e0236638.
Lal, R. (2008). "Soils and sustainable agriculture. A review." Agronomy for Sustainable Development **28**(1): 57-64.
Leech, F. J., A. E. Richardson, M. A. Kertesz, B. A. Orchard, S. Banerjee and P. Graham (2019). "Comparative effect of alternative fertilisers on pasture production, soil properties and soil microbial community structure." Crop and Pasture Science **70**(12): 1110-1127.
Lehmann, J., D. A. Bossio, I. Kögel-Knabner and M. C. Rillig (2020). "The concept and future prospects of soil health." Nature Reviews Earth & Environment **1**(10): 544-553.
Lehmann, J. and M. Kleber (2015). "The contentious nature of soil organic matter." Nature **528**(7580): 60-68.
Li, Y., H. Yu, A. Chappell, N. Zhou and R. Funk (2014). "How much soil organic carbon sequestration is due to conservation agriculture reducing soil erosion?" Soil Research **52**(7): 717-726.
Lindenmayer, D., S. Macbeth, D. Smith and M. Young (2022). Natural asset farming: creating productive and biodiverse farms. Canberra, ACT, CSIRO.
Lobry de Bruyn, L. and S. Andrews (2016). "Are Australian and United States Farmers Using Soil Information for Soil Health Management?" Sustainability **8**(4): 304.
Luke, H., C. Allan, W. Lake, S. McDonald, C. Baker, A. Curtis and M. Alexanderson (2021). Surveying on-farm practices: Drivers of farmer decision-making. Technical Report. Newcastle.
Lutfalla, S., S. Abiven, P. Barré, D. B. Wiedemeier, B. T. Christensen, S. Houot, T. Kätterer, A. J. Macdonald, F. van Oort and C. Chenu (2017). "Pyrogenic carbon lacks long-term persistence in temperate arable soils." Frontiers in Earth Science **5**(96): np.
Majdura, J., U. Jankiewicz, A. Gałązka and S. Orzechowski (2023). "The role of quorum sensing molecules in bacterial-plant interactions." Metabolites **13**(1): 114.
Mappin, B., A. Ward, L. Hughes, J. E. M. Watson, P. Cosier and H. P. Possingham (2022). "The costs and benefits of restoring a continent's terrestrial ecosystems." Journal of Applied Ecology **59**(2): 408-419.
Maraseni, T. N., K. Reardon-Smith, G. Griffiths and A. Apan (2016). "Savanna burning methodology for fire management and emissions reduction: a critical review of influencing factors." Carbon Balance and Management **11**(1): 25.
Marshall, N. A., B. M. Taylor, S. Heyenga and D. Butler (2018). "Vulnerability of the livestock industry in eastern Australia." Sustainability Science **13**(2): 393-402.
Maskell, Z. and S. Griffiths (2019). Gemini project, soil and land suitability assessment. AARC Environmental Solutions Pty Ltd.
McDonald, S. E., N. Reid, R. Smith, C. M. Waters, J. Hunter and R. Rader (2020). "Comparison of biodiversity and ground cover between a commercial rotationally grazed property and an adjacent nature reserve in semi-arid rangeland." Austral Ecology **45**(1): 60-69.
McDonald, S. E., N. Reid, C. M. Waters, R. Smith and J. Hunter (2018). "Improving ground cover and landscape function in a semi-arid rangeland through alternative grazing management." Agriculture ecosystems & environment **268**: 8-14.
McKenzie, D., T. Abbott, K. Chan, P. Slavich and D. Hall (1993). "The nature, distribution and management of sodic soils in New-South-Wales." Soil Research **31**(6): 839-868.

McKenzie, N., P. B. Hairsine, L. Gregory, J. Austin, J. Baldock, M. Webb, J. Mewett, H. P. Cresswell, N. Welti and M. Thomas (2017). Priorities for improving soil condition across Australia's agricultural landscapes. Report prepared for the Australian Government Department of Agriculture and Water Resources. Canberra, CSIRO Agriculture and Food.
Menzies, N., D. Harbison and P. Dart (2011). Soil chemistry – facts and fiction and their influence on the fertiliser decision making process. Grassland farmers - opportunities, threats & realities: 26th Annual Conference of The Grassland Society of NSW. G. Lodge, J. Scott and W. Wheatley. Bathurst, The Grassland Society of NSW Inc.
Meyer, R., B. R. Cullen, I. R. Johnson and R. J. Eckard (2015). "Process modelling to assess the sequestration and productivity benefits of soil carbon for pasture." Agriculture, Ecosystems & Environment **213**: 272-280.
Minasny, B., B. P. Malone, A. B. McBratney, D. A. Angers, D. Arrouays, A. Chambers, V. Chaplot, Z.-S. Chen, K. Cheng, B. S. Das, D. J. Field, A. Gimona, C. B. Hedley, S. Y. Hong, B. Mandal, B. P. Marchant, M. Martin, B. G. McConkey, V. L. Mulder, S. O'Rourke, A. C. Richer-de-Forges, I. Odeh, J. Padarian, K. Paustian, G. Pan, L. Poggio, I. Savin, V. Stolbovoy, U. Stockmann, Y. Sulaeman, C.-C. Tsui, T.-G. Vågen, B. van Wesemael and L. Winowiecki (2017). "Soil carbon 4 per mille." Geoderma **292**: 59-86.
Mitchell, E., C. Scheer, D. Rowlings, F. Cotrufo, R. T. Conant and P. Grace (2021). "Important constraints on soil organic carbon formation efficiency in subtropical and tropical grasslands." Global Change Biology **27**(20): 5383-5391.
MLA (2021) *Australian Beef Sustainability Framework: Materiality Assessment Report 2021*. North Sydney: Meat and Livestock Australia.
MLA (2022a). *Australian Beef sustainability Framework Annual Update 2022*, Meat and Livestock Australia.
MLA (2022b) *Sheep Sustainability Framework Annual Report 2022*. North Sydney: Sheep Sustainability Framework.
Murphy, S. R., S. P. Boschma and S. Harden (2017). "Soil water dynamics and dry-matter production of old man saltbush-, native grass- and lucerne-based pastures in a variable summer-dominant rainfall environment, Australia." Grass and Forage Science **72**(2): 290-307.
Murphy, S. R., S. P. Boschma and S. Harden (2019). "Soil water dynamics, herbage production and water use efficiency of three tropical grasses: Implications for use in a variable summer-dominant rainfall environment, Australia." Grass and Forage Science **74**(1): 141-159.
Naidu, D. R. (1993). "Distribution, properties and management of sodic soils - an introduction." Soil Research **31**(6): 681-682.
Natural Capital Coalition (2016) *Natural Capital Protocol*. London: Natural Capital Coalition. Available at: https://naturalcapitalcoalition.org/natural-capital-protocol/.
NCFA and PwC (2018) *Integrating natural capital in risk assessments: A step-by-step guide for banks*. Geneva, Oxford and London: Natural Capital Finance Alliance and PricewaterhouseCoopers.
NCFA and UN Environment World Conservation Monitoring Centre (2018) *Exploring natural capital opportunities, risks and exposure: A practical guide for financial institutions*. Geneva, Oxford and Cambridge: Natural Capital Finance Alliance and UN Environment World Conservation Monitoring Centre.
Neilly, H. and L. Schwarzkopf (2018). "Heavy livestock grazing negatively impacts a marsupial ecosystem engineer." Journal of Zoology **305**(1): 35-42.
Neilly, H., J. Vanderwal and L. Schwarzkopf (2016). "Balancing biodiversity and food production: A better understanding of wildlife response to grazing will inform off-reserve conservation on rangelands." Rangeland Ecology & Management **69**(6): 430-436.
Norris, C. E., G. M. Bean, S. B. Cappellazzi, M. Cope, K. L. H. Greub, D. Liptzin, E. L. Rieke, P. W. Tracy, C. L. S. Morgan and C. W. Honeycutt (2020). "Introducing the North American project to evaluate soil health measurements." Agronomy Journal **112**(4): 3195-3215.
Northcote, K. H., G. G. Beckmann, E. Bettenay and H. M. Churchward, Van Dijk, D. C., Dimmock, G. M., Hubble, G. D., Isbell, R. F., McArthur, W. M., Murtha, G. G., Nicolls, K. D., Paton, T. R., Thompson, C. H., Webb, A. A., Wright, M. J. (1960-1968). Atlas of Australian Soils, Sheets 1 to 10. With explanatory data. Melbourne, CSIRO Aust. and Melbourne University Press.
Northcote, K. H. and J. K. M. Skene (1972). Australian soils with saline and sodic properties, CSIRO.

Norton, B. E. (1988). "The application of grazing management to increase sustainable livestock production." Animal production in Australia **22**: 15-26.
Orgill, S., D. Antille, R. Armstrong, R. Bell, N. Bolan, R. Bush, M. Cann, C. Chen, S. Clarendon, J. Condon, D. Davenport, G. Dean, K. Dunsford, M. Esfandbod, J. Friend, B. Hackney, G. R. Hancock, M. Hardie, R. J. Harper, F. Hart, M. Hart, R. C. Hayes, D. Henry, M. Imhof, D. Kidd, G. Li, Q. L. Ma, B. Malcolm, J. McL. Bennett, R. Mitchell, D. Parsons, S. Raine, M. Rezaei Rashti, N. Robinson, T. J. Rose, B. Singh, E. Tavakkoli, J. Tullberg, D. Watt, M. Whatmuff and N. Wilhelm (2018). *Mapping projects on ameliorating soil constraints, and review of soil constraints, products and technologies* [Project 3.3.01]. Newcastle, NSW: CRC for High Performance Soils.
Orgill, S. E., C. M. Waters, G. Melville, I. Toole, Y. Alemseged and W. Smith (2017). "Sensitivity of soil organic carbon to grazing management in the semi-arid rangelands of south-eastern Australia." The Rangeland Journal **39**(2): 153-167.
Orton, T. G., T. Mallawaarachchi, M. J. Pringle, N. W. Menzies, R. C. Dalal, P. M. Kopittke, R. Searle, Z. Hochman and Y. P. Dang (2018). "Quantifying the economic impact of soil constraints on Australian agriculture: A case-study of wheat." Land Degradation & Development **29**(11): 3866-3875.
Osanai, Y., O. Knox, G. Nachimuthu and B. Wilson (2021). "Contrasting agricultural management effects on soil organic carbon dynamics between topsoil and subsoil." Soil Research **59**(1): 24-33.
Peck, G., S. Buck, A. Hoffman, C. GHolloway, B. Johnson, D. Lawrence and C. Paton (2011). Review of productivity decline in sown grass pastures. B.NBP.0624. Meat & Livestock Australia Limited, North Sydney.
Pereira, P., M. Francos, E. C. Brevik, X. Ubeda and I. Bogunovic (2018). "Post-fire soil management." Current Opinion in Environmental Science & Health **5**: 26-32.
Peverill, K. I., L. A. Sparrow and D. J. Reuter (1999). Soil analysis: an interpretation manual. Collingwood, CSIRO Australia.
Pillans, B. (1997). "Soil development at snail's pace: evidence from a 6 Ma soil chronosequence on basalt in north Queensland, Australia." Geoderma **80**(1): 117-128.
Pribyl, D. W. (2010). "A critical review of the conventional SOC to SOM conversion factor." Geoderma **156**(3): 75-83.
Purdie, A., C. , L. Ingram, R. Zadocks, K. Plain, A. McPherson, F. Dijkstra, S. Garcia and T. Bell (unpublished). Impact of bushfires on soil, pasture and the microbiome. Report P.PSH.1222. North Sydney NSW 2059, Meat and Livestock Australia Limited
Rabbi, S. M. F., M. Tighe, A. Cowie, B. R. Wilson, G. Schwenke, M. McLeod, W. Badgery and J. Baldock (2014). "The relationships between land uses, soil management practices, and soil carbon fractions in South Eastern Australia." Agriculture, Ecosystems & Environment **197**(0): 41-52.
Rabbi, S. M. F., M. Tighe, M. Delgado-Baquerizo, A. Cowie, F. Robertson, R. Dalal, K. Page, D. Crawford, B. R. Wilson, G. Schwenke, M. McLeod, W. Badgery, Y. P. Dang, M. Bell, G. O'Leary, D. L. Liu and J. Baldock (2015). "Climate and soil properties limit the positive effects of land use reversion on carbon storage in Eastern Australia." Scientific Reports **5**(1): 17866.
Ravansari, R., S. C. Wilson, B. R. Wilson and M. Tighe (2021). "Rapid PXRF soil organic carbon and organic matter assessment using novel modular radiation detector assembly." Geoderma **382**: 114728.
Red Meat Advisory Council (2019). Red meat 2030. Red Meat Advisory Council Limited, Manuka Australia.
Reid, A. M. and B. P. Murphy (2022). Forged by fire: burning the Australian tropical savannas. Global Application of Prescribed Fire. J. R. Weir and J. D. Scasta. Clayton South, Victoria, CSIRO Publishing**:** 73-85.
Richards, R. and P. Vollebergh (2018). What's in it for me – an evidence based approach to improve landholder adoption of riparian works. 9th Australian Stream Management Conference. G. J. Vietz and I. D. Rutherfurd. Hobart, Tasmania, River Basin Management Society**:** 350-357.
Ringrose-Voase, A. J., G. W. Geeves, R. H. Merry and J. T. Wood (1997). Soil indicators of changing land quality and capital value. CSIRO (Australia) Land and Water Technical Report 17/97.
Román Dobarco, M., A. M. J. C. Wadoux, B. Malone, B. Minasny, A. B. McBratney and R. Searle (2022). "Mapping soil organic carbon fractions for Australia, their stocks and uncertainty." Biogeosciences Discuss. **2022**: 1-38.
Sanderman, J., J. Reseigh, M. Wurst, M. A. Young and J. Austin (2015). "Impacts of Rotational Grazing on Soil Carbon in Native Grass-Based Pastures in Southern Australia." PLoS One **10**(8): e0136157.

Santin, C. and S. Doerr (2019). Carbon. Fire effects on soil properties. P. Pereira, J. Mataix-Solera, X. Ubeda, G. Rein and A. Cerda. Clayton South, Victoria, CSIRO**:** 115-128.
Schatz, T. J., K. D. McCosker and C. Heeb (2023). "Phosphorus supplementation improves the growth and reproductive performance of female Brahman cattle grazing phosphorus-deficient pastures in the Victoria River District, Northern Territory, Australia." Animal Production Science **63**: 544-559.
Schut, A. G. T. and K. E. Giller (2020). "Soil-based, field-specific fertilizer recommendations are a pipe-dream." Geoderma **380**: 114680.
Searle, R. (2021). Australian Soil Classification Map. Version 1.0.0. , Terrestrial Ecosystem Research Network. (Dataset).
Shaw, R. E., W. S. Meyer, A. McNeill and S. D. Tyerman (2013). "Waterlogging in Australian agricultural landscapes: a review of plant responses and crop models." Crop and Pasture Science **64**(6): 549-562.
Silver, W. L., T. Perez, A. Mayer and A. R. Jones (2021). "The role of soil in the contribution of food and feed." Philosophical Transactions of the Royal Society B: Biological Sciences **376**(1834): 20200181.
Simmons, A., A. Cowie, B. Wilson, M. Farrell, M. T. Harrison, P. Grace, R. Eckard, V. Wong and W. Badgery (2021) "US scheme used by Australian farmers reveals the dangers of trading soil carbon to tackle climate change." The Conversation.
Singh, K. and B. Whelan (2020). "Soil carbon change across ten New South Wales farms under different farm management regimes in Australia." Soil Use and Management **36**(4): 616-632.
Smith, G.S., F. Ascui, A. P. O'Grady and E. Pinkard (2021) 'Materiality Assessment of Natural Capital Risks in Australian Forestry', *Current Forestry Reports* **7**(4): 282–304.
Smith, R. W., M. Webb, D. Kidd and D. B. Hannaway (2019). "Mapping suitability of pasture species using fine-scale soils and rainfall data." Crop and Pasture Science **70**(12).
Smith, S (2000). Salinity. Briefing Paper No 7/2000. NSW Parliamentary Library Briefing Paper.
Soil CRC (2018). Supporting farmer decision making for soil stewardship and profitability. Technical Report, Program 1 – Investing in high performance soils. Newcastle.
Sorenson, P. T., J. Kiss, A. K. Bedard-Haughn and S. Shirtliffe (2022). "Multi-horizon predictive soil mapping of historical soil properties using remote sensing imagery." Remote Sensing **14**: 5803.
Speirs, S. D., B. J. Scott, P. W. Moody and S. D. Mason (2013). "Soil phosphorus tests II: A comparison of soil test–crop response relationships for different soil tests and wheat." Crop and Pasture Science **64**(5): 469-479.
Stace, H. C. T., G. D. Hubble, R. Brewer, K. H. Northcote, J. R. Sleeman, M. J. Mulcahy and E. G. Hallsworth (1968). A Handbook of Australian Soils'. Glenside, S.A., Rellim Technical Publications.
Steinfeld, H, P. Gerber, T. Wassenaar, V. Castel, M Rosales and C. de Haan (2006) *Livestock's long shadow: environmental issues and options*. Rome: Food and Agriculture Organisation of the United Nations.
Stephens, C. G. (1953). A Manual of Australian Soils, CSIRO, Melbourne.
Stone, G., B. Zhang, J. Carter, G. Fraser, G. Whish, C. Paton and G. McKeon (2021). "An online system for calculating and delivering long-term carrying capacity information for Queensland grazing properties. Part 1: background and development." The Rangeland Journal **43**(3): 143-157.
Teague, R., F. Provenza, U. Kreuter, T. Steffens and M. Barnes (2013). "Multi-paddock grazing on rangelands: Why the perceptual dichotomy between research results and rancher experience?" Journal of Environmental Management **128**: 699-717.
Teng, H., R. A. Viscarra Rossel, Z. Shi, T. Behrens, A. Chappell and E. Bui (2016). "Assimilating satellite imagery and visible–near infrared spectroscopy to model and map soil loss by water erosion in Australia." Environmental Modelling & Software **77**: 156-167.
Thaler, E. A., I. J. Larsen and Q. Yu (2019). "A new index for remote sensing of soil organic carbon based solely on visible wavelengths." Soil Science Society of America Journal **83**(5): 1443-1450.
TNFD (2022) *The TNFD Nature-related Risk & Opportunity Management and Disclosure Framework. Beta v0.1 Release*. Taskforce on Nature-related Financial Disclosures.
Tobin, C., S. Singh, S. Kumar, T. Wang and P. Sexton (2020). "Demonstrating Short-Term Impacts of Grazing and Cover Crops on Soil Health and Economic Benefits in an Integrated Crop-Livestock System in South Dakota." Open Journal of Soil Science **Vol.10No.03**: 28.
Tulau, M., X. Yang, R. McAlpine, M. Veeragathipillai, M. Zhang, S. JKarunaratne, S. McInnes-Clarke and M. Young (2020). "Impacts of a wildfire on soil organic carbon in Warrumbungle National Park, Australia." Proceedings of the Linnean Society of New South Wales: S209-S227.

Tulau, M. J., S. K. McInnes-Clarke, X. Yang, R. A. McAlpine, S. B. Karunaratne, Q. Zhu and D. T. Morand (2019). "The Warrumbungle Post-Fire Recovery Project—raising the profile of soils." Soil Use and Management **35**(1): 63-74.
United Nations, European Commission, Food and Agriculture Organization of the United Nations, Organisation for Economic Co-operation and Development, and World Bank Group (2014) *System of Environmental-Economic Accounting 2012 — Central Framework*. New York, NY: United Nations.
United Nations (2021) *System of Environmental-Economic Accounting—Ecosystem Accounting: White cover (pre-edited) version*. New York, NY: United Nations. Available at: https://seea.un.org/sites/seea.un.org/files/documents/EA/seea_ea_white_cover_final.pdf (Accessed: 23 June 2022).
van Gool, D. (2016). Identifying soil constraints that limit wheat yield in the south-west of Western Australia. Resource management technical report 399. Perth, Department of Agriculture and Food, Western Australia.
van Groenigen, J. W., C. van Kessel, B. A. Hungate, O. Oenema, D. S. Powlson and K. J. van Groenigen (2017). "Sequestering soil organic carbon: A nitrogen dilemma." Environmental Science & Technology **51**(9): 4738-4739.
Vincent, J. D. and H. Mihailou (2023). "Above-average rainfall stimulates short-term, passive recovery of ungulate mediated soil scalds in Australian mesic savanna." Rangeland Ecology & Management **86**: 26-34.
Viscarra Rossel, R., C. Chen, M. Grundy, R. Searle, D. Clifford, N. Odgers, K. Holmes, T. Griffin, C. Liddicoat and D. Kidd (2014). Soil and landscape grid national soil attribute maps – organic carbon (3" resolution).CSIRO.
Vogel, H.-J., E. Eberhardt, U. Franko, B. Lang, M. Ließ, U. Weller, M. Wiesmeier and U. Wollschläger (2019). "Quantitative Evaluation of Soil Functions: Potential and State." Frontiers in Environmental Science **7**.
Walsh P (2002) New method yields a worms's eye view. In 'Farming Ahead',**132**: 16-18.
Wang, B., J. M. Gray, C. M. Waters, M. Rajin Anwar, S. E. Orgill, A. L. Cowie, P. Feng and D. Li Liu (2022). "Modelling and mapping soil organic carbon stocks under future climate change in south-eastern Australia." Geoderma **405**: 115442.
Wang, B., C. Waters, S. Orgill, A. Cowie, A. Clark, D. Li Liu, M. Simpson, I. McGowen and T. Sides (2018). "Estimating soil organic carbon stocks using different modelling techniques in the semi-arid rangelands of eastern Australia." Ecological Indicators **88**: 425-438.
Wang, B., C. Waters, S. Orgill, J. Gray, A. Cowie, A. Clark and D. L. Liu (2018). "High resolution mapping of soil organic carbon stocks using remote sensing variables in the semi-arid rangelands of eastern Australia." Science of The Total Environment **630**: 367-378.
Wang, H. Z., R. Zhao, D. Zhao, S. Liu, J. Fu, Y. Zhang, N. Dai, D. Song and H. Ding (2022). "Microbial-Mediated Emissions of Greenhouse Gas from Farmland Soils: A Review." Processes **10**(2361): 1-14.
Wang, Y., H. Ji, R. Wang, S. Guo and C. Gao (2017). "Impact of root diversity upon coupling between soil C and N accumulation and bacterial community dynamics and activity: Result of a 30year rotation experiment." Geoderma **292**: 87-95.
Wang, L. and Y. Zhou (2023). "Combining multitemporal sentinel-2a spectral imaging and random forest to improve the accuracy of soil organic matter estimates in the plough layer for cultivated land." Agriculture 13(1): 8.
Waters, C. M., S. E. McDonald, J. Reseigh, R. Grant and D. G. Burnside (2019). "Insights on the relationship between total grazing pressure management and sustainable land management: key indicators to verify impacts." Rangeland Journal **41**(6): 535-556.
Waters, C. M., S. E. Orgill, G. J. Melville, I. D. Toole and W. J. Smith (2017). "Management of grazing intensity in the semi-arid rangelands of southern Australia: Effects on soil and biodiversity." Land Degradation & Development **28**(4): 1363-1375.
Webb, N. P., A. Chappell, C. L. Strong, S. K. Marx and G. H. McTainsh (2012). "The significance of carbon-enriched dust for global carbon accounting." Global Change Biology **18**(11): 3275-3278.
Webb, N. P., J. E. Herrick and M. C. Duniway (2014). "Ecological site-based assessments of wind and water erosion: informing accelerated soil erosion management in rangelands." Ecological Applications **24**(6): 1405-1420.

Webb, N. P., C. L. Strong, A. Chappell, S. K. Marx and G. H. McTainsh (2013). "Soil organic carbon enrichment of dust emissions: magnitude, mechanisms and its implications for the carbon cycle." Earth Surface Processes and Landforms **38**(14): 1662-1671.
Webster, R. (2011). "Ginninderra revisited: the contribution of B. E. Butler to statistical pedology." Soil Research **49**(3): 203-211.
Webster, R. and B. E. Butler (1976). "Soil classification and survey studies at Ginninderra." Soil Research **14**(1): 1-24.
Weng, Z., L. Van Zwieten, E. Tavakkoli, M. T. Rose, B. P. Singh, S. Joseph, L. M. Macdonald, S. Kimber, S. Morris, T. J. Rose, B. S. Archanjo, C. Tang, A. E. Franks, H. Diao, S. Schweizer, M. J. Tobin, A. R. Klein, J. Vongsvivut, S. L. Y. Chang, P. M. Kopittke and A. Cowie (2022). "Microspectroscopic visualization of how biochar lifts the soil organic carbon ceiling." Nature Communications **13**(1): 5177.
White, R. and B. Davidson (2020). "Is carbon farming an efficient means of offsetting Australia's greehnouse gas emissions?" Farm Policy Journal(Autumn): 16-21.
White, R. E., B. Davidson and R. Eckard (2021) "An everyman's guide for a landholder to participate in soil carbon farming in Australia." Australian Farm Institute **August 2021**, 1-9.
White, R. E., B. Davidson, S. K. Lam and D. Chen (2018). "A critique of the paper 'Soil carbon 4 per mille' by Minasny et al. (2017)." Geoderma **309**: 115-117.
Wiesmeier, M., L. Urbanski, E. Hobley, B. Lang, M. von Lützow, E. Marin-Spiotta, B. van Wesemael, E. Rabot, M. Ließ, N. Garcia-Franco, U. Wollschläger, H.-J. Vogel and I. Kögel-Knabner (2019). "Soil organic carbon storage as a key function of soils - A review of drivers and indicators at various scales." Geoderma **333**: 149-162.
Williams, G. T. (2017). "Cost-effective landscape revegetation and restoration of a grazing property on the Northern Tablelands of New South Wales: 65 years of change and adaptation at 'Eastlake'." The Rangeland Journal **39**(6): 461-476.
Williams, W. J., S. Schmidt, E. Zaady, B. Alchin, T. M. Swe, S. Williams, M. Dooley, G. Penfold, P. O'Reagain, J. Bushell, R. Cowley, C. Driscoll and N. Robinson (2022). "Resting subtropical grasslands from grazing in the wet season boosts biocrust hotspots to improve soil health." Agronomy-Basel **12**(1): 62.
Wilson, B. R. and V. E. Lonergan (2013). "Land-use and historical management effects on soil organic carbon in grazing systems on the Northern Tablelands of New South Wales." Soil Research **51**(8): 668-679.
Wilson, B. R., M. Tulau, L. Kuginis, S. McInnes-Clarke, S. Grover, H. Milford and B. R. Jenkins (2022). "Distribution, nature and threats to soils of the Australian Alps: A review." Austral Ecology **47**(2): 166-188.
World Economic Forum (2020) *The Global Risks Report 2020*. Geneva: World Economic Forum.
World Economic Forum and PwC (2020) *Nature Risk Rising: Why the Crisis Engulfing Nature Matters for Business and the Economy*. Geneva: World Economic Forum.
Wu, X., T. Ge, H. Yuan, B. Li, H. Zhu, P. Zhou, F. Sui, A. O'Donnell and J. Wu (2014). "Changes in bacterial CO_2 fixation with depth in agricultural soils." Applied Microbiology and Biotechnology **98**(5): 2309-2319.
Wulf, H., V. L. Mulder, M. Schaepman, A. Keller and P. Joerg (2014). Remote Sensing of Soils.
WWF (2021) *Bringing It Down to Earth: Nature Risk and Agriculture*. Oslo: WWF-Norway. Available at: https://wwfint.awsassets.panda.org/downloads/wwf_2021_bringing_it_down_to_earth__nature_risk_and_agriculture_report.pdf (Accessed: 31 March 2022).
Yang, X., J. Gray, G. Chapman, Q. Zhu, M. Tulau and S. McInnes-Clarke (2018). "Digital mapping of soil erodibility for water erosion in New South Wales, Australia." Soil Research **56**(2): 158-170.
Yang, X., J. Leys, M. Zhang and J. M. Gray (2023). "Estimating nutrient transport associated with water and wind erosion across New South Wales, Australia." Geoderma **430**: 116345.
Yang, T., Siddique, K.H.M. and Liu, K. (2020) 'Cropping systems in agriculture and their impact on soil health-A review', *Global Ecology and Conservation*, 23, p. e01118. Available at: https://doi.org/10.1016/j.gecco.2020.e01118.
Yao, Y., Y. Liu, S. Zhou, J. Song and B. Fu "Soil moisture determines the recovery time of ecosystems from drought." Global Change Biology **n/a**(n/a).
Zhan, T., Z. Zhang, J. Sun, M. Liu, X. Zhang, F. Peng, A. Tsunekawa, H. Zhou, X. Gou and S. Fu (2020). "Meta-analysis demonstrating that moderate grazing can improve the soil quality across China's grassland ecosystems." Applied Soil Ecology **147**: 103438.

Zhang, B., G. Fraser, J. Carter, G. Stone, S. Irvine, G. Whish, J. Willcocks and G. McKeon (2021). "An online system for calculating and delivering long-term carrying capacity information for Queensland grazing properties. Part 2: modelling and outputs." The Rangeland Journal **43**(3): 159-172.
Zhang, Y., L. Guo, Y. Chen, T. Shi, M. Luo, Q. Ju, H. Zhang and S. Wang (2019). "Prediction of soil organic carbon based on landsat 8 monthly NDVI data for the Jianghan plain in Hubei province, China." Remote Sensing 11(14): 1683.
Zhang, M., R. A. Viscarra Rossel, Q. Zhu, J. Leys, J. M. Gray, Q. Yu and X. Yang (2022). "Dynamic modelling of water and wind erosion in australia over the past two decades." Remote Sensing **14**(21): 5437.
Zhang, M., R. A. Viscarra Rossel, Q. Zhu, J. Leys, J. M. Gray, Q. Yu and X. Yang (2022) "Dynamic Modelling of Water and Wind Erosion in Australia over the Past Two Decades." Remote Sensing **14** DOI: 10.3390/rs14215437.
Zimmermann, M., M. I. Bird, C. Wurster, G. Saiz, I. Goodrick, J. Barta, P. Capek, H. Santruckova and R. Smernik (2012). "Rapid degradation of pyrogenic carbon." Global Change Biology 18(11): 3306-3316.
Žížala, D., R. Minařík and T. Zádorová (2019). "Soil organic carbon mapping using multispectral remote sensing data: prediction ability of data with different spatial and spectal resolutions." Remote Sensing **11**: 23.

13 Appendices

13.1 APPENDIX 1 - MLA INVESTMENT TO DATE IN SOILS

Eighty-eight projects measured a soil property within the project. Projects were divided into those that had soil as a key focus of the project measuring several parameters and those that considered a soil property as an incidental measure. The projects were then categorised by the MLA website areas.

Soil is the Key Project Focus	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2028**	**Total**
NO	**1**	**2**		**1**	**5**	**2**	**3**	**4**	**2**	**4**	**11**	**3**	**4**	**2**	**1**		**1**		**47**
Animal health and welfare		1					1				2								4
Animal nutrition												1							1
Capacity building									1	1		1							3
Digital agriculture											1		1	2					4
Environmental sustainability						**1**				**1**	**4**	**1**	**1**				**1**		**9**
Feedbase		**1**			**3**	**1**	**1**	**3**	**1**	**2**	**1**		**1**						**14**
Grazing land management				1			1	1											3
Processing productivity								1											1
Producer adoption	1				2						3								6
Food safety and traceability													1						1
Producer demonstration sites															1				1
YES	**1**	**3**	**6**	**1**	**6**	**6**	**1**	**2**		**2**	**1**		**4**		**3**	**1**	**3**	**1**	**41**
Animal health and welfare			1																1
Capacity building				1		1													2
Digital agriculture															1				1
Environmental sustainability		2	1			1				2									6
Feedbase					1	1		1					1						4
Grazing land management	1	1	3		5	3	1	1					1		1		2		19
Livestock production													1						1
Producer adoption			1								1		1						3
Producer demonstration sites															1	1	1	1	4
Total	**2**	**5**	**6**	**2**	**11**	**8**	**4**	**6**	**2**	**6**	**12**	**3**	**8**	**2**	**4**	**1**	**4**	**1**	**87**

Projects were categorised by the Australian and New Zealand Standard Research Classification to assess trends in soil research over time for projects without (a) and with (b) soil as the key focus.

Soil is the Key Project Focus (a)	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2028**	**Total**
NO	**1**	**2**		**1**	**2**	**1**	**3**	**5**	**2**	**4**	**8**	**2**	**3**	**1**			**1**		**36**
Biology								1			1								2
Chemistry				**1**	**1**		**1**	**2**	**1**	**1**	**2**								**9**
Chemistry + C		1									2						1		4
Physical					**1**	**1**	**1**		**1**	**2**		**1**	**1**	**1**					**9**
Chemistry Physical								2											3
Chemistry + C Physical		1																	1
Chemistry Biology							1				1								2
Chemistry + C Biology										1									1
Soil productivity Chemistry												1							1
Biology Chemistry Physical											1								1
Other	1												2						3

Projects were categorised by the Australian and New Zealand Standard Research Classification to assess trends in soil research over time for projects without (a) and with (b) soil as the key focus.

Soil is the Key Project Focus (b)	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2028**	**Total**
YES	**1**	**3**	**5**		**4**	**4**		**2**		**1**	**1**		**3**		**3**	**1**	**2**	**1**	**31**
Biology			1			1													2
Chemistry		**1**	**1**		**2**	**1**		**2**					**1**						**8**
Chemistry + C		**1**				**1**				**1**					**1**	**1**			**5**
Physical		1	1		1														3
Chemistry Physical			1												1		1		3
Chemistry Biology						1							1		1				3
Chemistry + C Biology			1								1								2
Chemistry Land capability																		1	1
Soil productivity Biology Chemistry					1														1
Soil productivity Biology Chemistry + C	1																		1
Chemistry Biology Physical													1				1		2

13.2 APPENDIX 2 - MLA Soil Programs

e-LEARNING	The toolbox	The toolbox – online training | Meat & Livestock Australia (mla.com.au)
PROGRAMS ON HEALTHY SOILS HUB	Healthy Soils Hub within Feedbase Hub	Kicking off with healthy, fertile soils | Meat & Livestock Australia (mla.com.au)
	Five Easy Steps to ensure you are making money from phosphorus fertiliser	5-easy-steps-guide.pdf (mla.com.au)
		MLA Soil Phosphorus Tool
	Producer Demonstration Sites program assessment of products on offer	Principles and approaches for choosing soil and pasture treatments | Meat & Livestock Australia (mla.com.au)
	How do I make sense of soil test results	how-do-i-make-sense-of-soil-test-results.pdf (mla.com.au)
	Soil Testing	Soil testing - The Toolbox - MLA eLearning
	Visual indicators of soil condition	Visual indicators of soil condition - The Toolbox - MLA eLearning
PROFITABLE GRAZING SYSTEMS	Pay Dirt and Pay Dirt North	A package developed to value-add to soil testing results and to help producers determine how to get the most bang for their fertiliser buck.
PRODUCER DEMONSTRATION SITES	Various sites – see excel list	Aims to increase the rate of adoption of key management practices and technologies which improve business profitability, productivity and sustainability.
EDGE network	Grazing Fundamentals	EDGE network | Meat & Livestock Australia (mla.com.au)
	Grazing Land Management	
CARBON CN30 PROGRAMS	Carbon 101	Carbon 101 - The Toolbox - MLA eLearning
	Measuring your own emissions	Measuring your own emissions - The Toolbox - MLA eLearning
	Carbon sense	Carbon Sense - The Toolbox - MLA eLearning
MLA PROGRAMS THAT ARE > 10 YEARS OLD	Making better fertiliser decisions	Making Better Fertiliser Decisions for Grazed Pastures in Australia
	More beef from pasture – build and maintain soil nutrients to improve soil fertility and health in pasture zones	Build and maintain soil nutrients to improve soil fertility and health in all pasture zones | MBFP | More Beef from Pastures (mla.com.au)

13.3 APPENDIX 3 – Soil mapping by State/Territory

13.3.1 Western Australia.

13.3.1.1 Soil Landscape Mapping - Best Available (DPIRD-027)

https://catalogue.data.wa.gov.au/dataset/soil-landscape-mapping-best-available

Soil-landscape mapping covering Western Australia at the best available scale (Version 05.01). It is a compilation of various surveys at different scales varying between 1:20,000 and 1:3,000,000. Mapping conforms to a nested hierarchy established to deal with the varying levels of information resulting from the variety of scales in mapping.

For further information refer to Department of Agriculture Resource Management Technical Reports RMTR No. 280 and RMTR No. 313.

Land capability and land quality attribution is included, refer to Department of Agriculture Resource Management Technical Report No. 298 for a description of the methodology employed.

13.3.1.2 SALINITY:

https://catalogue.data.wa.gov.au/dataset/groundwater-salinity-statewide

13.3.1.3 ACIDITY:

https://catalogue.data.wa.gov.au/dataset/?q=acidity

13.3.2 South Australia

https://www.data.gov.au/dataset/ds-sa-ae914203-50c3-4194-acc5-402c2cd62841/details?q=south%20australian%20soils

13.3.2.1 Soils (soil type)

Department for Environment and Water / Created 06/06/2016 / Updated 18/02/2020.

Sixty one soils (soil types) represent the range of soils found across South Australia's agricultural lands. Mapping shows the most common soil within each map unit, while more detailed proportion data are supplied for calculating respective areas of each soil type (spatial data statistics).

13.3.2.2 SALINITY:

https://data.sa.gov.au/data/dataset?q=salinity&sort=extras_harvest_portal+asc%2C+score+desc%2C+metadata_modified+desc

13.3.2.3 ACIDITY:

https://data.sa.gov.au/data/dataset?q=acidity&sort=extras_harvest_portal+asc%2C+score+desc%2C+metadata_modified+desc

13.3.3 Victoria

https://datashare.maps.vic.gov.au/search?q=soil

13.3.3.1 Victorian Soil type mapping

Resource Name: SOIL_TYPE. Publication Date: 01-02-2018. ID: c6499383-f8eb-5cf6-9463-b04bc4b017fe

A spatial map layer of soil type (Australian Soil Classification) for Victoria. The harmonised map consists of 3,300 land units (totalling about 225,000 polygons) derived from around 100 soil and land surveys carried out in Victoria over the past 70 years. The land units have been attributed according to the Australian Soil Classification (Order and Suborder levels of the classification scheme)

13.3.3.2 SALINITY:

https://datashare.maps.vic.gov.au/search?q=salinity

13.3.3.3 ACIDITY:

https://discover.data.vic.gov.au/dataset/soil-grids-of-victorian-soil-ph-cacl21

13.3.4 New South Wales

https://datasets.seed.nsw.gov.au/dataset/land-and-soil-capability-mapping-for-nsw4bc12

13.3.4.1 Great Soil Group (GSG) Soil Type map of NSW

https://www.data.nsw.gov.au/search/dataset/ds-nsw-ckan-bb1f895b-ceaa-45eb-a056-3423fd7588d9/details?q=soil

Department of Planning and Environment / Created 05/09/2018 / Updated 30/06/2022.

This map provides soil types across NSW using the Great Soil Group classification. It uses the best available soils resource mapping coverage incorporating over 55 different datasets of multiple scales. Hence the published scale of this linework is between 1:100,000 - 1:500,000 depending on the dataset it originated from. Further information about these datasets is available in the 'Lineage', 'Positional accuracy' and 'Attribute accuracy' sections of the metadata.

13.3.4.2 SALINITY:
https://www.data.gov.au/dataset/ds-dga-aa2cc095-5a2b-4b43-9d20-07a1cd9da012/details?q=south%20australian%20salinity

13.3.4.3 ACIDITY:
https://www.data.gov.au/dataset/ds-nsw-3487c224-d0fe-4d18-af22-04cebca5a9c0/details?q=nsw%20acidity

13.3.5 Tasmania

https://www.asris.csiro.au/themes/Atlas.html#Atlas_Downloads

https://nre.tas.gov.au/agriculture/land-management-and-soils/land-and-soil-resource-assessment/soil-maps-of-tasmania

https://www.thelist.tas.gov.au/app/content/data/geo-meta-data-record?detailRecordUID=98f416e6-f381-48e2-8b16-5c31a8e45ba5

A WMS soils service is available.

https://www.arcgis.com/home/webmap/viewer.html?webmap=00052050c11b4b32beff8cbe6b71904d&extent=144.9626,-42.8865,150.4612,-40.1815

https://maps.thelist.tas.gov.au/listmap/app/list/map?bookmarkId=822830

13.3.5.1 SOIL DOWNLOAD:
https://www.thelist.tas.gov.au/app/content/data/geo-meta-data-record?profileType=&groupName=&bboxNorth=&bboxWest=&bboxSouth=&bboxEast=&sc_tc_code=geoscientificInformation&titleSearch=true&query=soil&_keywordCategory=-1&isTasmania=true&custodian=&detailRecordUID=87e87ea0-ad62-4c59-b09d-6ffa14c9740b&searchCriteriaURL=query%3Dsoil%26perPage%3D10%26sortBy%3DTitle%3AASC%26sc_tc_code%3DgeoscientificInformation%26titleSearch%3Dtrue

13.3.6 Queensland

The state coverage in one map is based on dominants soil orders (https://qldspatial.information.qld.gov.au/catalogue/custom/detail.page?fid={A4EAC62F-A8F4-4E98-A52F-95A9F67AEA36}) , many small to regional surveys.

https://www.data.qld.gov.au/dataset/soils-series

13.3.7 Northern Territory

https://www.asris.csiro.au/themes/Atlas.html#Atlas_Downloads

https://www.ntlis.nt.gov.au/metadata/export_data?metadata_id=2DBCB771214A06B6E040CD9B0F274EFE&type=html