SOIL CRC

Performance through collaboration

FINAL PROJECT REPORT

Mapping projects on ameliorating soil constraints, and review of soil constraints, products and technologies

Project 3.3.01

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The Soil CRC recognises the value of knowledge exchange and the importance of objective peer review. It is committed to encouraging and supporting its research teams in this regard.

The author(s) confirm(s) that this document has been reviewed and approved by the project's steering committee and by its program leader. These reviewers evaluated its:

- originality
- methodology
- rigour
- compliance with ethical guidelines
- conclusions against results
- conformity with the principles of the Australian Code for the Responsible Conduct of Research (NHMRC 2007), and provided constructive feedback which was considered and addressed by the author(s).

PROJECT PARTICIPANTS

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EXECUTIVE SUMMARY

This report summarises findings from interrelated activities that consolidated and reviewed existing soil constraint maps, ameliorants, current and previous research and lists the magnitude and cost of soil constraints to agriculture. The aim was to identify future Research and Development priorities for Program 3 (with flow on to Program 4) of the Soil CRC. Thirty six Soil CRC members (representing 13 organisations) contributed to this review. Using expertise across the spectrum from adviser, technical expert and next-users this report identifies key priorities to overcome important soil constraints across a range of different industries and regions of Australia. Key soil constraints include: dispersive clays, alkalinity, acidity, salinity, poor/coarse/compacted soil structure, nutrient deficiency and declining organic carbon and problematic sandy soils. A baseline industry survey of 135 farm advisers servicing 11 million hectares of agricultural land, have identified and prioritised these key soil constraints.

Prioritisation was strongly related to the region and industry serviced by the adviser. Key Development and Extension (D&E) needs were also identified as part of the survey. A review of soil constraint mapping highlighted the need for consistent national, regional and industry-wide products for several key soil constraints. Development of these maps would help contextualise current, and target future, activities for priority land uses, regions and constraints.

This report highlights that considerable productivity gains are possible using targeted R, D & E which defines and maps soil constraints, accounts for multiple soil constraints and addresses soil x region x industry specificity of amelioration responses. There is a need to better understand the mechanisms underpinning plant response to current soil ameliorants to guide the improvement and development of new and alternative ameliorant products. Practical, economic, accessible and system-integrated amelioration strategies that target the major (multi-) constraints are more likely to be adopted than expensive novel and niche products. Future investments should be guided by impact, production and profitability gains. Any amelioration strategy must be validated with next-users to maximise practice change.

OBJECTIVES	RESULTS
To identify the location and impact of soil constraints, including mapping products and current and past research projects, and identifying future research needs for soil amelioration strategies and products for the Soil CRC to consider. Specific objectives: 1. Consolidate and review existing soil constraint maps and compile a summary of the magnitude and cost of soil constraints to agriculture 2. Identify current and past soil constraint and amendment research	This report contains: 1. A review of soil constraints to agricultural production in Australia 2. Results from a survey of over 135 farm advisers on soil constraints 3. A comprehensive review of soil constraint mapping products 4. Key considerations for evaluating the economic and environmental impacts of soil constraints, their management and research investment In addition, this scoping study has enabled 5. Networks to develop among the project team

NEXT STEPS	TIMING
Development of projects focused on mapping, economic analysis and mitigation of soil constraints to be submitted for Research Call 18-3	November 2018.

1. INTRODUCTION

Soil constraints can be any physical or chemical characteristic that limits root access to moisture and/or nutrients and reduces biological activity. In Australia, approximately 75% of agricultural soils have constraints that limit productivity. Soil constraints may be present in the surface of the profile, in the subsoil or often in combination. Some examples of soil constraints include: nutrient deficiencies, acidity, alkalinity, salinity, sodicity, dispersion, compaction, gravel layers, non-wetting soils, hard pans and hard setting soils. Identifying, understanding and managing these constraints are the major challenges to increasing agricultural productivity. Soil amelioration materials such as manure, composts and calcium products, and technologies such as subsoil manuring through injection and the addition of clay and organic matter into bleached horizons of lighter texture soils are currently being trialled to manage constraints. However, producers still face the challenge of identifying what particular constraints are limiting production, where these constraints occur (both within the profile as well as spatially across a paddock), the effectiveness of different amelioration strategies to improve productivity and ways to economically ameliorate or manage them, especially when there are multiple constraints.

The aim of this project was to identify the location and impact of soil constraints, including mapping products and current and past research projects, and identify future research needs for soil amelioration strategies and products for the Soil CRC to consider. This Scoping Study is critical in prioritising the future directions of research in Output 3 (Novel materials to address surface and subsurface soil constraints) of Program 3, and links strongly to Program 2 and Program 4. Specifically, this Scoping Study (3.3.01) addresses: Research Program 3 Milestone Output 3 - Novel materials to address surface and subsurface soil constraints, and Research Program 3 Milestone 3.1 Complete a review on technologies for advanced organic-based materials for ameliorating subsurface acidity and sodicity constraints.

The project had two objectives:

1. Consolidate and review existing soil constraint maps and compile a summary of the magnitude and cost of soil constraints to agriculture, and
2. Identify current and past soil constraint and amendment research.

To achieve this we:

- Collected and collated current industry practice for managing soil constraints (including type of ameliorant, rate and method of application)
- Documented and reviewed past and current soil constraint research
- Identified the interaction effects of site-specific multi-soil constraints
- Identified appropriate machinery considerations for applying amelioration products, including strategies to integrate these into the development and selection of amelioration strategies
- Identified emerging technologies and novel solutions that are yet to be fully developed and tested for managing soil constraints
- Identified technological and economic barriers to the implementation of existing and future amelioration strategies

This report identifies the major soil constraints to agriculture as determined by the scientific literature, soil researchers, advisers and industry stakeholders. The report will serve as a baseline account of current soil constraint research including available mapping products, lists current research on soil amelioration strategies and products and identifies future research needs in this field. Each of the (five) activities related to these components were deemed necessary by the Scoping Study team to provide useful feedback to the Soil CRC (Figure 1) and achieve the aims of this project. The purpose of the information gathered for this Scoping Study, and reported here, is to guide and ensure relevant and farm ready research is pursued to enable producers to bridge the gap between soil science and decision making on-farm and ultimately increase profitability.

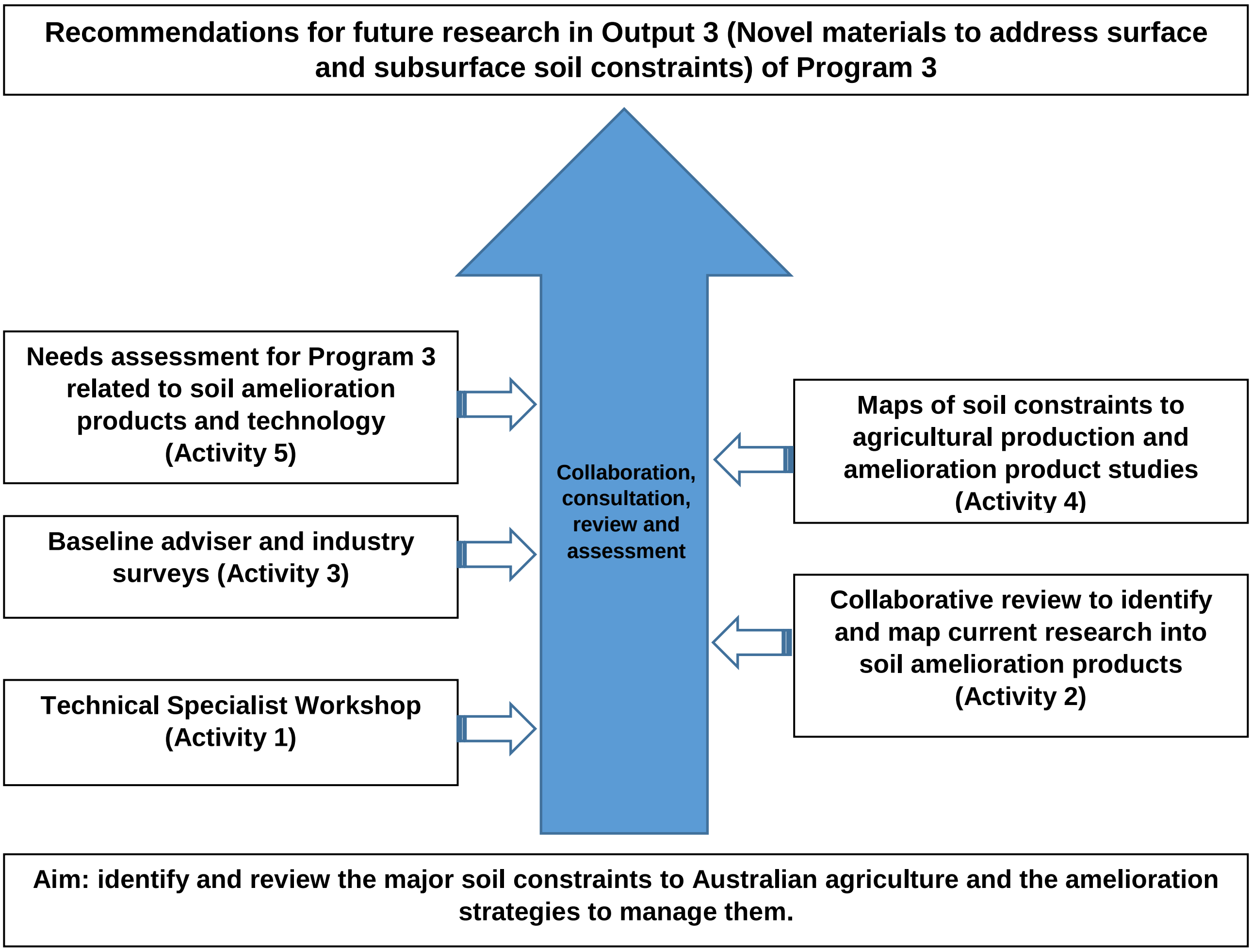

Figure 1. Outline of the approach taken in Scoping Study 3.3.01 to determine key recommendations for future research in Output 3 (Novel materials to address surface and subsurface soil constraints) of Program 3.

2. PREVIOUS RESEARCH AND LITERATURE

This Section is presented later in the Final Report as "Collaborative review to identify and map current research into soil amelioration products" (Activity 2).

3. METHODOLOGY

The purpose of this Scoping Study was to capture expertise across the spectrum of stakeholders including: practitioners, managers, technical experts and innovators. Five interrelated activities were conducted including a combination of desktop reviews, mapping activities (to define the location, scale and magnitude of soil constraints), technical working groups (to bring together literature and findings on soil constraint mapping and amelioration products) and adviser and industry surveys (to collect baseline information on current amelioration strategies and limitations to adoption).

3.1 Technical Specialist Workshop (Activity 1)

This Activity was led by Dr Susan Orgill and Prof Roger Armstrong.

A two-day workshop was held at the Stamford Plaza, Sydney on the 12th and 13th March 2018. The workshop was facilitated by John Cameron (ICAN), and 31 Scoping Study participants (i.e. Soil CRC members) attended. The aim of the workshop was to identify past and current research addressing soil constraints to agricultural production and identify future research priorities. The specific workshop objectives were to: 1) identify and agree on prioritised soil constraints (in terms of relative scale and impact) to agriculture in Australia, 2) identify past and current soil amelioration research, 3) identify soil amelioration products and technologies that are available and the scope of their application and impact, 4) discuss the current and future (emerging issues) gaps and 5) reach consensus on overriding principles and considerations for future R&D on soil amelioration strategies. The workshop agenda (see Appendix 1) included a combination of presentations and focus groups based on themes.

Soil constraint theme leaders were nominated before the workshop through an expression of interest and included:

- Dr Ehsan Tavakkoli (NSW DPI; dispersive soils and alkalinity)

- Dr Jason Condon (CSU; soil acidity)

- Assoc. Prof John McLean Bennett (USQ; salinity and soil physical constraints)

- Dr Dio Antille (USQ; machinery and engineering solutions)

- Dr Qifu Ma (Murdoch University; nutrient constraints)

- Prof Richard Bell (Murdoch University; sandy soils)

Workshop preparation included:

- Reviewing past and current research on soil amelioration based on theme/industry/region
- Preparation of a short (3-4 page) paper that was presented by the theme leader and which outlined the soil constraint and listed the amelioration research to date (where, when, who, outputs).

3.2 Collaborative review to identify and map current research into soil amelioration products (Activity 2)

This Activity was led by Prof Richard Bell and Dr Susan Orgill, with themes led by Dr Ehsan Tavakkoli, Dr Jason Condon, Assoc. Prof John McLean Bennett, Dr Qifu Ma, Prof Richard Bell and Dr Dio Antille.

Technical specialist working groups were formed to identify the spatial and temporal characteristics of the soil constraints, and review the scope, impact, opportunities and limitations of the current or potential amendment and/or technology. This included reviewing literature, engaging with internal and external (of the Soil CRC) research groups on current activities and the collation of current research. This activity built on the outcomes of the Technical Specialist Workshop (Activity 1).

3.3 Baseline adviser and industry surveys (Activity 3)

This Activity was led by Melissa Cann, with support from other Agriculture Victoria staff: Rebecca Mitchell, Lisa Cowan, and NSW DPI staff: Dr Susan Orgill, Dr Belinda Hackney, Abigail Jenkins and Luke Beange.

This activity aimed to better understand the soil constraints to production as perceived by farm advisers and key industry personnel and document the current amelioration strategies and the barriers to practice change.

A small team of Agriculture Victoria, NSW DPI and University of Tasmania staff worked together to develop questions to gather information from farm advisers and key industry representatives on:

- Management of soil constraints
- Barriers to adoption
- Innovative amelioration techniques being used to overcome soil constraints

Information was gathered through an online survey (of advisers) and one-on-one interviews with key industry representatives. The survey comprised 14 questions, both tick box and open/qualitative questions (see Appendix 2). The platform used was Survey Monkey. This scoping study purposefully targeted farm advisers, to differentiate from the Scoping Study 4.2.1 (Program 4) and to enable a collective response to be used in decision making for future research directions by the Soil CRC.

Agriculture Victoria and NSW DPI considered Human Ethics Approval, and undertook due diligence prior to the survey being released. Internally, three levels of review and approvals were sought, as well as oversight and review from one of Agriculture Victoria's leading social researchers. Through this committee, it was determined that this particular research fitted in the category of negligible risk (2.17), as the survey was deemed to be an 'audit of information'. If any participant chose to provide their contact details to enable further follow up they completed a separate survey. In this way there was nothing to identify an individual's response to the survey, thus fitting the category "exempted from review".

To gain traction, the survey was emailed out directly to key stakeholders, consultancy firms, key industry representatives, with the request that they forward it through their networks. In addition, Agriculture Victoria and NSW DPI utilised social media (e.g. Twitter, Facebook and Soils Community of Practice Newsletter) to further promote the soil survey. Key industries targeted for this survey included: cropping, beef, sheep, dairy, sugar cane, rice, cotton, irrigated cropping and fruits and vegetables, but it was open to any farm adviser wanting to participate.

The survey was open for four weeks (5th April to 11th May 2018). Agriculture Victoria compiled and analysed the data. This report highlights some of the key data from the survey and will focus on a couple of key constraints to compare current amelioration techniques used and new practices that advisers would like to see validated in their region.

The key industry personnel interviews were designed to provide qualification of the feedback from the survey of the key soil constraints, barriers to production and the technologies used in their industry. Questions were also asked of their current and planned future investment in soils R, D and E and their propensity to engage with Soil CRC projects throughout the next decade, and of the potential gains to the industry they represented. Most of these interviews occurred over the phone.

3.4 Maps of soil constraints to agricultural production and amelioration product studies (Activity 4)

This Activity was led by Mark Imhof, Dr Nathan Robinson and Dr Darren Kidd, with support from members of the National Committee on Soil and Terrain.

A specialist mapping team was formed to identify and review existing soil constraint maps. This included reviewing the limitations of current soil constraint maps (for all States where available) and collating all relevant publicly-available and confidential soil spatial layers.

3.5 Needs assessment for Program 3 related to soil amelioration products and technology (Activity 5)

This Activity was led by Prof Roger Armstrong and Dr Susan Orgill, with the economic analysis contributed by Dr Bill Malcolm and a ‘Needs’ panel consisting of Prof Nanthi Bolan, Dr Lukas van Zwieten and Dr Richard Doyle.

Part A: Economic Analysis of Investing in Ameliorating Soil Constraints

The aim of this activity was to apply a farm economics approach to analysing the potential benefits and costs of interventions in soil management to overcome constraints to production in cropping and grazing systems. Economics is the principal factor determining many grower decisions, although other considerations such as logistical and knowledge constraints, values and aspirations and attitudes to risk are also important. Ultimately, unless the financial returns from undertaking a particular practice result in greater returns than the ‘cost’, farmers will be reluctant to implement the change (or will remain solvent). This practice change does not necessarily have to be profitable immediately, but where there is a delay in this change, a suitable discount must be applied. Overall, the approach used is the farm management economics approach, summarised as: ‘Farm Management Economic Analysis: A Few disciplines, A Few Perspectives, a Few Figurings, a Few Futures,’ (Malcolm 2002, Malcolm et al 2005).

Part B: Development of a short document that is informed by the Scoping Study findings, and that recommends future Soil CRC research priorities in the field of soil constraint research and amelioration. Part B will involve Activity coordinators from this Scoping Study (3.3.01), the Program 3 Leader, the Project Leader for Scoping Study 3.1 and Program 2 and 4 leaders.

4. RESULTS

4.1 Major outcomes of the Technical Specialist Workshop (Activity 1)

4.1.1 General messages

- Purpose of the Soil CRC is to help farmers achieve greater profitability
- Stronger interest from the Soil CRC in soil constraints to broadacre agriculture
- Research needs to be new and different, cover a considerable geographic area and be collaborative
- Innovative – do not repeat what has been or is being done
- Soil constraints can be present in the surface (or top) soil, subsurface and subsoil
- Multiple soil constraints and tailored solutions are the key areas for new research
- Solutions might be an integrated approach to address multiple constraints or a farming systems approach where rotations (crop sequence) and livestock are part of the solution to address the soil constraints
- Solutions should to address farmer needs in order to understand and predict the problem. It was suggested that this should include easy on-farm methods for monitoring
- At one level, the Soil CRC has a mandate for all Australian agricultural sectors across all of Australia. However, with limited resources, major focus will be aligned with that of the participant members (incl. universities, state agencies, farmer groups). As such, there is a focus on the broadacre industries (grains, grazing livestock (beef, wool, lamb)) and sugar. Dairy, horticulture and viticulture are not a major focus of the Soil CRC at this stage, but should there be investment from those industry sectors in the future, the Soil CRC will respond accordingly. Soil CRC coverage, via participants, is across all states of Australia, albeit with less focus on the rangeland areas. Irrigated agriculture is not the major focus, but it is not to be excluded either.

Dispersive and alkaline soils – general discussion

- One-third of the world's soils are alkaline (pH > 8). In Australia, alkaline sodic soils occupy 24% of the total land area (while other categories of salt-affected soils occupy 7% of the land area). Over 80% of soils in agricultural zones in South Australia are alkaline.
- Direct and indirect impacts associated with sodicity include: bicarbonate toxicity, transient salinity, soil structural deterioration, nutrient constraints (for example: decreasing levels of calcium, magnesium, zinc, boron, iron, and micronutrient toxicity of aluminium, boron, manganese and molybdenum in soil solution)
- Poor use of subsoil water = reduced yield and quality = less profit

- Solutions have to be tailored and must address the multiple soil constraints associated with sodicity and alkalinity
- Moderate to high economic impact due to scale and magnitude of problem

Soil acidity – general discussion

- Still partly a D&E issue: quality of lime, placement, how to apply. Need to engage and educate farmers
- Acid stratification is an issue, accentuated by modern farming systems (e.g. minimum/no tillage)
- Technology exists to sense or non-destructively measure soil pH, but cost is prohibitive
- Need to update information on acidification rates. Higher production = increased rate of acidification. Modelling is required to better understand contemporary acidification rates.
- Soil acidity rarely occurs in isolation. Acidity is inter-related with other soil constraints such as nutrient deficiencies and toxicities. Therefore projects could share experimental resources to better understand interactions.
- Most of the soil acidity work was completed in the 1980's. Soils and farming systems have changed since then and therefore solutions need to be modified and more research is required to better understand the issue and management in modern day farming systems. Economics relating to benefit of liming typically have been undertaken under significantly different commodity price structures than those that currently exist particularly with regard to livestock prices. Revisiting economics would be very valuable.
- Benefit of new soil acidity research is building on known processes and applying this to new farming systems
- Soil acidity in the low rainfall zone is an emerging problem associated with increased yields (resulting in a net-export of alkaline material) and an extended period of not ameliorating acidity. The cost-benefit of liming in the low rainfall zone is likely to be very marginal. More information is required on the optimum liming strategy, for example deep ripping, incorporate with an organic amendment and/or supplement the liming program with a pasture rotation.
- What is the cost-benefit of treating subsoil acidity? Potentially the biggest production gains and improvements in soil pH will be made when ameliorating multiple subsoil constraints.
- What is the real cost of not ameliorating acidity, and maintaining farming practices that continue to acidify soils?
- In 95% of cropping soils, acidity is increasing. On alkaline soils, this may be beneficial in terms of production
- Liming models use bulk soils, rather than soil layers and hence there is inadequate information on lime placement

Soil salinity and soil physical constraints – general discussion

- Plant solutions are well established – perhaps need to better link with plant breeding projects for plant-based engineering (note: this is likely out of scope for the Soil CRC)

Salinity (irrigation)

- Where irrigation water is saline, it may be better to treat the water rather than the (soil constraint) consequence of using the water. For these situations we need to come up with site-specific thresholds.
- Use drainage models and outputs to see the cost-benefit of managing soil salinity through water treatment and using 'precision irrigation' to leach salts (to account for different soil properties spatially)

Compaction

- In 2002, compaction was estimated to be costing growers over $850M per year in lost production (Walsh 2002; it should be noted that in this source there is no explanation on how this figure was calculated). Other estimated costs of compaction are: $350M/yr in Western Australia (Western Australian Department of Primary Industries and Regional Development 2018), >$50M/yr in the cotton industry (Bartimote et al. 2017; only one site but the best current estimate), ~$45M/yr in the Northern Grains regions (GRDC tender 2017) and ~$140M/yr in the sugar industry (Braunack, 2000).
- Despite the magnitude and impact, we still have few tools available to diagnose and manage compaction.
- Suggested that many farmers do not use controlled traffic due to high capital expenses (of machinery). While low-impact machinery costs may be high, so too are the soil and production benefits of amelioration.
- Need to (re)evaluate the role of manipulating wetting and drying cycles and the extent to which they can alleviate compaction
- Need mechanical solutions in the first instance and then progress to plant solutions
- Need simple and cheap tools to measure compaction (link with Program 2)

Water repellent or hydrophobic soils

- In south-western Australia, hydrophobic soils are estimated to cost growers over $150 million per year. There is a $5M GRDC project in this region (WA) on water repellent soils (ends 2019).

<u>Nutrient constraints – general discussion</u>

- There is a lot of information already available on managing soil nutrients and projects investigating crop nutrition
- Soil nutrient constraints are often unrecognised and occur together with other constraints
- Evidence suggests that farmers are not putting on optimal amounts of nutrients to achieve water-limited yield (WLY)
- Opportunities to unlock nutrients in soil
- Crop rotations could be optimised to enhance nutrient availability and build up

- More information is needed on root-soil interactions (high priority)
- Conventional soil testing can be time consuming and expensive – efficiencies can be made with rapid soil testing (link to Program 2)
- New products may include silicon due to early indications of beneficial impact on crops under stress
- Are there soil management solutions which increase the quality (i.e. nutrient content) of products, for example grains? Internationally, importers are looking for higher nutrient value products.
- Significance of nutrient stratification on fertiliser management/crop response (see recent scoping study funded by GRDC)

<u>Sandy soils – general discussion</u>

- Oldest clay sites in SA are approximately 60 years old
- Largely a WA and SA issue; grain growing and livestock producing systems
- Major investment in water repellence funded by GRDC (West – ends 2019 and South– ends 2021)
- Beneficial impact of clay type is unknown. This is likely to influence the amount of clay required. Clay does not necessarily need to have a high CEC to be of benefit
- Clay has to be incorporated, not left on soil surface
- Available clay 'deposits' are related to soil landscape pattern however are not well mapped. Ideally, locally sourced or *in situ* clay (clay at depth) to maximise cost-benefit of claying or delving. Need to better predict amount, type and depth of subsoil clay layers.
- Soil-root functions as impacted by claying remains largely unknown so it is hard to quantify the soil performance benefits
- Potential to double yield with clay incorporation
- More research is required on the role of organic amendments (topsoil and subsoil application) on sandy soils

<u>Machinery – general discussion</u>

- Better to modify the product to use existing farm machinery, than create more expensive and specialist machinery
- Need to identify equipment that is adaptable
- Need to identify right material, timing and rate and modify machinery around these factors
- New products should be designed with ideal physical properties (and re-engineered where necessary to achieve this) to be readily adopted
- Efficiencies can be made with spatial diagnostics and material placement
- Major scoping study funded by GRDC (DAV00149) reviewed machinery options

4.1.2 Key findings of focus groups for future research based on theme

Workshop participants self-nominated to one or more themes for the focus group sessions. Each theme leader facilitated the focus groups sessions differently. There was also a ‘research-style speed dating session’ to ensure participants could contribute across themes. Below are the key findings from these sessions.

Dispersive and alkaline soils

Suggested strategy to evaluate the issue

- Diagnosis of the problem? (e.g. farming system WUE)
- Understanding the problem (nature of constraint) when multiple issues present, e.g. Na+ toxicity; waterlogging, high soil strength.
- Prediction - variable responses, e.g. Genotype x Environment x Management
- Potential solutions: ameliorate (gypsum, organic matter/subsoil manuring, polymer-based products), genetic/biology, management/agronomy, ‘live with the problem’ (adjust variable cost input to match revised yield potential)
- Machinery/Field implementation/economics; dryland and irrigated

Considerations

- Multiple landuse/farming systems, irrigation, sugar cane etc. not just dryland cropping
- Single vs multiple amendments
    - Interactions?
    - Physical and chemical/nutritional constraints? (High priority #1)
- Holistic or individual factor focus?
- Plant biology/ soil factor approach?
- Inconsistent response to treatments - soil specificity (High priority #2)
- Is sodicity in soils increasing - spatially, temporally?
- Amendments - is type important, or more about amount; where in profile to apply; how much to apply? (High priority #3)
- Natural materials v e.g. Polymers - interaction of amendments - aggregation - machinery - best method for application - spacing, depth, rate (High priority #4)
- Economics - residual effect
- Understanding the precise nature of the constraint/s

Priorities

1. Tailor solutions for key agricultural systems - sugar; cotton (Vertosols) - grains (sand/clay, Calcarosols, Vertosols, Sodosols)
2. Improve farm level diagnostic options (spatial tool with economics)

Potential dispersive and alkaline constraint projects identified as a priority by the theme group and workshop attendees for this theme only

1. Multiple constraints in sodic, alkaline soils - what to target? (Theme group: High, Workshop group: #1)

- Large gap in extending existing knowledge, linkage with Program 4.2 farm trials, innovative amendments, focus of the future work should be grains-based growers vs …., solutions should ideally use commercial available machinery

2. Can we make a non-sodic (sub) soil from a sodic soil? Irrigated vs dryland (Theme group: High, Workshop group: #2)
3. Innovative amendments; e.g. hydrogels, +/- nutrients (Theme group: High, Workshop group: #3)
4. Plant options to facilitate root growth (Theme group: High, Workshop group: #4)
5. Products, e.g. micro/nano gypsum (Theme group: High, Workshop group: #5)

<u>Soil acidity</u>

Gaps

- Rates of surface/subsurface acidification with new farming systems and considering the acidification that has occurred over the past couple of decades
- Variability within paddock and measurement given existing sampling methodology
- Cost of inaction including: production penalty, off site impact, soil condition and viable crop choices
- Acidification penalty of increased production (i.e. increase production = increased transfer of alkaline product offsite)
- Interaction of lime and organic matter (pH and/or nutrient, physical), and the potential to increase the rate of lime movement down the soil profile when products are used in combination
- Identification of geographical areas of Al toxicity, Mn toxicity, Mo def
- Optimal rotation sequence for liming (cultivation) - plant options - seasonal effects - optimise $ return
- Test of spatial and vertical measurement/VRT outcome
- Deep placement only suits some acidic soils

Potential soil acidity constraint projects identified as a priority by the theme group and workshop attendees for this theme only

- Where? Mixed cropping zone in WA, VIC, NSW and high rainfall permanent pasture in VIC and NSW
- Chance of research success: High - build on current knowledge (need long term)

1. Magnitude of acidification in new/current farming systems (Theme group: High, Workshop group: #1)

- What is the “acid penalty of production”
- Cost of inaction
- Cost benefit to quantify the theoretical need
- Value to researchers is high. Farmers = liming frequency, lease implications?

2. Optimal liming/amelioration action in farming system/sequence including: placement, co-application with organic matter, yield and soil biology (Theme group: High, Workshop group: #2)

- Lime, nutrient, crop, cultivation, interactions
- OM x lime interaction
- Placement and lime quality
- Barriers? Commodity price variation, unwillingness to cultivate/incorporate, site specific outcomes, expectations in plant response of an ameliorant as opposed to a fertiliser.

3. Measurement and identification of spatial variability of pH and associated problem (Al^{3+} and Mn^{2+}) allowing use in precision lime application (spatial and vertical) (Theme group: High, Workshop group: #3)

- Spatial variability
- Geographic areas of limitation and need for improved identification
- Farmer knowledge and awareness of soil acidity is an issue (and also opportunity)
- Benefits unknown but farmer interest is very high
- Leads to VRT use or not: precision lime applicator - spatial/depth, efficient lime applicator/use
- Barrier: technology/method

4. Standardisation of lime quality/requirement reporting (Theme group: High, Workshop group: #4)

- Lime quality
- Standardise of measurement lime quality

<u>Saline soils and other physical constraints</u>

Gaps

a) Saline soils priorities

- Alternative to pumping (Low/Med based on area)
- Use of saline-sodic + alkaline water for strategic irrigation - site specific thresholds - management options & system guidelines (High)
- Beneficial use of saline water (non-ag), e.g. biofuel “can we create a new ag industry”? (Low priority for Soil CRC, but noted as an important gap)
- Are drainage models/mechanisms correct? (High)

- Precision application and management, e.g. deep drainage spatially

b) Compaction and hardsetting soils

- What is non-compacted soil? How do we quantify the cost of lost potential? There is a complete lack of benchmark in most cases.
- CTF conversion options + row spacing
- Enduring solutions for hard pans and compaction impact generally (deep tillage matched with additives)
- Soil-specificity - matrix of management approach
- Rotation options

c) Irrigated soils (must be considered with other constraints)

- Soil Specific Strategic Irrigation
- $ = unknown, but can be calculated in terms of ML + soil productivity. Need to estimate.
- Prediction of soil-specific TEC and tailoring management/treatment options; new guidelines needed include water treat options
- Cost-benefit: Low-Med/Med-High, success = High
- Precision Irrigation:
- $= N/A initially - scientific - outputs have $ value; salinity costs at least $130M/yr in lost production
- Developing techniques to better determine deep drainage and spatial sub-surface water movement
- Demonstrate that precision irrigation process will be of benefit
- Cost-benefit: Med, success = Med

Potential salinity and soil physical constraint projects identified as a priority by the theme group and workshop attendees for this theme only

1. Precision management of compaction: compaction soil specific management option matrix (Theme group: High, Workshop group: #1)

- Why? Large cost of compaction to grain, cotton and sugar industries
- How? Soil x industry enduring management options (tailored approach), decision support (linked with Program 4) or on-farm machine size optimisation, ripping + OM application machinery
- Benefits? Linked to measurable indicators/surrogates with rapid sensing potential (link with Program 2)
- Cost-benefit Low/High, success = High

2. Development of new guidelines + on-farm water treatment options (Theme group: High, Workshop group: #2)
3. Developing techniques to better determine deep drainage and subsurface water movement (Theme group: High, Workshop group: #3)

4. Spatial and temporal precision irrigation on farm app (High)

Nutrient constraints

Gaps

- Value of nutrient at depth in profile
- Optimising amendment placement to avoid loss of nutrients
- Evaluation of soil/nutrient tests
- Fertiliser use
    - Social licence of inorganic (energy intensive) fertilisers
    - Soil test = Analytical & Interpretation
    - Negative feedback from N-mineral fertiliser
- N (nutrient) use efficiency and alternate fertiliser
- N:K interaction?
- How many farmers using accurate-detailed data to guide nutrient plan?
- Lack of knowledge (consideration) of root growth/function/distribution especially in subsoil
- Value of nutrients in different rotations
- Rapid soil tests for nutrients e.g. robot
- Fertiliser - novel fertilisers and deeper placement (for all nutrients)
- Unlocking soil nutrients, for example trace elements and P could be big constraint in saline/acidic/alkaline soils
- Deeper nutrient placement in the zone with more soil moisture
- Need capacity to do thousands of tests to guide yield/soil interpretation (link with Program 2)
- Algorithms/ sensors / correlations / robust devices/ spectroscopy (multiple variables) (link with Program 2)
- Nutrient budget modelling
- Nutritional value of product x soil nutrient status
- More information needed on plant roots (based on crop, diversity, system, agronomy), for example: depth exploration, function (water extraction and nutrient interactions)
- Not enough off-farm commercial organic matter to go around – need to be mindful of negative feedbacks

Potential nutrient constraint projects identified as a priority by the theme group and workshop attendees for this theme only

1. Achieving nitrogen use efficiency through novel fertilisers, improved placement, legume rotations (Theme group: High, Workshop group: #1)

2. Information on root/soil interaction with a focus on diversity of crops/farming systems and agronomic practices (Theme group: High, Workshop group: #2)
3. More information on deep soil nutrients (Theme group: High, Workshop group: #3)
4. Unlocking nutrients such as P + trace elements (Theme group: High, Workshop group: #4)
5. Development of 'rapid soil tests' to fine-tune systems (temporal/spatial resolution) (Theme group: Low, Workshop group: #5)
6. Clarifying link with soil nutrient/status with plant nutrient status (Theme group: High, Workshop group: #6)
7. Match soil testing with high spatial/temporal resolution yield data (Theme group: High, Workshop group: #7)
8. Refined nutrient budget models (Theme group: High, Workshop group: #8)

<u>Sandy soils</u>

Gaps

- Modelling (biophysical and economic) is needed to allow farmers to make more informed investments with regards to sandy soils
- Spatial distribution of clay type/quality is largely unknown
- Soil-root interactions post-claying and the influence on WHC and PAW is largely unknown
- Re-engineering soils - what is the ideal for sandy soils (amount, depth/placement, configuration for sandy soils)
- Plant roots; where are they and how do we measure them? (to be considered across the Soil CRC and note: high risk/technically very challenging but high reward)
- What machinery is required for optimised mixing and placement?
- What form of organic material is best in sandy soils (i.e. labile vs stable)?
- What is the opportunity for crop diversification as a consequence of modified sands? (i.e. what are the production opportunities?)
- Could slow release fertilisers and other novel products reduce nutrient leaching on sandy soils?
- Improved modelling needed on sandy soils to better predict constraints and benefits of modified sands

Potential sandy soil constraint projects and their priority assigned by theme group and workshop attendees for this theme only

1. Organic amendments for sandy soils; type, form, amount, placement, longevity, soil configuration (Theme group: High, Workshop group: #1)

- Research question: How do C-based amendments change soil and plant processes compared to mineral fertilisers?

- Why? They work and we don’t know why or for how long. They offer the potential to double yield in a low rainfall environment.
- Where? Nine million hectares of sandy soils with benefits for calcareous soils unknown.
- Potential barriers? Cost (to transport, spread, incorporate), confidence in product, distance to source, availability, machinery cost and access to capital

2. Optimising claying to improve soil strength of sandy soils and better understand cementing mechanisms (Theme group: High, Workshop group: #2)

- Research question: a) Are there major limitations to plant growth due to P and S + compaction and how does this vary with sand type? b) Can we super-charge clay?
- Why? Variable results of claying depending on type of sand and significance of limitation and everything else only gets to 70% WLY - this may contribute to rest.
- Where: subset sandy soils - need more information

3. Better understanding the role of clay type and opportunity for synthetic clays to overcome sandy soil constraints (High)

- Research question: What are the ‘soil health’ benefits provided by clay addition, and how much and what form of clay is required?
- Why? Yield increases are variable (but have potential to be considerable) and non-wetting soils are a major constraint
- Where? Subset of 9M ha where (deep) sandy duplex soils or dune/swale systems.
- Potential barriers? Cost (delving; $250-300 ha; claying $600-$800/ha), suitable clay (e.g. Ca-clays to minimise nutrient tie-up), cost of clay mining

4. Modelling to better predict impact and benefits of sandy soil management (High)
5. Fertilisers for sandy soils (e.g. slow release, mineral-based, organic-based, deep placement and soil configuration) (Medium)
6. Root functions on sandy soils and modified sands (Theme group: Medium, Workshop group: #3)
7. Crop diversification options on modified sandy soils (Low)

<u>Machinery</u>

- Define what the machinery needs to do (informed by soil and agronomic research)
    - type of ameliorant and rate,
    - placement (depth and location within the soil)
- Inform machinery design based on pre-defined machinery functions
    - Modelling component (draft, implement geometry, soil disturbance, material flow through the machine)
    - Validation of technology/ improve machinery already developed

- Material optimisation
    - Re-engineering the ameliorant to meet requirements of 1. modern equipment (physical and aerodynamic properties), and 2. crop and soil (optimise chemical composition)
- Mineral fertilisers
    - Fertiliser placement to inform use efficiency/recovery/losses

<u>Mapping</u>

Considerations

- Definition of constraints: standardisation, e.g. sodic soils could be dense, coarse structured, dispersive or could be based on measurement
- Multiple constraints (context): hierarchy approach, multiple benefits from treatments (integrated 'package' approach tailored to soil traps etc)
- Bias in maps currently to grains industry: focus needed on pastures, integrated systems, horticulture
- Other (non CRC) sites - potential value and mechanism for Soil CRC to value-add trial data (site details - archive samples - soil characteristics - trial responses)
- Archived soil samples and new analysis: update maps and models
- Paddock variability (soil biology; chemical; physical) rezone, farm upscaling
- Corporate expert knowledge (Soil CRC specialists, farmer groups etc)

Mapping soil constraints 'needs'

- Integrate = other portals (e.g. NSW Seed)
- Ways to indicate confidence and reliability of mapping and appropriate scale for use 'fit for purpose' approach; value vs likelihood of approaching critical thresholds
- How do you indicate degree of variability?
- Soil biology – contextualising functional groups based on soil type etc and using new knowledge
- Link with Program 2
- Need protocols and methods for characterising Soil CRC trial sites (metadata etc)

4.2 Current research into soil amelioration products (Activity 2)

Below is an overview of the soil constraint issue, current status of research and key knowledge gaps based on the discussions in Activity 1 and a review of the literature.

<u>4.2.1 Dispersive and alkaline soils (led by Dr Ehsan Tavakkoli, NSW DPI)</u>

1. *Define the issue*

Alkaline soils (pH_{Ca}>8) cover 24% of Australia, with 62 million hectares occurring in south-eastern Australia (de Caritat et al 2011). Much of the crop and pasture production in southern Australia occurs on alkaline soils which are especially prevalent in the low rainfall regions of the cropping zone. Neutral to alkaline soils may contain multiple soil physicochemical constraints, often occurring simultaneously in the one soil (Nuttall et al. 2003), including: sodicity (resulting in both high soil strength and temporal water logging), high boron, salinity, bicarbonate toxicity and nutrient deficiencies (Rengasamy et al 2003; Adcock et al 2007, Dang et al 2010). In particular, dispersive and alkaline soil conditions adversely affect soil water and plant available water capacity (PAWC) by: i) impeding water entry into the soil, ii) restricting water movement within the soil, iii) reducing the soil's ability to store plant-available water and nutrients and iv) reducing the ability of plants to access and extract stored water and nutrients. Such constraints can occur in the soil surface layer or throughout the soil profile (e.g. in the subsoil), and tend to occur heterogeneously across the landscape. Despite the wide distribution of alkaline soils in Australia and the recognition that their properties limit plant productivity, detailed studies on the chemistry and agronomy of alkaline soils are not common.

Sodicity vs dispersion: Traditionally, clay dispersion has been related to the exchangeable sodium percentage (ESP) of soil or to the sodium adsorption ratio (SAR) of soil solutions. However, the roles of the other exchangeable cations, potassium and magnesium, in clay dispersion have been debated in the literature and their importance is unresolved. Recently, based on the relative dispersive and flocculating powers of sodium, potassium, magnesium and calcium, a new concept for describing dispersive soil is proposed (Rengasamy et al 2016). Because the dispersive charge is based on the charge available for water interaction, the roles of clay mineralogy, organic matter and pH are integrated into the estimation of dispersive charge

Soil sodicity also has significant off-site impacts. Accelerated soil loss and run-off result in increased sedimentation and potential transport of OM, nutrients and pesticides (absorbed on clay particles) into waterways. This can lead to a decline in surface water quality due to increased turbidity and eutrophication.

2. *Outline the magnitude and extent of the problem*

The impact on production varies with soil and crop type, and exhibits large temporal (especially seasonally based) and spatial variation at paddock to regional scales. Studies have identified that the gap between actual and potential water-limited yields in the cropping regions of southern Australia due to these (sub)soil constraints range from 30% (Nuttal et al 2003) in low-medium rainfall cropping, up to 80% in high rainfall regions of Victoria (Sale et al 2016).

The National Land and Water Resources Audit (2000) estimated that sodic soils occupy over 109 million hectares and salinity over 3 million hectares. The cost of soil sodicity to agricultural production alone is estimated to be between \$1.5 and \$2 billion annually. The total cost of the off-farm impacts of sodic soils has not been estimated.

3. *Identify the industries impacted by the soil constraint (incl cost to industry where possible)*

This review focuses primarily on dryland crop production, although the principles and mechanisms are applicable to pasture, sugar and irrigated cropping systems.

4. Outline the current farmer practice ameliorations strategies

A range of practices including deep ripping, subsoil manuring, clay incorporation, gypsum application, installing underground drainage or use of 'primer-crops' have been tested to overcome dispersive and alkaline soil constraints, usually with variable productivity increases and sometimes resulting in greater financial costs than benefits for growers. There are also plant-based or 'genetic solutions' to the problem (Hobson et al 2006 ; Nuttal et al 2010).

5. List the major research projects to date (including current programs)

DAV400 What is limiting the water use efficiency of grain crops in the southern Mallee and Wimmera? (1998-2002)

DAV00049 Farmer group project combats sodic subsoils

DAFF FtRG: Increasing carbon storage in alkaline sodic soils through increased productivity and enhanced carbon retention (2012-2015)

DAV00149 - 2016.05.07 Understanding the amelioration processes of the subsoil application of amendments in the Southern Region (2016-2021)

GRDC funded project on economics of subsoil constraints in the Northern region (Current)

A range of reviews and externally funded projects (GRDC; LWRRDC; AWI etc) have been undertaken over the decades including Adcock et al (2007); Dang et al (2010), Davenport et al (2015) most of which were summarised by Sale et al (2016).

6. Key references

A comprehensive review and list of key references is provided in a scoping study as part of GRDC Project DAV00149. Understanding the amelioration processes of the subsoil application of amendments in the Southern Region by Sale et al. (2016). Further references are provided below.

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7. List the current knowledge gaps

Plant growth is governed by Liebig's 'Law of the Minimum' – if a particular constraint to plant growth is addressed, the next most 'limiting' constraint determines plant response. The challenge for growers and advisers is to identify the best (most economically viable) strategy for managing a particular soil type.

- If a particular strategy is used to overcome a particular constraint, what is the likely yield response before the next most limiting constraint comes into play? Are there strategies that are better at ameliorating 'multiple constraints'? For example, nutrient-enriched organic sources to simultaneously overcome poor soil structure and nutrient deficiencies, as opposed to use of plant varieties with a specific tolerance e.g. acidity or high B?
- Can 'soil types' / 'regions' be described as having 'characteristic' constraint profiles? This may enable soil type/regional specific management recommendations without growers needing to self-diagnose (by soil testing) and trialling a particular management approach' on a paddock by paddock basis.

- Understanding the soil specific response to ameliorant interventions. For example, why do two soils that disperse to the same extent differ in their response to an ameliorant? It is likely related to the mineralogy, particle size and subsequent dynamics of charge development. Rengasamy et al. (2016) proposes that managing the reduction in the dispersive charge, or the increase in the flocculating charge, or both, may reclaim dispersive soils. Innovative ways of using inorganic and organic amendments should focus on this mechanism.

4.2.2 Soil acidity (led by Dr Jason Condon, CSU)

1. Define the issue

Soil acidity is a soil chemical condition that alters the availability of plant nutrients, interacts with soil biology and influences plant growth and function. Acidity is reported on pH scale and typically soils below pH 5.5 in 0.01M calcium chloride in a 1:5 soil:solution (pH_{Ca}) are considered acidic. Problems associated with soil acidity include: aluminium (Al) and manganese (Mn) toxicity, molybdenum (Mo) and phosphorus (P) deficiency (Foy 1984) and inhibition of microbial function, for example biological N-fixation by rhizobia. Soil acidity causes root stunting which decreases water and nutrient use efficiency (Hayes et al 2016) and can result in negative off-site impacts such as eutrophication and excessive recharge causing secondary salinity. Whilst varietal breeding has selected tolerance to some conditions of acidity in some crops, others remain highly susceptible thereby limiting rotation and cash crop options of growers to tolerant crops only.

Much of the research of acidic soil management and acidification as the causal problem, was conducted last century and does not account for the technological advances in precision agriculture nor the loss of legume pastures and increase canola production in some cropping systems resulting in increased rates of nitrogen (N) fertiliser use and increased removal of alkaline harvested products since that time.

2. Outline the magnitude and extent of the problem

It has been estimated that approximately 50% of the Australian agricultural land area has soil below pH 5.5 (de Caritat at al 2011). Specifically, 35 million hectares are considered highly acidic (pHCa < 4.8) and 55 million hectares = moderately or slightly acidic (pHCa 4.9–6.0) (AACM 1995). It should be noted that such estimates are often based on historic soil survey data and do not represent changes in land management (e.g. lime application) at a local or regional scale.

The economic cost of acidity has been estimated to be $1.58 billion annually to the agricultural sector (Hajkowicz and Young 2005) and $500 million annually across the West Australian wheatbelt alone (Herbert 2009), however, these estimates are dated and are limited by the inadequate resolution (spatial and temporal) in available maps.

3. Identify the industries impacted by the soil constraint (incl cost to industry where possible)

Acidity affects cropping, pasture and horticulture at an estimated cost of $1.58 billion annually to the entire agricultural sector (Hajkowicz and Young 2005). Appendix 3 outlines the estimates for agricultural industries based on 1996 values and landuse estimates (Hajkowicz and Young 2005). It should be noted that in some industries commodity prices (for example, livestock) have substantially changed. The estimates also do not take account of opportunity cost of alternative cash crops or landuse if acidity was corrected.

4. *Outline the current farmer practice ameliorations strategies*

Acid soils are currently ameliorated with the application of alkaline products such as lime (calcium carbonate) or dolomite (calcium and magnesium carbonate). The rates of ameliorants used are largely determined by “rules of thumb” or recommendations stemming from research in the 1980s based on economics relevant to that time period. Whilst models exist which can predict liming rates required, access to these models remains limited due to platform function developments in the IT industry. With the move to no-till farming systems, there is a lack of willingness of some growers to cultivate lime into the soil and in some cases incorporation is not possible due to erosion risk. The lack of incorporation of lime results in enhanced stratification of soil pH in the surface soil. The presence of pH stratification often goes undetected due to standard 0-10cm sampling strategies of the surface soil. Improved sampling methodology is required to be developed and possible benefits assessed.

5. *List the major research projects to date (including current programs)*

GRDC projects:

DAN00191 N fixing crops and pastures for the high rainfall zone acid soils

CWF00019 Soil acidity and pH management for central west farming districts

DAN00206 Innovative approaches to managing subsoil acidity in the southern grain region

DAW00014 - Development of new methodologies to treat subsurface acidity - maximising the benefits of removing subsurface constraints

DAN349 - Managing Acid Soils Through Efficient Rotations

UWA259 - Soil Acidity Management in Western Australia - an integrated project

DAW00236 Soil acidity is limiting grain yield

DAV00152 Spatial variability of soil acidity and response to liming in cropped lands of the Victorian High Rainfall Zone

6. *Key references*

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Hayes, R. C., Li, G.D, Conyers, M.K., Virgona, J.M. and Dear B.S. (2016). "Lime increases productivity and the capacity of lucerne (*Medicago sativa* L.) and phalaris (*Phalaris aquatica*

L.) to utilise stored soil water on an acidic soil in south-eastern Australia." *Plant and Soil* 400(1): 29-43.

Herbert, A (2009). Opportunity Costs of Land Degradation Hazards, in: South-West Agriculture Region. Resource management technical report 349, DAFWA.

7. List the current knowledge gaps

- What is the best sampling strategy to identify and monitor soil acidification and effectiveness of amelioration actions?
- How can precision agriculture technologies be used to enhance management and amelioration of soil acidity?
- What is the effect of current farming practise (N fertiliser use, continuous cropping) on acidification rates and depth of acidity formation in the profile?
- What are the optimal amelioration practices for high rainfall grazing zones?
- Can novel alkaline products ameliorate subsurface and subsoil acidity?

4.2.3 Soil salinity and soil physical constraints (led by Assoc. Prof John McLean Bennett, USQ)

PART A Salinity: Secondary salinity and its management

1. Define the issue

Salinity refers to dissolved salts occurring within the soil solution, changing the osmotic potential of the soil water (affecting plant water-uptake and soil stability) and influencing the cation suite on the clay exchange (affecting soil stability). Primary salinity is that occurring naturally, and is generally a function of salt accession, landscape drainage and parent material. Secondary salinity is that induced through management of the land resource. Secondary salinity can occur both in dryland and irrigated agriculture, and is therefore a function of the water-table, or irrigation (including run-on), water quality.

In terms of plant production, due to the lower water potential in saline soils, plant roots are required to increase the salt concentration inside their cells in order to absorb water. Hence, there becomes a need for osmotic regulation within plants, and toxicity of ions can be expected. The net result of increased salinity within the soil solution is reduced plant growth, depending on the salt tolerance of the plant species and variety being grown. In cases where salts continue to accumulate within the soil system, the system is driven toward a point where halophytes become the only option in terms of vegetative production, without changing any other management aspect. Approximately a 50% reduction in plant productivity can be expected at 4.0, 7.0, 11.0, 15.5 dS/m for sensitive, moderately sensitive, moderately tolerant and tolerant plant species, respectively; sea water has a salinity of ≈50 dS/m, as a point of reference.

Secondary dryland salinity is usually induced by a combination of clearing perennial native vegetation and replacing them with annual crops, or pastures. This results in increased recharge to the water table directly, in environments with sufficient rainfall, and decreased suppression of the water table through less prolific rooting systems. Where discharge points are also cleared, salinity becomes exacerbated and approaches a highly limiting environment. Comparatively, secondary irrigated salinity is induced by either direct use of saline irrigation water, or increased deep-drainage resulting in recharging the water table at a greater rate than would naturally occur.

Water quality is, therefore, a major focus of the management of soil salinity in terms of crop production and irrigation water suitability. However, in the consideration of water quality, it is not as simple as the use of pure water (effectively deionised water, or rainfall), nor picking single salinity level as a threshold for water suitability. Soil structure is a function of the cation suite at the clay exchange and the osmotic potential of the soil solution. Even non-sodic (by Australian definition of sodic) soils irrigated with very low electrolyte concentration, where that concentration is not the current soil-environment equilibrium concentration, could be expected to disperse. On the other hand, soils that are considered sodic (by the same definition) and irrigated with sufficiently high concentration within solution should be expected to remain stable. Therefore, the salinity of the soil-solution and any irrigation water must not be considered in isolation, but in tandem with the factors that affect soil structure.

2. Outline the magnitude and extent of the problem

In terms of dryland salinity, Table 1 provides a summary of the area impacted within Australia. The estimated cost to agriculture is $130M of lost production potential (Hajkowicz and Young 2005), with a further $100M worth of impact on infrastructure yearly, with the 1999 Murray Darling Basin salinity audit suggesting that for every 5000 ha of affected land there is a combined cost of $1M to agriculture, infrastructure and environment.

Table 1. Extent of dryland salinity in Australia assessed as affected area in hectares

State/Territory	All land (1998/2000)*	Agricultural land (2002)†	All land (2050)*
New South Wales	181 000	124 000	1 300 000
Victoria	670 000	139 000	3 110 000
Queensland	Not assessed	107 000	3 100 000
South Australia	390 000	350 000	600 000
Western Australia	4 363 000	1 241 000	8 800 000
Tasmania	54 000	6000	90 000
Northern Territory	—	2000	—
Total	**>5 658 000**	**1 969 000**	**17 000 000**

* National Land and Water Resources Audit (1998/2000)
† Salinity on Australian Farms, Australian Bureau of Statistics (2002)

Of the agricultural land in Table 1, 93% was considered non-irrigated, suggesting that 137,830 ha (7%) of saline land is due to irrigation salinity. Australia's irrigated land represents approximately 3,053,500 ha (based on 343,629,000 ha of agricultural land), or 0.88% (ABARES 2015-16). On this basis, 4.5% of irrigated land is considered salinity affected. Based on the fact that irrigated agriculture represented 30% of the gross value of agricultural production in the 2015-16 year, we can contend that irrigated agriculture is 48 times more productive than dryland agriculture, meaning that of the $130M of lost economic potential due to salinity, $101.7M of this is attributable to irrigated land. Therefore, the focus of managing saline land should be on irrigation.

3. *Identify the industries impacted by the soil constraint (incl cost to industry where possible)*

All industries involved within agriculture are impacted by salinity. On the basis of the extent and magnitude above, irrigated agriculture incurs the greatest lost economic potential annually (Table 2).

Table 2. Extent of dryland salinity in Australia assessed as affected area in hectares

Industry	Saline land (ha)	Lost economic potential ($ million)*
Irrigated farms		
Nurseries and flowers	543	0.40
Vegetables	2,685	1.99
Grapevines	2,766	2.05
Fruit	1,697	1.26
Grain	18,393	13.61
Mixed grain and beef/sheep	24,897	18.42
Beef and/or sheep	58,360	43.17
Dairy	19,895	14.72
Other livestock	1,150	0.85
Cotton	n.a.	n.a.
Other crops	4,314	3.19
Other industries	1,318	0.97
Total irrigated farms	137,539	101.7
Non-irrigated farms		
Nurseries and flowers	487	0.01
Vegetables	89	0.00
Grapevines	2,851	0.04
Fruit	263	0.00
Grain	627,616	9.69
Mixed grain and beef/sheep	375,145	5.79
Beef and/or sheep	809,124	12.49
Dairy	4,927	0.08
Other livestock	4,654	0.07
Cotton	960	0.01
Other crops	1,827	0.03
Other industries	3,124	0.05
Total non-irrigated farms	1,831,067	28.3
Total agriculture	**1,968,606**	**130.0**

* This assumes that all industries contribute to the Gross Value of Agricultural production equally, which would not be true. Thus, the data should only be used as an initial comparative means. This could be improved with GVAP where the industry categories match.

4. Outline the current farmer practice amelioration strategies

Management practices for both dryland and irrigation-based secondary salinity are generally well understood. In terms of dryland salinity management, these management priorities equate to, maximising of water use, more perennials, agroforestry, retain native vegetation, plant salt tolerant species, and improved drainage (in that order), assuming the land-use begins as cleared agricultural land used for crops/pastures within an agricultural system.

In terms of irrigation, the basic management approach is to achieve efficient irrigation application (Table 3), which means having the irrigation water balance worked out as a function of the irrigation water quality applied, the required leaching fraction (based on the irrigation salinity and crop factors to avoid undue salt build up in the rooting zone) and the threshold electrolyte concentration (soil response to the EC and SAR of the irrigation water, which is dependent on a number of other soil factors also).

The threshold electrolyte concentration (C_{TH}) was pioneered by Quirk and Schofield (1955) and stipulates that there is salinity sufficient to maintain a soil aggregate in an aggregated state for a given SAR that will be dependent on soil factors such as clay mineralogy, the net negative charge, organic matter, the soil pH, carbonates and oxides. They nominally describe the C_{TH} as being a 10-15% reduction in saturated hydraulic conductivity from a Ca-saturated environment. While this might sound arbitrary, they describe this hydraulic reduction as a measureable reduction from the potential minima that occurs when soils are Ca-saturated. Bennett and Raine (2012) demonstrated that the C_{TH} was soil-specific, even within the same soil order, which was further confirmed by Ezlit *et al.* (2013) who developed a mathematical equation to describe the relationship. Importantly, the C_{TH} differs from the point a system goes from aggregated to spontaneously dispersed, which is called the turbidity concentration (C_{TU}). Recently, Dang *et al.* (2018a) demonstrated that reduction in saturated hydraulic conductivity at the aggregation-dispersion (C_{TU}) was as much as 80%, depending on the soil (this too being soil-specific). Therefore, equating the aggregation-dispersion boundary with irrigation practical guidelines has not been advised, and the C_{TH} is used within industry to provide practically useful irrigation water quality thresholds on a soil-specific basis. Using the C_{TH} provides a safety buffer under systems where rainfall, and changing irrigation water quality, can dilute the soil-water system (Dang *et al.* 2018b).

Table 3. Management of secondary salinity from Peck (1993) in McTanish and Broughton (1993).

Priority order	Shallow water table	Saline irrigation or run-on water
1	Reduce irrigation application	Change irrigation source
2	Reduce natural recharge to aquifer	Divert saline water
3	Increase natural discharge from aquifer	Change irrigation method
4	Pump from aquifer	Increase leaching fraction
5	Install drainage system	Change crop
6	—	Abandon irrigation

5. *List the major research projects to date (including current programs)*

Programs addressing salinity:

- National Dryland Salinity Program (1993-2004)
- National Action Plan for Salinity and Water Quality (2001-2008)
- Caring for our Country (2008-2013)
- Queensland healthy headwater water use efficiency project (2009-2016)

- Caring for our Country (2013-2018)

Programs addressing soil-specific use of marginal water quality for strategic irrigation:

- Queensland coal seam gas development: Beneficial reuse of associated water for irrigation (2007-2014)
- Soil-specific strategic irrigation: Saline-sodic water as an irrigation resource (CRDC PhD Scholarship NEC1403 2014-2017)

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7. *List the current knowledge gaps*

With regard to dryland salinity management, there are few remaining knowledge gaps of significance, owing to the number of funding programs over the last 20 or so years. Two specific knowledge gaps of note are transient salinity and salinity-waterlogging interactions as identified by Barrett-Lennard et al. (2016). The major remaining issue is our capacity to reliably model salt movement through the landscape in terms of spatially via lateral movement, spatially with depth, and through time. This is common to irrigation also, and is explored further in the subsequent knowledge gaps.

The following knowledge gaps from Raine et al. (2007) still require significant investigation with regards to precision irrigation, and address the modelling comment above:

Soil and irrigation management

There is a need to develop quick, simple and robust techniques to characterise soil infiltration and leaching efficiencies to enable evaluation of in-Weld soil heterogeneity and potential impacts on irrigation and salt leaching performance;

- Soil structural problems associated with changes in soil chemistry need better description, greater identification of current and potential problems and better collation of management options.
- Determination of the accuracy and adequacy of using simple mean values of varying soil salinity levels in the root zone to estimate the effect of salt on the plant;
- There is currently little understanding of the physiological responses of crops to various salt distributions within the root zone. Priority investigations should be undertaken on the most salt sensitive crops where precision irrigation is being currently or likely to be implemented;
- Point scale modelling of any kind will need to be complemented by models that account for the dynamics of weather, crops, irrigation practice, salt loading, and groundwater interactions to assist general applicability i.e. extend beyond the immediate study area.
- There is potential to better evaluate the impact of transient flux gradients on soil–water movement and salt accumulation under commercial conditions particularly with respect to the:
    a. application of water at different times of day/night,
    b. effect of root extraction, evaporation and transpiration,
    c. effect of various cultural practices (e.g. mulching); and,
    d. impact of soil heterogeneity on distribution of water and solutes in relation to placement of drippers.
- There is sufficient evidence to suggest that in situations of point water applications and associated salt distribution that rainfall could be used to advantage in displacing salt and moving it below the root zone. This dynamic situation needs to be explored further and the limits and management options determined. This will involve better characterisation and modelling of solute transport in relation to climate and soil properties.

Modelling specific

- Development and extension of existing models to any combination of soil properties, flow rates and application times. This can be done by replacing the present dimensional databases with non-dimensional databases.
- Packaging of existing analytical models into user friendly front ends for calculation of wetting patterns and salt distributions.
- Verification of analytical models by comparison with numerical models in cases where the underlying assumptions are violated.
- Use existing numerical models to determine the effects of heterogeneity on water and salt distribution patterns and the interaction with climate. From these studies develop simple non-dimensional rule-based knowledge systems.
- The models should be used to develop and evaluate any experimental work, so that redundant data sets are not produced (note some replication is required).

- The analytical and rule-based models can be included in GIS models to assist with interpretation of wider landscape issues.

Capacity

- There is a significant lack of appropriate mathematical skills and capacity in relation to soil–water modelling within the Australian research community.
- There are currently a range of tools (both sensory and modelling) available to understand the plant–soil–water interactions. However, these tools are currently poorly linked and the skill sets and capacity to operate these tools selectively are rarely available with single projects. Hence, there is a need to (a) build capacity in the operation and interpretation of the constituent components, (b) develop cross-disciplinary studies which take a whole of- system view; and (c) investigate the development of integrating frameworks between existing tools and models. However, there would also be a need to investigate error propagation and validation within such a framework.

PART B Soil compaction

1. *Define the issue*

Soil compaction remains the most constraining soil issue affecting global agriculture, affecting 10% of the worlds agricultural land, based on the globally utilised agricultural land area (38.4% of the world's land area) and the extent of compaction (approximately 68 million ha, or 4% of total global land area) (Tullberg 2010; FAO and ITPS 2015). It reduces the permeability of soils, which decreases a soil's ability to store and supply water and nutrients, ultimately resulting in crop and pasture yield decline (Drewry et al. 2008; Hazma and Anderson 2005). Decreasing the permeability increases erosion hazard and subsequent offsite transport of nutrients and inputs, such as phosphorus, and other nutrients, and pesticides/herbicides (McHugh et al. 2009; Silburn et al. 2013).

Soil compaction results where an applied load exceeds the pre-compression strength of a soil, subsequently decreasing soil pore geometry (macropores affected first), which increases the bulk density (Bennett et al. 2015; Antille et al. 2016). The applied load may be from machinery, or livestock, or due to an overburden; i.e. at 1.0 m depth the load at this point will be a function of the 1.0 m soil mass above and gravity (assuming no external forces applied to the surface), throughout an extended period of wetting and drying. In general, soils have consolidated over extremely long periods of time, so the overburden is often considered in equilibrium, although in reconstructed landscapes there will be a natural settling period during which the soil would be expected to continue to consolidate. Such environments might include mine-site rehabilitation, deep-ripping lines, profile inversion and claying/delving.

The extent of soil compaction occurring under a given applied load is a function of soil characteristics (texture, mineralogy, organic matter, hydraulic conductivity, drainage, structure, depth, and stone content), climatic/environmental factors (temperature, evapotranspiration, precipitation, depth to water table) and management (prior load application – machine and/or livestock, vegetation type, tillage practices, intensity/frequency). Therefore, the risk of compaction can be thought of as equating to the vulnerability of a given soil to compaction and the exposure of that soil to management and climatic/environmental factors (Figure 2; Troldborg et al. 2013).

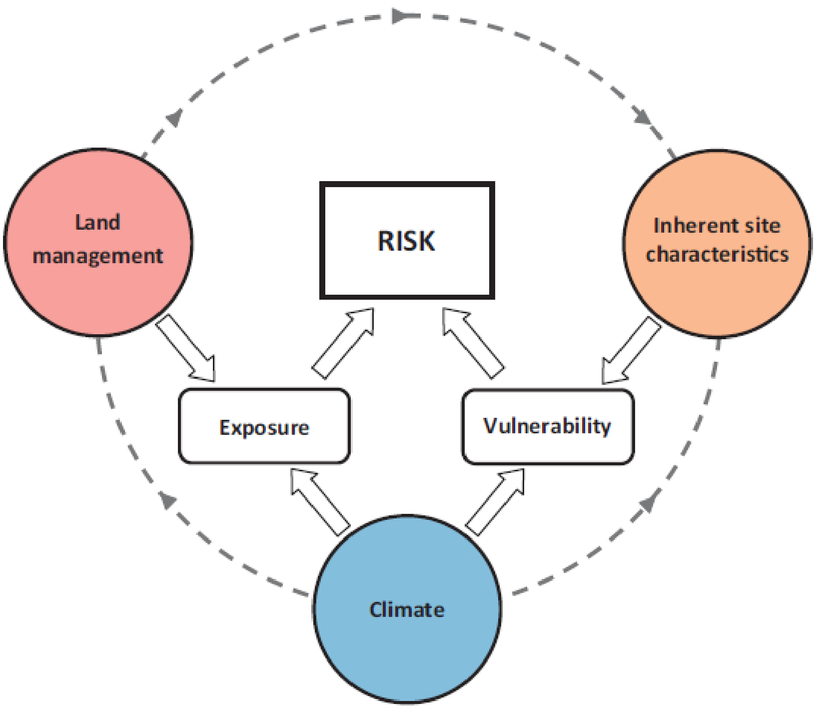

Figure 2. Generic model framework for assess threats to soil physical quality via compaction (Troldborg et al. 2013)

On this basis, it is clear that soil compaction is not limited to crop land but is also prevalent in livestock grazing fields (managed pastures) and rangelands, as well as natural non-disturbed systems (Drewry et al 2008).

Soil compaction effects are long lasting or even permanent, depending on the depth at which they occur (Håkansson and Lipiec, 2000). Livestock trampling mechanically breaks down soil aggregates and their structures, with the imparted energy also reducing aggregate stability in water (Rengasamy et al. 1983; Drewry et al. 2008), which increases with stocking intensity and pasture decline. The compaction under livestock tends to be shallow, not extending into the subsoil (below 0.3 m). On the other hand, the weight and power on-farm machinery has approximately tripled since 1966 (FAO and ITPS 2015; Bennett et al. 2015), and wheel loads have risen by a factor of six (Chamen, 2006), meaning that subsoil compaction has become more common and affects production substantially where not managed (Antille et al. 2016).

Remediation of shallow compaction (<0.3 m) is a viable option with the use of cultivation, but removal of compaction at subsoil depths below 45 cm is both difficult and expensive (Batey, 2009). Therefore, machinery based agriculture with extreme wheel-loads (>5 t at the wheel) presents the greatest threat to soil compaction throughout the soil depth, while both livestock and machinery contribute to shallow soil compaction.

2. *Outline the magnitude and extent of the problem*

Soil compaction can reduce crop yields by between 8 and 100% (Table 4), with the range of yield effects being highly variable, and dependent partly on the crop, as well as the factors described in Figure 2. Sidhu and Duiker (2006) suggest that compaction effects on yield are greatest when the crop is under stress, occurring during drought or excessively wet growing seasons. The former is a clear concern for Australian agriculture.

There is a misconception that compaction of cropping land does not occur on some soil types, or in some regions, which is frankly impossible whenever the applied load is sufficient to overcome the pre-compresison strength. Håkansson (1990) states that machines with contact pressure at the wheel of >200 kPa should not be allowed into agricultural fields, while Antille et al. (2016) and Bennett et al. (2015) document that machines with contact pressures approaching 600 kPa are common place in modern day agriculture within Australia. It is difficult to determine the full magnitude and extent of soil compaction on the basis there is no reference point (i.e. no indication of the starting bulk density for agricultural fields). However, it is safe to assume that soil compaction has occurred anywhere that a machine with wheel contact pressure >200 kPa has traversed, which would account for the majority of Australian cropped agricultural land. Effects of compaction due to a single pass can have impact >10 years after initial wheeling (Raper 2005; McHugh et al. 2009).

Table 4. Relative yield achieved in the absence of traffic-based soil-compaction and expressed as percentage of yield obtained in situations with traffic intensities typical of the cropping system. Data collated by Antille et al (A), Bennett et al. (2015) (B), Chamen (2006) (C) and FAO and ITSP (2015). Number shows the geographical location of the study: 1, Australia,; 2, Israel,; 3, US,; 4, Turkey; 5, Pakistan; 6, Argentina; 7, Morocco

Crop type		Relative yield (%)	Soil type	Source
Wheat	(1)	115–130	Clays and Sandy loams	White, 2007
Wheat	(1)	157	Clay	Bennett et al., 2017
Winter cereals	(1, B)	127	Clay	Radford et al. 2001
Winter cereals	(1, B)	117	Clay	Neale 2011
Sorghum	(1, B)	100	Clay	Jensen et al. 2000
Maize	(1, B)	175	Clay	Radford et al. 2001
Winter cereals	(1, C)	135	Sand, sandy loam	Hamilton et al. 2003
Winter cereals, grains and legumes	(1, C)	112	Red brown earth	Sedaghatpour et al. 1995
Oilseed rape	(1, C)	194	Sodic clay	Chan et al. 2006
Winter cereals	(1, C)	114	Clay	Tullberg et al. 2001
Cotton	(2, A)	106–112	Silt loam	Hadas et al. 1985
Cotton, seed	(3, B)	120–128	Silt loam	Kulkarni et al. 2010
Maize	(3, D)	119	Silt loam	Sidhu and Duiker, 2006
Cotton	(4, A)	108–115	Silty clay	Akinci et al. 2004
Cotton, seed	(5, B)	108	Sandy clay loam	Ishaq et al. 2003

Soybeans	(6, B)	143	Clay loam	Botta et al. 2007
Sugarcane	(7, D)	140	Clay	Jouve and Oussible, 1979
Wheat	(7, D)	112–123	Clay loam	Oussible, Crookstone, Larson 1992

3. Identify the industries impacted by the soil constraint (incl cost to industry where possible)

It is difficult to determine the cost of soil compaction to Australian agricultural industries each year, as many cropping soils across Australia are already compacted. The fact that soil compaction has not been monitored as a key soil constraint costing Australian agriculture yearly in lost potential requires rectification. The information in Table 4 coupled with the probabilistic approach of compaction risk in Troldborg et al. (2013) may provide a reasonable approach to estimating compaction potential cost. That said, there are some estimates of the cost of compaction:

- The cost of lost crop and pasture production from subsoil compaction is estimated at $330 million for Western Australia's agricultural soils (Western Australian Department of Primary Industries and Regional Development 2018).
- Sugar industry lost potential yield valued at $54.7– $174.2M/yr of (Braunack, 2000).
- Approximately $50M/yr of lost economic potential in the grains industry.
- An estimated cost of approximately $60M/yr due to compaction in the cotton industry (Bennett et al. 2017).

It is clear that a better understanding of the economic cost of compaction is required, and that the tools and/or framework for determining this are similarly required.

4. Outline the current farmer practice amelioration strategies

In terms of soil compaction management, it is well established that the best management strategy is to avoid traffic on soil, which equates to true controlled traffic farming (CTF) systems within cropping systems. For livestock systems, avoiding traffic of livestock is not possible, so management comes down to grazing-based best management practices and maintenance of the pasture, which go hand-in-hand.

Controlled traffic farming systems have long been advised for the management of soil compaction. With 25% of Australian agriculture using CTF, we are globally, one of the highest adopters of this technology (Tullberg 2007). Recent grains industry research suggests that adoption in the grains industry increased from 15% in 2008 to 21% in 2011 (GRDC 2013). Given that CTF has been prescribed as best management practice since the late 1980s, these adoption rates are rather low and not in line with the potential cost of the issue. The reason for this is twofold. Firstly, compaction is not something that is easily seen, so many do not even believe they have compaction, and there is an associated cost in converting machinery and implements to have matching wheel track widths. Secondly, cost of machinery conversion is often cited as a disincentive in the adoption of CTF. However, conversion costs range from $24–$100K for a harvester/cotton picker and tractor, which when spread across the area on which such machinery operates, the potential economic gain achieved via increased yields is probably the cheapest ameliorative approach to compaction that might be used.

SOILpak for cotton growers (Daniells and Larsen 1991; McKenzie 1998) provides a good summary of other treatment options for compacted soil: including the use of deep-ripping, bio-drilling/ripping using rotation crops, and the use of wet-dry cycles in Vertosol soils. However, it is noted that these work best in alleviating existing compaction after converting to CTF, rather than relying on them to alleviate compaction between conventional farming system year to year crop rotations. Indeed, a single wheeling has been demonstrated to completely revert the positive benefits of deep-ripping, bio-drilling rotation cropping, and wet-dry cycles in Vertosol soils (McGarry 2003; McGarry 1990; Pillai-McGarry 1991; McHugh et al. 2009; Bennett et al. 2017). On this basis, such management options should not be considered as options for controlling compaction, but rather management options for the rehabilitation of compacted land that is no longer subject to traffic. In terms of controlling soil compaction, this is a function of the applied load and is well described in Figure 3.

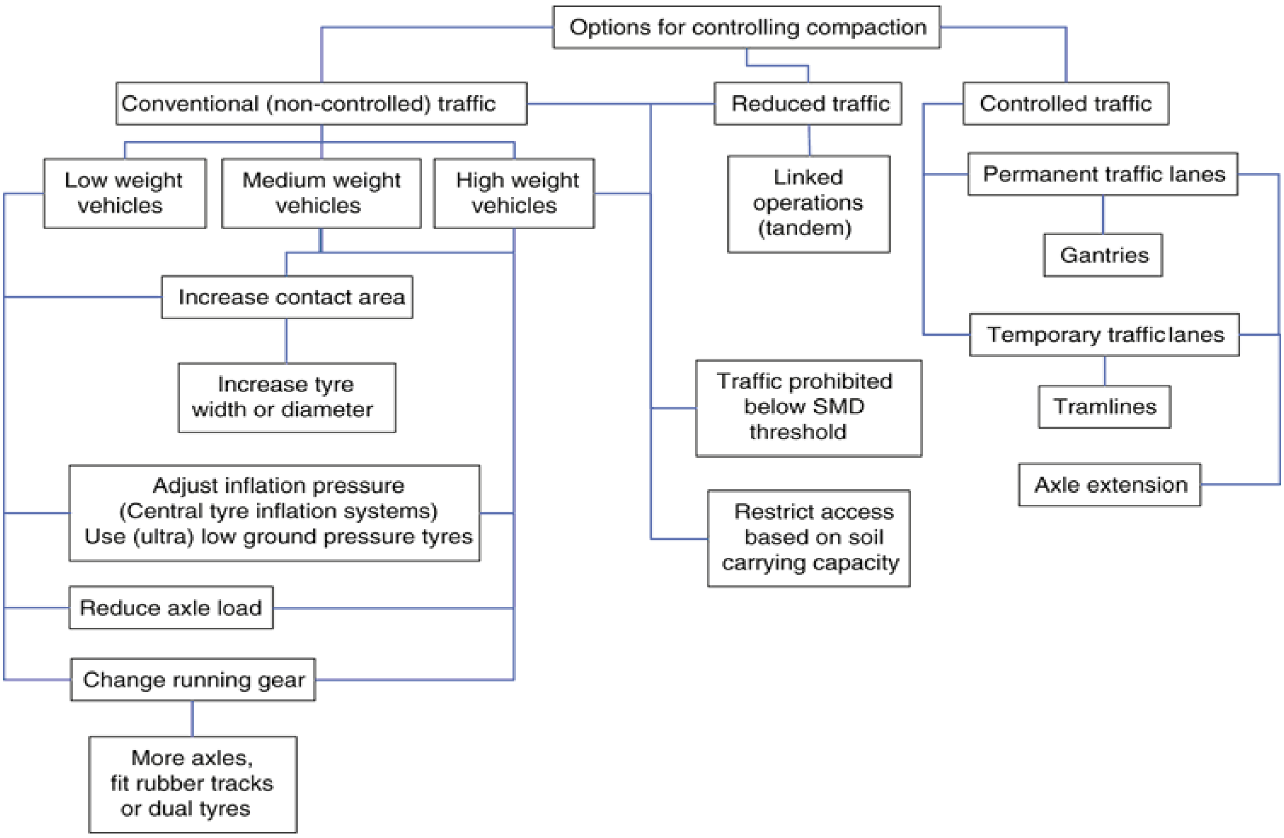

Figure 3. Options for controlling compaction in agricultural soil (redrawn and modified by Antille et al. 2016 from Soane et al. 1979, 1982). SMD, Soil moisture deficit.

5. List the major research projects to date (including current programs)

Below is a non-exhaustive list of projects that have considered compaction as a key constraint in projects:

- CRDC SOILpak for Cotton Growers (1990s)
- GRDC Subsoil constraints program (2002-2007)

- CRDC Mitigating the impacts of the John Deere 7760 (2013-2016)
- GRDC Soil constraints projects in Western, Southern and Northern regions (Current)
- CRDC Soil constraints (Current)

6. List the key references

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7. List the current knowledge gaps

The current knowledge gaps with respect to soil compaction were largely presented in the review of Antille et al. (2016), albeit for cotton, and the relevant remaining knowledge gaps have been reproduced here, informed by insights (e.g. knowledge gaps) that arose through the current review:

1. Identification of soil compaction effects on wider aspects of farm economics to aid decision-making. This requires the development of decision support systems that incorporate the economics of managing soil compaction and provide advice on options available to specific farming systems (farm-scale analysis) including conversion to CTF coupled with adoption of precision agriculture technologies such as variable rate technology (water and fertiliser), use of low-ground-pressure tyre technology, and precision tillage.

2. Prediction of soil-compaction risk at the field or sub-field scale based on soil type and soil water content (non-CTF systems only).

a. Approaches such as those of Earl (1997) and Vero et al. (2014), based on soil moisture deficits, appear robust, yet simple, to establish thresholds for limits to trafficability with heavy machines.

b. Site-specific information on trafficability conditions used in conjunction with central tyre-inflation systems may enable ‘on-the-go’ adjustments of running gear. Subsequently, site-specific compaction may be corrected based on the principles of precision tillage (spatially and depth variable).

c. Risk based methodologies, such as that developed by Troldborg et al. (2013), may also be readily applicable in terms of data inputs and offer the advantage of accounting for uncertainties in the assessment of compaction risks.

3. The replacement of dual by single tyres in the front axle (and axles extension) of recent models of heavy harvesting equipment to accommodate permanent traffic lanes with 3-m centres is at the expense of increased inflation pressure. Although some loss of tractive efficiency may be expected (e.g. increased wheel-slip and rolling resistance) under relatively soft soil conditions, the effect may be minimal on consolidated wheel-lanes. However, this requires investigation, together with optimal design of traffic lanes, particularly within surface-irrigated systems to ensure safe discharge of runoff.
4. Rapid determination of soil compaction extent is still required, with no single method providing a reliable means by which to ascertain the historic level of compaction exiting in a current field since the natural bulk density condition is not known. Compaction magnitude within fields is therefore largely unknown, meaning that the associated yield loss is also largely unknown. A system for referencing current compaction magnitude to some continuum of compaction extent is required, and the tools to inform this will need to be identified.

4.2.4 Nutrient constraints (led by Dr Qifu Ma, Murdoch University)

1. Define the issue

With the wide adoption of conservation agriculture (minimal soil disturbance, crop residue retention), soil nutrient stratification is becoming more prevalent, as phosphorus (P), potassium (K), copper (Cu), zinc (Zn) and manganese (Mn) concentrate more in the fertilised topsoil (0-10 cm). In water-limited environments where surface drying limits root access to topsoil nutrients, the nutrients in moist subsoil may play a larger role in crop nutrition and growth. To date, nutrient resources in the subsoil have been largely neglected in most agronomic and plant nutrition studies. While there remains a need for improved crop nutrient management based on topsoil nutrient levels (as shown by recent large GRDC investments on these issues), the main focus of the current review is on the subsoil.

2. Outline the magnitude and extent of the problem

Over 90% of grain cropping in WA and SA now uses no-till planting, and the adoption is over 50% in Vic, NSW and Qld (Rochecouste and Crabtree 2014). Hence stratification of nutrients is likely to become more common in grain cropping. There is strong evidence that nutrient acquisition from the subsoil can contribute to significant amounts of N, P and K taken up by crops (Kautz et al. 2013). The extent to which subsoils contribute to plant nutrition may vary greatly from <10% to >70% of total plant uptake for certain soil nutrients (Ma et al. 2018). The role of subsoil nutrition in crop growth is often limited by subsoil constraints that restrict deeper rooting, including physical constraints e.g. gravel layers and soil compaction, and chemical constraints e.g. acidity, alkalinity, salinity, sodicity, nutrient deficiency and element toxicity.

3. Identify the industries impacted by the soil constraint (incl cost to industry where possible)

Nutrient stratification and reliance on subsoil nutrients is likely to become a major issue for the dryland grains cropping industry. Considering the increasing cost of nutrient supply as fertilisers (20-30% of costs for grain cropping), there is a need to establish the availability of nutrients stored in the subsoil for crop growth and the effects of physical and chemical constraints on subsoil nutrient uptake.

4. Outline the current farmer practice ameliorations strategies

- Low availability of plant nutrients under drought can be improved by placing fertilisers (e.g. P, K) deeper in soil profiles, where crops would have better access to soil moisture and deeper root growth for greater uptake and use of applied fertilisers and subsoil nutrients (e.g. Jarvis and Bolland 1990; Ma et al. 2009). However, deep placement of fertiliser is not widely practiced.
- Cultivation and inversion tillage of the nutrient-stratified soils can redistribute nutrients in the profiles and aid nutrient uptake by crops.
- Application of lime and gypsum in acidic soils increases root growth and enhances absorption of water and nutrients by plants.
- Deep ripping facilitates subsoil root growth by alleviating compaction.
- Growing tolerant genotypes on nutrient deficient, acid and saline soils is a practical approach to the management of subsoil limitations and reflects the shift to a strategy of ‘tailoring the plants to fit the soil’ from the older strategy of ‘tailoring the soil to fit the plant’.

5. List the major research projects to date (including current programs)

The list below includes projects that examined subsoil constraints, although they generally were not specifically targeted to crop nutrition.

GRDC-funded research projects on improving diagnostics and management strategies for subsoil constraints at a regional and paddock scale.

DAQ00148 Defining critical soil nutrient concentrations in soils supporting grains and cotton in Northern NSW and Queensland (2009-12)

RSS00011 - Mapping the Extent of Subsoil Constraints and Identifying the Cost of Subsoil Constraints across the Southern and western grains regions (Jan – Dec 2014, Rural Solutions SA - PRIMARY INDUSTRIES AND REGION)

UWA00081 - Combating subsoil constraints: Unlocking crop potential through innovative subsoil management. June 2002 – June 2008, University of Western Australia

DAW00242 - Subsoil constraints - understanding and management. Jan 2014 – June 2019, Western Australian Agriculture Authority (WAAA)

DNR00004 - SIP08 (north) Combating subsoil constraints. Jul 2002 – Jun 2007, Department of Science, IT, Innovation and the Arts

DNR00008 - SIP08 (north) Advanced Techniques for Managing Subsoil Constraints. July 2007 – June 2010, Queensland Department of Science, Information, Technology and Innovation

DAQ00200 - National project tackles subsoil constraints (current until 2020)

CSO00031 - Innovative solutions to subsoil constraints for a profitable and environmentally sustainable grains industry in WA (Mar 2003 – Feb 2007, CSIRO Land and Water)

CWF00005 - Combating subsoil constraints Jul 2003 – Sep 2007, NSW DPI)

DAV00056 - Understanding subsoil constraints in the high rainfall zones (HRZ). Apr 2004 – Mar 2006, Department of Primary Industries, PIRVic

CSU00008 - The contribution of subsoil constraints to Canola Yield Decline. Jul 2006 – Mar 2010, EH Graham Centre for Agricultural Innovation (I&I NSW and CSU)

DAV00049 - Improving the profitability of cropping on hostile subsoils. Jul 2003 – Dec 2008, Department of Primary Industries Victoria

CSO217 - Management of subsoils which limit production by constraining root growth. Jan 2000 – Jun 2003, CSIRO Land and Water

CSP343 - Identifying and Evaluating 'Primer crops' for Hostile Subsoils. Jan 2002 – Jun 2006, CSIRO Plant Industry

DAS00012 - Improved yield and yield quality through amelioration of degraded subsoil. Jul 2002 – Jun 2005, South Australian Research & Development Institute SARDI, Business group of PIRSA.

ULA00008 - Validating subsoil manuring in the High Rainfall Zone. Jan 2010 – Dec 2010, La Trobe University

DAV00149 - Understanding the amelioration processes of the subsoil application of amendments in the Southern Region. Jun 2016 – Jun 2021, Department of Economic Development, Jobs, Transport

GRDC9175108- Understanding the stratification of nutrients in soils in the southern region and developing appropriate fertiliser practices. 2018, Department of Economic Development, Jobs, Transport

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7. List the current knowledge gaps

- With on-going global climate warming and more frequent summer drought in the regions under agriculture, exploration of subsoil water and nutrient resources could be of increased future relevance.
- The extent of crop reliance on subsoil nutrient supply has not been quantified in Australian dryland cropping environments
- The direct limitations to subsoil root growth from low levels of the nutrients with low phloem-mobility (Mn, B, Cu, Zn, Ca) has not been assessed in field grown crops.

- The utility of subsoil N and P placement (as fertiliser or organic amendments) to stimulate subsoil root growth and the uptake of water and nutrients from subsoils has not been assessed.

4.2.5 Sandy soils (led by Prof Richard Bell, Murdoch University)

1. *Define the issue*

Sands are not generally considered to be high performance soils. There are some exceptions. For example in intensive vegetable production, there are advantages to using sand (they are well drained and easy for multiple land preparation operations each year compared to loam or clay textured soil), if the risks associated with sands can be managed (leaching of chemicals into groundwater, subsoil compaction, wind erosion, limited chemical buffering, low water retention). More commonly, despite the best technology, crop productivity is not as great on sands as that on loam and clay soils under the same environment.

For broadacre agriculture, our focus is on high performance sands rather than high performance soils. That is, we recognise that sands have limitations relative to other texture classes, but regardless, there are likely means to increase the performance of sands. Sands cover large areas of the agricultural enterprise in Australia, hence high performance sands is likely to pay off for growers. Furthermore, for the Soil CRC, high performance has been described as performance in the top percentile of a soils capability to produce/perform.

A recent review by Scanlan et al. (2018) encapsulate one of the major truths about sands: “Soils used for a crop production that have sand texture or gravel in the subsoil have one common feature; they have a limited capacity to supply resources to the crop”.

Sands are distinctive in their properties for management. While soils and their properties vary across a continuum, sands have a number of quite distinctive properties. The main one is that generally multiple limitations occur on sands. On loam and clay soils, one or two limitations might be the focus of attention, but for sands there are many to deal with. Hence, diagnosis of the limitations is a key focus for working on sands. Then, packages of technologies that alleviate constraints will be necessary. Limitations include:

- Sands are poorly buffered, which means that management can induce rapid and substantial changes in soil properties, such as the decline in pH under acidifying cropping practices.
- Sands have low organic matter content relative to other texture classes. Clay is needed to stabilize and protect soil organic matter. With very low clay content, organic matter breaks down rapidly. It is also difficult to raise soil organic matter levels in sands even with high inputs unless those inputs are regular and substantial.
- Small differences in clay percentages among sands can have quite large effects on their properties for management. Sands with 5% clay have substantially greater reactive surface for nutrient and water reactions than sands with 1% clay. Hence, for sands there is a need to differentiate among small differences in clay percent.

- Responses to inputs, especially fertiliser, generally increase considerably when organic matter is also added with the input to the sand.

With sands, there are also significant degradation risks.

- Episodic wind erosion can strip valuable topsoil from sands if the surface is not well protected by ground cover.
- The high permeability of sands means that water, ions and molecules can readily leach past the root zone and can be lost or cause groundwater contamination.
- Due to low biological activity, low organic matter levels and low soil water content, residues of herbicides may persist for longer and at higher concentrations than in loam and clay soils.

A few properties of sands are somewhat unexpected, at least from a lay point of view.

- Water repellence is prevalent on sands in southern Australia, and restricts the infiltration of rainfall into the topsoil.
- P can leach on pale sands. This doesn't occur on any other class of soils unless available P levels reach well above the critical level for crops.
- Compaction - subsoil compaction is a major limitation induced by cropping in sands due to tillage and the surface tension created when soils dry, as well as heavy machinery and the compressive force from the weight of the machinery

2. Outline the magnitude and extent of the problem

Tenosols in the Australian Soil Classification (ASC) are the major groupings of deep sandy soils. The deep sandy Tenosols in ASC contain <15% sand in the B horizon.

For crop management, we also consider a range of sandy duplex soils when discussing sandy soils and their management. In many places, sandy soils often have sand horizons to no more than 20 cm which is where most of the roots of crops are confined especially if the profile has hostile subsoil properties.

Hence in crop agronomy what are called sandy soils, include soils with sandy surface and sub-surface layers to less than 1m on a wider range of Soil groups than Tenosols, for example Rudosols, Sodosols and Chromosols.

Sands and deep sandy duplex soils come in many varieties. The major sand and deep sandy duplex Soil groups in WA are shown in the Table 5. In WA, sands are fairly widely distributed across the wheatbelt and southwest regions. In SA and Victoria, sands are mostly in the Mallee and Eyre Peninsula. Sandy soils occur in southwest NSW and sub-coastal and northern Qld (McKenzie et al. 2004)

Sandy soils are a valuable production resource in the cropping regions of Southern Australia, accounting for 5 million hectares of the land cropped in the region (Uncovich 2014). Sandy soils in southern Australia form 30% of the cropping and grazing landscape across central and southern inland New South Wales (NSW), and parts of Victoria and South Australia. These soils often produce lower crop yields than other soils in surrounding areas and are acidic (pH_{Ca} 4 to 5 in NSW mainly), highly erodible, carrying high in weed numbers and often accommodate limited root growth which causes soil moisture to remain after harvest. Sandy soils are often characterised as containing >75% course textured sand and cation exchange capacities of <5 mg/kg. They are therefore naturally low in fertility and store minimal plant available water (<60 to 80 mm PAW).

Table 5: Sand profiles in WA wheatbelt: Main Soil Groups and areas (>0.5 million ha). Supplied by Van Gool, DPIRD.

Group Code	Group Decode	Area (M ha)	Distributions
403	Grey deep sandy duplex	1.48	Common in the south-west (especially Esperance sandplain and west to the Fitzgerald and Great Southern)
446	Yellow deep sand	1.33	Common on coastal plain from Augusta to Geraldton
444	Pale deep sand	0.95	Common on the Swan coastal plain, Scott River Plain and Cape Arid east of Esperance
302	Duplex sandy gravel	0.76	Reticulite subsoils common in the southern part of central wheatbelt and Great Southern. Clayey subsoils common in forest
464	Yellow sandy earth	0.61	Widespread on sandy uplands in central, eastern and northern wheatbelt, extending into Murchison and Goldfields
407	Yellow/brown deep sandy duplex	0.53	Occurs throughout the south-west, but rarely common

3. Identify the industries impacted by the soil constraint (incl cost to industry where possible)

The constraints of sand are most evident in the broadacre grains industry, mixed farming and in livestock grazing systems.

Even with the best conventional technologies, grains on deep sands achieve 30-40% of water-limited yield potential (Hall et al. 2011; Hall et al. 2017). Claying can raise this to 65-75% of water limited yield potential. The increase in NPV ($/ha) after 6 years when compared to the Control was $61/ha for clay addition and incorporation to 15cm (Hall et al. 2017).

4. Outline the current farmer practice ameliorations strategies

For sands, the key to achieving high performance is to diagnose all the limitations, and devise cost-effective treatments. The management solutions for sands are likely to be a package of interventions.

Examples of the limitations are:

- Nutrients: generally there will be two or more deficiencies in sands. Such deficiencies are likely in topsoil and subsoils.
- Acidity: While there are naturally-occurring acid sands, many others have acidified over 20-30 years of farm practices that disrupted the N and C cycles.
- Alkalinity: In other cases sands are alkaline.
- Salinity: Salinity has become a constraint in sands over shallow water tables in southern Australia.
- Poor water storage: Low soil water storage is the most intractable of the multiple limitations in sands.

With multiple limitations, there will generally be weak responses to inputs unless all the major limitations are overcome at the same time. That is, there are positive interactions from the combined application of inputs. This is illustrated by the response to a range of nutrients (including N, P, K, S, Ca, Mo) on sands in NE Thailand which was minimal unless B was also added. Without B, the investment in other fertiliser was wasted (Bell et al. 1990).

When we look at a sand, or at the texture analysis of a sand, the property that stands out is the very high sand content. In sands, sand content covers range from 85-99%. However, if we focus on the silt+clay percent of the sands, different insights emerge. What we see is sands where the silt+clay varies 15-fold from 1 to 15%. Important differences in pH, organic C, Olsen P, CEC are evident across that range. Small differences in clay content among sands, even between 1 and 3% can have quite profound effects on properties for management.

This is also true for soil water storage. Doubling of the silt+clay percentage more than doubled the plant available water in sands (Bell et al. 2015). When there is not much water storage, a doubling is significant. Not only are small variations in topsoil clay percentage important to recognise among sands, but also small variations in clay with depth. Profiles where clay percentage increases with depth may store substantially more water in the root zone that those where clay percentage decreases with depth.

It is very difficult to achieve a significant increase of OM on sands. Many previous attempts have failed or at best achieved very modest increases (soilquality.org.au Fact sheet).

The Department of Primary Industries and Regional Development (DPIRD) Esperance worked with the University of Western Australia on a Filling the Research Gap project on soil organic matter (SOM). They postulated that perennial pastures after 1-15 years, would improve SOM on the Esperance sand plain soils compared to annual pastures. Without tillage and with time under perennial pastures the increase in SOM was expected to be significant. They found no increase in SOM across a range of rainfall and soil types in Esperance. They modelled with Roth-C and found that only after 40 years would there be much increase in SOM, but even so the increase was <10 t/ha, i.e. 0.25 t/ha/yr.

Water repellence is a paradoxical property of sands. While sands typically have excessive drainage, water-repellent sands restrict the entry of water into the surface of the profile. Hence the soils that need rainfall to maintain crop water supply can have reduced infiltration of rainfall. There are at least 3 million hectares of water repellent sands and sandy duplex soils in WA and over 5 million hectares Australia wide. GRDC has a large investment in this area in WA and southern Australia where water repellency remains a major soil constraint. Several solutions have been developed including: wetting agents, inversion tillage, winged tynes and disk openers. The Soil CRC needs to monitor current research and evaluate further investment opportunities in managing water repellent soils.

High soil strength is a common constraint of sands in WA. A recent study by DPIRD shows typical soil penetration resistance values for profiles from the north to the south of the WA wheatbelt. Values about 1.7 mPa, which is commonly recognised as a limit to root elongation were found in all profiles below5-10 cm, and in most this extended to 35 cm or more. The increasing weight of machinery is probably the main factor. Even since 2010, the greater weight of machinery has increased the soil stress at 40 cm depth from 1.5 mPa to 2.4 mPa.

Deep ripping alleviated high soil strength in the subsoil. However, even after 1 year, most of the compaction has been returned to the 0-40 cm depth. Tramlining immediately after ripping on the other hand can maintain low soil penetration resistance in all areas of the paddock except under the wheel track. Tramlining technology is well established on 10-15% of WA grain farms and up to 70% in the Central Highlands of Queensland.

5. List the major research projects to date (including current programs)

Soil Constraints – West is a major collaborative initiative to develop and deliver solutions for a range of soil constraints which limit productive grain cropping in Western Australia; these are non-wetting soils, subsoil constraints, soil compaction and soil acidity. The GRDC, Department of Agriculture and Food (DPIRD), CSIRO and Murdoch University are providing more than $33 million of new research investment to address these significant issues over the next five years. (Current)

Delivering enhanced agronomic strategies for improved crop performance on water repellent soils. DAW00244 – Steve Davies (DPIRD), with Phil Ward and Margaret Roper (CSIRO), and Richard Bell and Richard Harper (Murdoch University). (Current)

Soil Acidity is limiting grain yield - Coordinating the improved management of soil acidity in Western Australia and the GRDC Southern Region. DAW00236 – Chris Gazey (DPIRD).

Subsoil constraints - understanding and management. DAW00242 – David Hall (DPIRD), with Yvette Oliver (CSIRO).

Minimising the impact of soil compaction on crop yield. DAW00243 – Paul Blackwell, Bindi Isbister (DPIRD).

CSP00203 - Increasing production on sandy soils in low and medium rainfall areas of the Southern Region 30 June 2016 Project End Date 1 July 2021. Therese McBeath (CSIRO). The current research project (GRDC project number CSP00203) builds on previous research in the region on sandy soil types (GRDC project number AG00002, 2015).

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7. List the current knowledge gaps

- Reactive surface area and subsoil compaction: claying, delving and SOM

The fundamental limitation of sands is the lack of reactive surface area. The problems that afflict sands, which limit crop productivity, and are at the core of most research to improve their performance, are the limited capacity to supply resources to the roots of crops, whether it be water or nutrients or both.

What do we need to do to realise high performance sands? Unkovich (2014) provides a useful framework to summarise the approaches. There are many inherent properties of sands that can be managed or alleviated: low root growth, water repellence, low fertility, acidification, low OM, and poor options for crop rotation. Some of these properties decline further under management, e.g. acidification, water repellence. Others have been partly alleviated such as nutrient supply. Improvements in performance of sands have been achieved (liming, zero tillage, deep ripping). But on some of these sands, these technologies are still only achieving 30-40% of water-limited yield potential (Hall et al. 2010).

While many technologies have been developed to improve the performance of sands, there is an argument that the most profound change that can be made in sands is to increase their reactive surface area. We have argued in the Soil CRC project, that the breakthrough in high performance sands is to permanently raise the reactive surface area, either with added clay or recalcitrant organic matter.

Across a wide range of soil, especially if the climate is similar, SOM is positively correlated with clay or clay + silt percent. By increasing clay in sands, there is also the potential to boost SOM. With increased SOM, come a range of co-benefits for soil performance- more water storage, greater buffering, more nutrient storage, less leaching, greater rate of herbicide residue breakdown etc.

Consistent and highly significant yield increases were obtained from clay amendment of deep sands over time. Over 15 years, the 200-300 t of subsoil/ha has boosted yields by 50% at Esperance (Hall et al. 2017). The clay amendments have also increases soil pH, organic C, Colwell P, Colwell K, extractable S and CEC (Hall et al. 2011).

Improvements in reactive surface area can be achieved by adding clay and organic matter. There is scope for increasing reactive surface area in both topsoil and subsoils. Questions remain regarding the relative value of different clay types and type of mixing in the soil. Similar questions remain regarding the incorporation of organic matter into subsoils of deep sands: what is the relative benefit of different types of organic matter; how should it be incorporated and mixed; what rates should be applied; what is the longevity of the beneficial effects what is the added benefit of incorporating clay together with organic matter?

However, even with the substantial improvements in performance of these sands with clay addition, they are still not high performance sands. The treatments to date alleviate limitations in the top 40 cm, but leave high levels of soil penetration resistance below 40cm. Hence only 70% of the water limited yield potential is being realised. The next frontier for high performance sands is to work out how to alleviate the compaction deeper in the profile so that roots can explore a greater volume for water and nutrients. After the alleviation of deeper compaction there may be scope for deeper application of nutrients and lime also.

Despite the difficulty of increasing SOM on sands, there is a significant body of literature showing addition of organic amendments to sands increases crop response to inorganic fertilisers. Much of this evidence comes from SE Asia (e.g. Hoang et al. 2015). However, it is a concept that should be tested more rigorously in Australian sands.

On sands, management of nutrients is generally linked to the management of water. This is especially true for irrigated agriculture and intensive horticulture on sands but also with dryland crop and pasture production. Crops on sands respond to improved nutrition, but are further enhanced by optimised irrigation and nutrition.

4.2.6 Machinery-based solutions (led by Dr Diogenes Antille, USQ)

1. *Define the issue*

From the machinery perspective, the following engineering challenges are highlighted:

- Large variability in subsoil-improving machinery performance observed across soil types and environments. There are however some commonalities as well as differences in machinery limitations across the various baseline technologies,
- Several field-ready commercial machines are available as part-solutions able to address specific problems relating to subsoil amelioration operations. The main challenge appears to be in integrating successful machine design solutions to suit specific contexts,
- Increased complexity of problems as amelioration products and biomass used tend to be less processed, bulkier and more variable in consistency (both chemical composition, and physical/mechanical and aerodynamic properties). The problem of variable consistency is two-fold: (1) variable agronomic and environmental performance of the ameliorant following soil application, and (2) the machine-

material interaction and material behaviour (e.g., flowability, mechanical strength and density properties, particle segregation) are significantly affected, which in turn affects the uniformity of distribution during field application, increases the risk of machine blockage and affects work rates (field operating efficiency).

2. *Outline the magnitude and extent of the problem*

The problem is significant because of the trend towards the use of less processed, bulkier and inexpensive materials. Some of the unknown factors directly linked to the selection and performance of the right machinery are: the type of material, rate and depth of application. Additional requirements in terms of machinery design, settings and configuration may be the case for soils managed under controlled traffic farming (CTF) systems. Currently, about 30% of grain growers use CTF, and the majority of CTF systems are also zero-tillage. Minimal soil disturbance (low risk of soil blending/layer inversion) associated with incorporation of amendments is therefore a requirement in these situations.

3. *Identify the industries impacted by the soil constraint (incl. cost to industry where possible)*

All agricultural industries where machinery is used to work the soil, apply product or remove product.

4. *Outline the current farmer practice ameliorations strategies*

- Current practice for application of organic materials includes surface spreading, typically using muck spreaders, followed by shallow incorporation in minimum and conventional tillage systems.
- In zero-tillage systems, surface-applied organic materials may not necessarily be incorporated because of the need to minimise soil disturbance.
- Subsoil manuring has been trialled both at experimental and commercial-scales in a small number of studies and has shown promising results in terms of agronomic response and cost-effectiveness.

5. *List the major research projects to date (including current programs)*

- ULA00008 - Validating subsoil manuring in the High Rainfall Zone
- DAV00149 - 2016.05.07 Understanding the amelioration processes of the subsoil application of amendments in the Southern Region (2016-2021)

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Gill, J. S., Sale, P. W. G., Peries, R. R., Tang, C. (2009). Changes in physical properties and crop root growth in dense sodic subsoil following incorporation of organic amendments. *Field Crops Research,* 114: 137-146.

Gill, J. S., Clark, G. J., Sale, P. W., Peries, R. R., Tang, C. (2012). Deep placement of organic amendments in dense sodic subsoil increases summer fallow efficiency and the use of deep soil water by crops. *Plant and Soil,* 359(1-2): 57-69.

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Sale et al (2005) Subsoil manuring – can the successful agronomic and economic impacts be extended to moderate and low rainfall zones? GRDC Update

Sale and Malcolm (2014) The economics of subsoil manuring - the numbers are out. GRDC Update

7. List the current knowledge gaps and research priorities

The following engineering solutions are required:

- Product storage within the machine
    - Hopper design
    - Predictability of flow characteristics of the ameliorant.
- Product metering
    - Ease of calibration and adjustment
    - Incorporation of variable rate technology/delivery systems for variable rate.
- Product delivery/delivery mechanism
    - Allow for flexibility and control over the placement within the soil profile; e.g., banding or mixing within the soil volume.
- Efficiency and energy considerations
    - Minimise draft by optimising tines configurations, geometry, operating speed and depth,
    - Construction: minimise tear and wear,
    - Satisfactory work rates compatible with commercial-scale farming.
- Versatility – to enable application of a range of ameliorants, including liquid materials (sludge, slurries).
- System-related aspects

- o Surface finish (minimal disturbance) to enable soil moisture conservation and crop establishment,
- o Ability to handle high-surface residue levels (minimal blockage/obstruction/residue build-up ahead of tine unit)
- o Compatibility with controlled traffic and zero-tillage systems.

4.3 Baseline adviser and industry surveys (Activity 3)

4.3.1 Baseline adviser surveys

The total number of responses to the survey was 162. Eligibility to complete the survey was based on participants nominating that they were a farm adviser. A total of 135 were eligible to advance to the remainder of the survey of whom 108 identified as farm advisers, 27 as other advisers. All questions were voluntary, and in some cases not every question was answered.

Of the 135 respondents, 98 identified the region they worked; 55 VIC, 29 NSW, 13 SA, 8 QLD, 7 TAS and 6 WA. Ninety six respondents estimated working with a total 3,275 clients, of which 81% of these clients use farming as their primary source of income.

The survey covered a broad spectrum of industries, as identified in Figure 4 (NB: many advisers reported working across multiple industries). Of the 99 advisers who responded, 79, 75 and 67 worked with crop, sheep and beef producers, respectively. Irrigated cropping (35) and dairy (34) farmers were the second largest group of industries serviced, whilst rice (5) and sugar cane (3) were least represented in this survey.

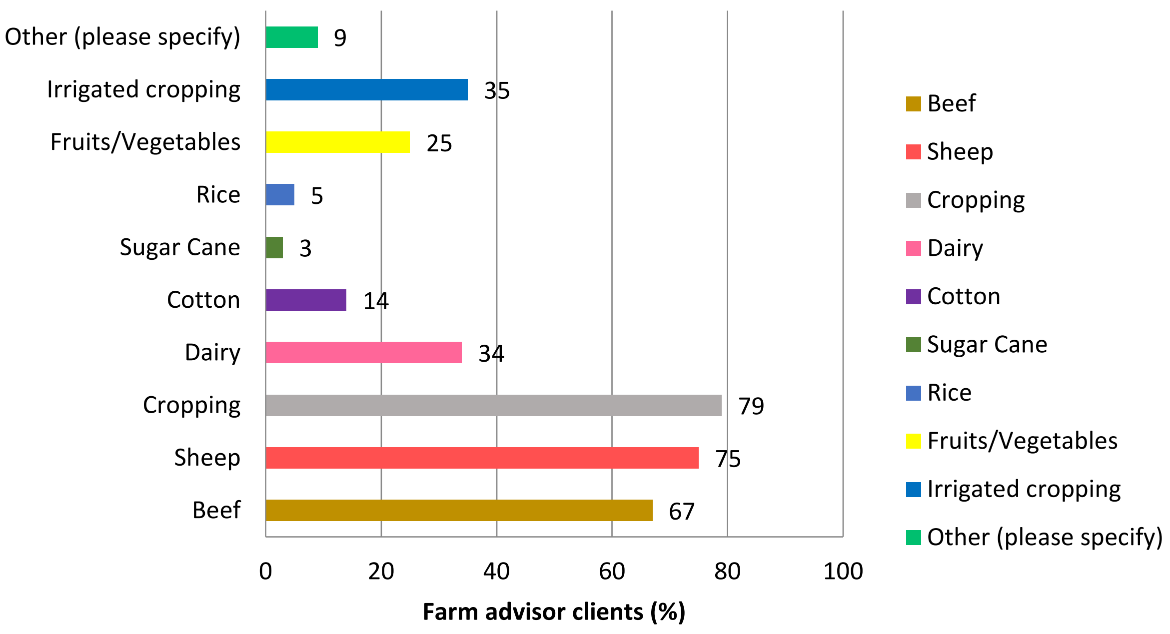


Figure 4. Farm advisers (n=99) from the survey who identified the industries in which they work.

Sixty four respondents provided information on the area farmed for each of the industries they work with (Table 6). Based on this, and considering over 100,730,100 ha of Australian land is farmed (excluding rangeland grazing and intensive agricultural industries) (ABARES 2016), this survey accounts for at least 11% of Australia's agricultural land.

Table 6: The area (ha) represented in the adviser survey (n=64) based on industry

Industry	Area (ha)	Industry	Area (ha)
Beef	1,399,200	Rice	13,000
Cropping	1,148,100	Cotton	12,650
Sheep	709,500	Fruits/Vegetables	5,600
Dairy	102,150	Not specified	7,757,657
Irrigated cropping	63,100		
		TOTAL	**11,210,957**

Advisers were able to list up to six soil constraints of greatest concern to their clients. Initially, regardless of industry type and region, the major constraints were rated from highest to lowest, dependent on the respondent priorities. Overall, acidity, and nutrient decline and deficiencies rated extremely high; low organic carbon, compaction and sodicity rated very high, and waterlogging, water use efficiency, loss/lack of soil structure and drainage rated high (Table 7a). When responses were analysed according to region, soil acidity did not rate as a high priority in the low-medium rainfall cropping regions (that is, Wimmera, North Central and Mallee regions of Victoria, the South Australian Mallee and the Central North of NSW; Table 7b).

The key soil constraint priorities for dryland industries (i.e. cropping, beef, sheep) and irrigated cropping were acidity, nutrient decline and deficiencies, low organic carbon, compaction and sodicity (rated extremely high and very high). For the irrigated industries (i.e. dairy, fruit/vegetables, cotton, sugar cane, rice) the key soil constraint priorities were waterlogging, acidity, compaction, nutrient decline and deficiencies, low organic carbon, loss/lack soil structure, water use efficiency, alkalinity and high soil strength. Due to the nature of the survey it was not possible to identify soil constraints, amelioration practices and barriers to adoption for each industry in each region. Appendix 4 outlines the soil constraint priorities by industry type.

Table 7a: Soil constraints of most concern to farmers as perceived by advisers: a) responses grouped according to priority across all advisers and b) grouped by region

Priority	Agricultural Industry Soil Constraint Priority
Extremely high	Acidity
	Nutrient decline and deficiencies
Very high	Low organic carbon
	Compaction
	Sodicity
High	Waterlogging
	Water Use Efficiency
	Loss or lack of soil structure (non-friable)
	Drainage
Medium	Low soil water holding capacity
	High soil strength e.g. hard setting, dense
	Low levels of soil biology
	Salinity
	Surface crusting
	Infiltration rates, porosity
	Poor retention of groundcover
	Water repellency
Low	Diseases and Pests
	Wind erosion
	Alkalinity
Very low	Nutrient toxicities
	Water erosion
	Contamination

Table 7b: Soil constraints of most concern to farmers as perceived by advisers grouped by region

Region Priority	Victoria Grampians/ South West (4)#	Wimmera/Mallee*/ North Central (12)	Hume (4)	Gippsland (6)	South Australia South East (5)	Lower EP (4)
Extremely high	Nutrient decline and deficiencies	Nutrient decline and deficiencies Compaction	Nutrient decline and deficiencies Acidity	Acidity Nutrient decline and deficiencies	Nutrient decline and deficiencies	Acidity
Very high	Acidity	Water use efficiency Salinity Sodicity	Compaction Diseases and Pests	Waterlogging Drainage	Acidity Alkalinity	Low organic carbon Nutrient decline and deficiencies Water repellency
High	Drainage Water erosion Compaction Loss/lack of structure	High soil strength Surface crusting Waterlogging Loss/lack of structure Low levels biology	Sodicity Waterlogging	Low organic carbon Low levels biology	Sodicity Compaction	Sodicity

Region Priority	New South Wales Central North (3)	Central (8)	Central West (10)	Queensland (6)	Western Aust (4)	Tasmania (6)
Extremely high	Compaction	Acidity Sodicity	Acidity	Nutrient decline and deficiencies Sodicity	Acidity Water repellency	Waterlogging
Very high	Low organic Carbon Diseases and Pests High soil strength	Nutrient decline and deficiencies Compaction	Nutrient decline and deficiencies Low organic Carbon	Compaction Low organic Carbon	Nutrient decline and deficiencies Compaction	Compaction Loss/lack of structure
High	Surface crusting Infiltration, porosity Contamination	Low organic Carbon Wind erosion	Sodicity Water use efficiency Groundcover Low water holding capacity	Acidity Water use efficiency High soil strength	Low organic Carbon	Drainage Nutrient decline and deficiencies Low organic Carbon

*Includes SA Mallee, # number of responses by region

Respondents provided details on the current amelioration techniques being used to overcome the key soil constraints that they had prioritised. As suspected many were utilising agronomic and mechanical techniques to overcome constraints. The following comparisons have been made for three key soil constraints and the variety of amelioration practices identified by the advisers: acidity (Figure 5), soil structure (Figure 6) and Water Use Efficiency (WUE; Figure 7).

Soil acidity was the highest ranked soil constraint by advisers overall however, the current use of amelioration techniques in their regions are relatively limited. Liming, both top-dressed and incorporated, is the major strategy (77%) used across all regions to overcome soil acidity (Figure 5). Across Central West NSW, North and Western Victoria and Eastern SA, other techniques being used to a lesser extent included: spading, acid tolerant species and compost. Most advisers indicated that their clients soil test however we acknowledge that the informants may not represent the full range of farmers. That is, growers may be more likely to soil test if they are using an adviser.

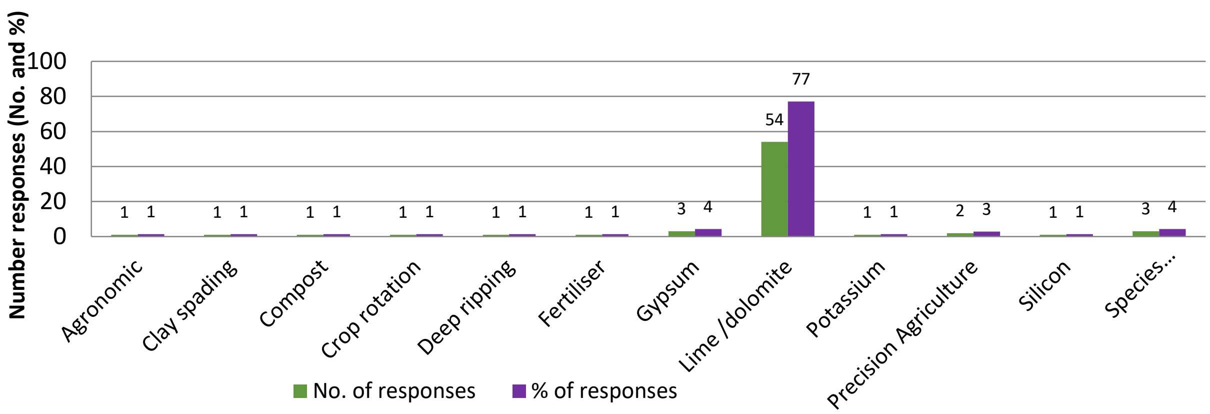


Figure 5. Amelioration practices currently used to address soil acidity. The number (green bar) and proportion (% of total; purple bar) of advisers whose clients use the amelioration strategy are reported.

In comparison to soil acidity, there are a wide variety of amelioration techniques (both agronomic and mechanical) being used to overcome soil structure constraints (Figure 6). For this constraint, we grouped together the responses for compaction, sodicity and loss/lack of soil structure. Advisers from all regions identified using most of the techniques in Figure 6. Only South West Victoria and Central North NSW made no mention of deep ripping as a key mechanical strategy to manage poor soil structure. Gypsum application (18%) and deep ripping (17%) were the two highest ranking strategies currently being used to manage soil structure issues, with CRT/PA/VRT systems (10%), strategic tillage (7%) and use of lime/dolomite (7%) being the next most commonly used strategies. Again, key amelioration techniques used were concentrated on fertiliser use (45% responses) and soil testing (18%). Legume rotations (9%), compost (6%), manure application (6%) and green/brown manure crops (5%) were other techniques used across all regions covered in the survey.

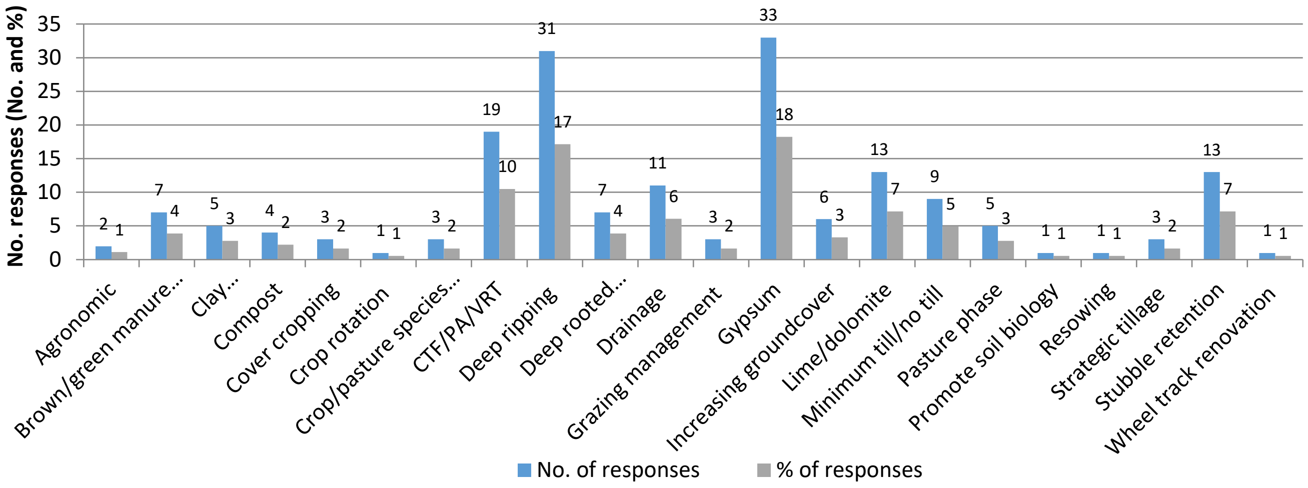


Figure 6. Amelioration practices currently used to address soil structure issues (compaction, sodicity, loss of soil structure). The number (blue bar) and proportion (% of total; grey bar) of advisers whose clients use the amelioration strategy are reported.

Agronomic practices, more so than mechanical means, stand out as the current major strategies used to address WUE across all regions involved in the survey. Unlike soil acidity and nutrient decline, farmers are using a wide range of techniques to improve WUE (Figure 7). Crop/pasture species selection (12%) and stubble retention (11%) are the major practices used, while others included: deep ripping (7%), groundcover (7%), monitoring soil moisture (7%), fallow management (6%), fertiliser application (6%), and to a lesser extent (<5%): irrigation scheduling, agronomy, time of sowing, sowing perennial pastures and minimum/no till.

According to advisers (n=74), in response to the multiple selection question 'What is preventing your clients from implementing practices to address their soil constraints' the top three factors are cost (74%), knowledge/skills (66%) and confidence in the practice (62%) (Figure 8). In addition to practicality, other key factors that farmers consider when considering new technologies to overcome soil constraints are the capital (41%), equipment (50%), time (47%), relative advantage (38%) and risk (27%) associated with undertaking a practice change.

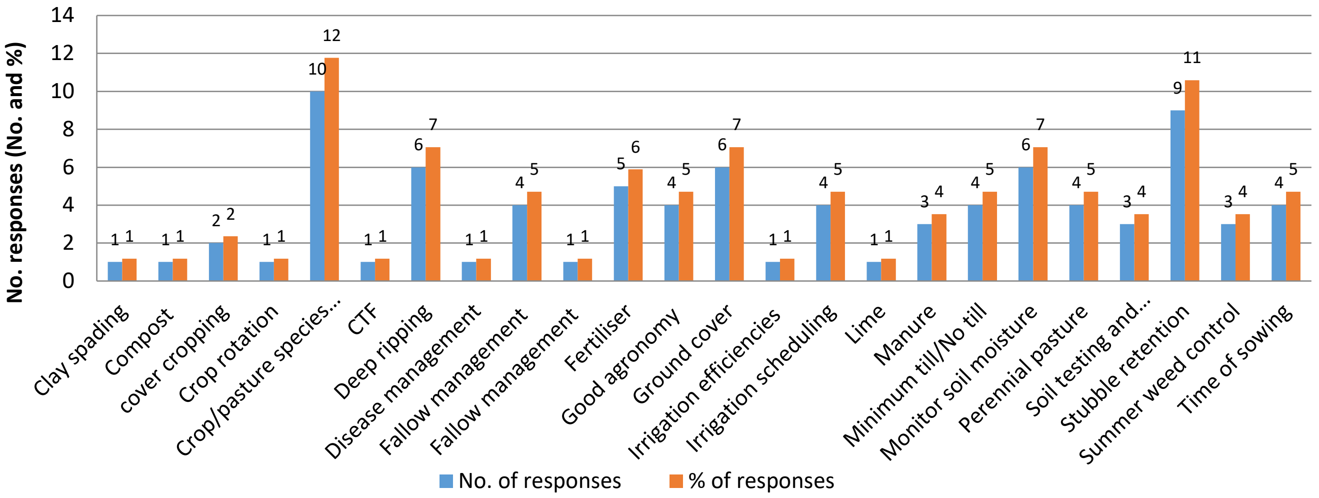


Figure 7. Number of advisers who use water use efficiency (WUE) practices by type of practice. The number (blue bar) and proportion (% of total; orange bar) of advisers whose clients use the amelioration strategy are reported.

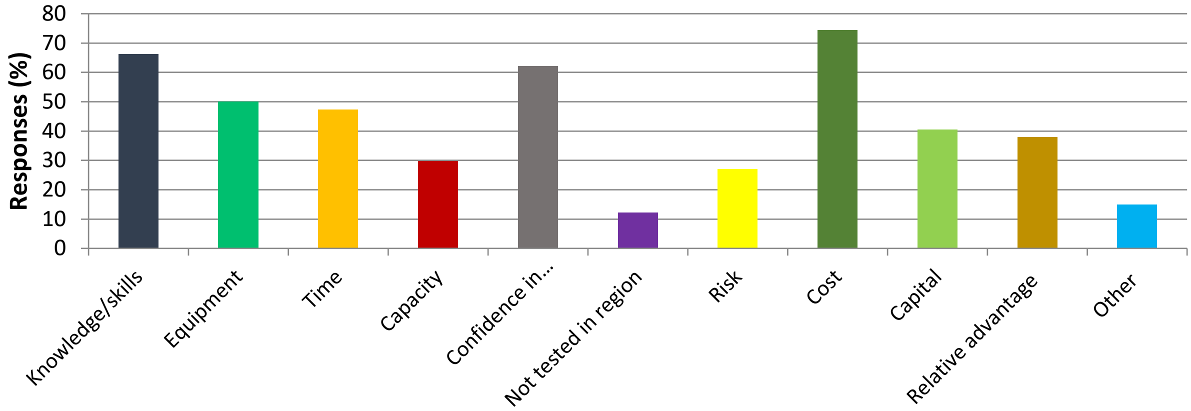


Figure 8. Advisers perception on why farmers are not implementing practice change.

A wide range of channels are used by advisers to source their soil information, from other private agronomists (77%), State Government Departments (73%), Universities (58%), agricultural industry groups (52%), professional memberships (47%), Catchment Management Authority/Natural Resource Management Groups (30%) and social media (23%). Other sources of information that were noted by respondents included: CSIRO, industry funded bodies (e.g. GRDC, DA), farmers, books/literature, soil tests and yield maps, personal experience/observation and sustainable agriculture organisations.

Advisers indicated two key triggers that will drive farmers to address soil constraints and change practice; economic returns (37%) and productivity gains (21%) (Figure 9). Confidence in the information (10%) was identified as the third major driver to manage soil constraints, and other factors included: resilience/sustainability, ease of implementation and proof of concept.

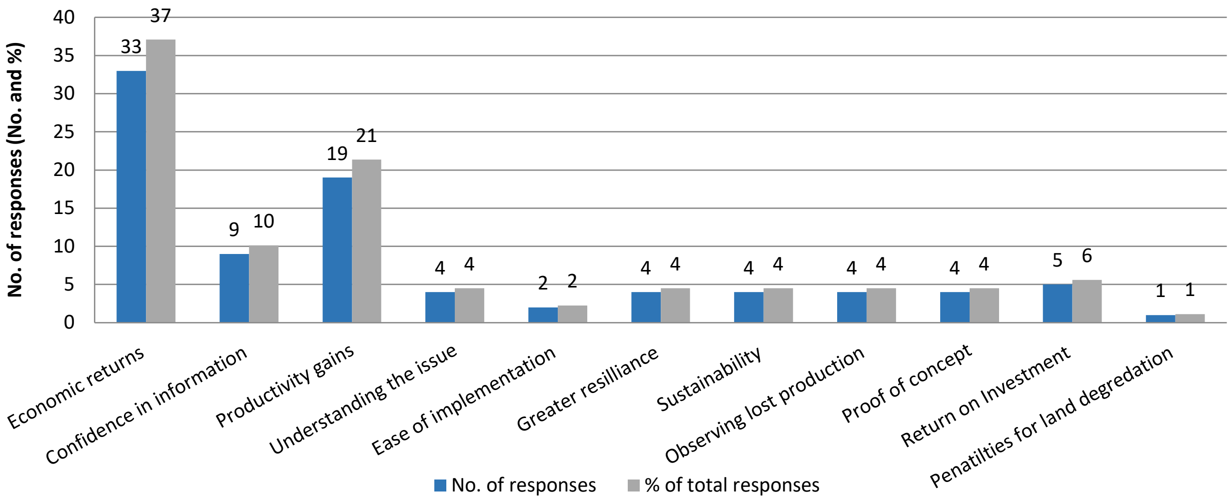


Figure 9. Key drivers for farmers to address their most limiting soil constraint.

Advisers were also asked to identify where the biggest gains are to be made in their industry/region. This open-ended question allowed participants to identify key production priorities. The 57 respondents to this question commented from both production and financial gains perspectives, and their collective responses included:

Production gains:

- Water use efficiency (20%) and fulfilling nutrient requirements of plants/fertiliser use (20%)
- Chemical amelioration (clay/gypsum) or mechanical amelioration (deep ripping) (12%)
- Species/variety selection (perennials, right plant right place right time) (9%)
- Adaptation to climate variability/risk management/accurate forecasting (8%)
- Building soil carbon (through stubble retention, crop and pasture growth) (6%), grazing management (6%), consistent crop/pasture growth and production (6%)
- Rotation management of crop/pasture (5%)
- Drainage (3%), understanding of soil health (3%)
- Increasing rooting depth (2%), uptake of new technologies/practices (2%)

Financial gains:

- Increasing yield/efficient use of fertiliser and resources/value adding (24%)

- Grazing management /stocking rate (11%), Water use efficiency (11%)
- Increasing physical structure of soil (Chemical amelioration (Clay, gypsum) or mechanical amelioration (deep ripping) (7%), uptake of new technologies/ practices/ knowledge (7%)
- Reduced input costs (5%), marketing (higher prices for product) (5%), adaption to climate variability/risk (5%), maintaining and improving soil health (5%), species/variety selection (perennials, more profitable crops) (5%), consistent crop/pasture growth and production (5%)
- Sustained income (better cash flow) (4%)
- Reduced transport costs (2%), benchmarking (2%).

Summary of adviser survey findings:

- Key soil constraints identified in the adviser survey aligned with those identified by researchers as part of the Technical Specialist Workshop
- Some soil constraints were region-specific, highlighting the importance and relevance of research targeted at industries and regions
- Nutrient decline was the most universal soil constraint observed in this survey regardless of industry or region
- Key barriers to practice change are the cost of intervention and farmer's capacity (knowledge, skills and confidence) to undertake the change
- Depending on the soil constraint, there are few to many amelioration strategies used to overcome it
- Advisers get their information from a wide range of sources
- Well executed and targeted extension and farming community engagement will increase the adoption of new technology
- More information is needed on how farmers are dealing with multiple soil constraints

4.3.2 Industry personnel interviews

As part of Activity 3, interviews were conducted with key industry personnel to provide an overview of the key soil constraints, amelioration strategies and barriers to practice change from an industry perspective. Industry's included grains (GRDC Southern and Western Region), cotton (Cotton RDC), dairy (Dairy Australia; DA) and wool (AWI). All of the industry personnel interviewed indicated that they would consider a collaborative project with the Soil CRC on a case by case basis and that they were supportive of investment in soil research. Unfortunately, contacts within GRDC - Northern Region, Sugar RDC and MLA were unavailable within the timeframe of the scoping study.

A brief overview of industry perceptions is provided below. Similar to the adviser survey (Section 4.3.1), more time would enable a thorough analysis and in-depth interpretation of the information provided in the interviews.

Grains - Southern Region

- Major soil constraints:
    - Clay soils - sodicity and poor structure
    - LRZ - sandy soils, compaction, low water holding capacity, water repellent sands, herbicide resistance (alkaline sands)
    - HRZ – waterlogging
    - Nutrient decline
- Amelioration strategies: subsoil manuring, surface liming and liming to depth
- Barriers to change: machinery, feasibility (perceived or actual) and lack of understanding and awareness (i.e. often growers are dealing with multiple constraints and do not know which is the major one or the most important to target).

Grains - Western Region

- Major soil constraints: multiple constraints in one soil, e.g. acidity, non-wetting, compaction
- Amelioration strategies: liming (surface), deep banding of lime (slotting lime in fallow), wetters, mouldboard plough (occasional tillage) and ripping (for compaction and hard pan layers). Innovations include: wetters (which are still at the development stage), need to look at the molecular side of non-wetting sands and use of the mouldboard plough.
- Barriers to change: cost and soil type applicability and evidence of response (e.g. good uptake on sandplain soils, but on heavier duplex soils there is less confidence to undertake practice change).

Cotton industry

- Major soil constraints: compaction (#1; due to machinery), sodicity (#2; but localised issue) and decline in soil carbon (#3; although not compromising yield or causing significant problems so far). It was noted that traditionally cotton was grown on the more forgiving Vertosols but it's now grown from Victoria to Qld on other soil types.
- Amelioration strategies: deep ripping and rotation crops (mainly wheat). Controlled traffic would help but very significant modifications (including difficult row spacings) are needed to existing machinery to make it suit cotton (which is difficult and expensive). Some machinery has changed from 2m to 3m row spacings for wheel tracks but this is specialised and expensive. Innovations include: irrigated cover cropping, sacrifice crops and machinery modification.
- Barriers to change: economics (often cotton is the most profitable crop so growers don't want to grow wheat and controlled traffic modifications are expensive) and water availability (cotton often preferred to cereals when water only allows one of them to be

grown). Other: how to demonstrate the cost ($) associated with lost production due to compaction and the need to cultivate to pupae bust.

Dairy

- Major soil constraints: nutrition (mainly N), drainage (i.e. cattle pugging), soil structure, infiltration and soil acidity (surface and subsoil).
- Amelioration strategies: liming, composting and use of biological products (although these have declined with regulations from Dairy companies). Other (education): the FertSmart Program is raising awareness of soil constraints and appropriate use of fertilisers (e.g. DA is currently updating liming resources and has a target of 100% farms with nutrient management plans). Innovations include: variable rate irrigation for centre pivots, acid soil amelioration and use of EM38 to improve understanding of soils and drainage.
- Barriers to change: awareness of the issue, for example liming is not a regular practice for some growers as they are unaware of subsoil/surface acidity or the impact is masked by cropping.

Wool

- Here key constraints to practice change for improved soil management in general were offered. For example, knowledge of soil sampling protocols, soil analysis and interpretation; grower education and reduction in State-based extension officers.
- Innovations: currently updating online systems (e.g. Evergraze, Pasture Picker and will be able to input soil test results) and improving diagnostic tools and interpretation.
- Barriers to change: knowledge and awareness (e.g. how to take samples, interpret soil data, know what the numbers mean) and uncertainty about where dollars are best invested (e.g. overcoming soil constraints vs pasture regeneration or combination of both).

4.4 Inventory of soil constraints mapping in Australia (Activity 4)

This activity was led by Mark Imhof and Dr Nathan Robinson, with support by Dr Darren Kidd.

This section documents the available mapping products related to soil constraints to Australian agriculture. These products have been reviewed and grouped according to soil constraint 'theme' with additional mapping products that directly or indirectly relate to the soil theme also included (for example, the soil acidity section includes aluminium maps). A brief overview of the soil constraint is provided to contextualise the maps.

4.4.1 Dispersive soils and alkalinity

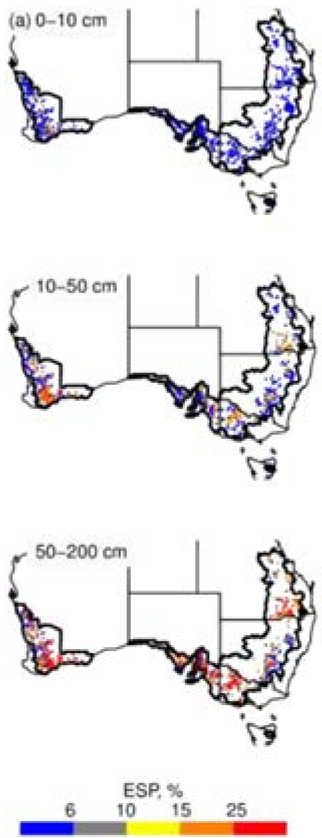
Sodicity

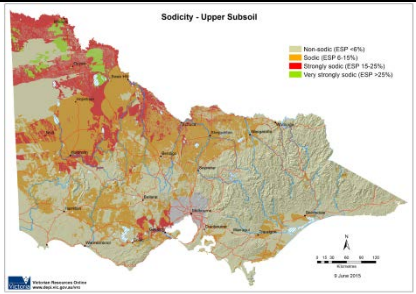
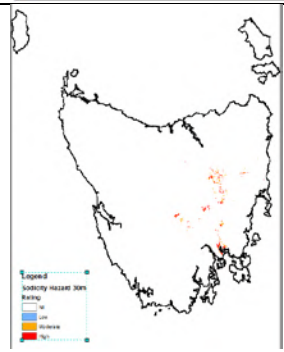
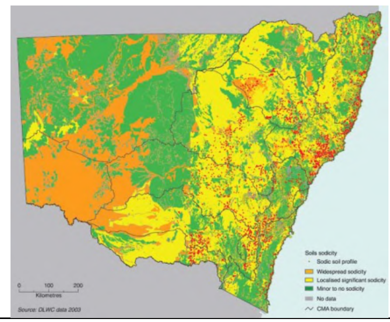
Many soils in the grain belt of southern Australia have very high levels of deep subsoil sodicity (i.e. ESP exceeding 25), generally at depths of between 50 and 100 cm, sometimes shallower. These conditions are invariably, but not exclusively, associated with high pH, moderate salinity and often high boron concentrations, all of which are natural features of these soils. They are not necessarily associated with poor soil structure. Mapping of sodic soils has been carried out in a number of ways, as described in Table 8.

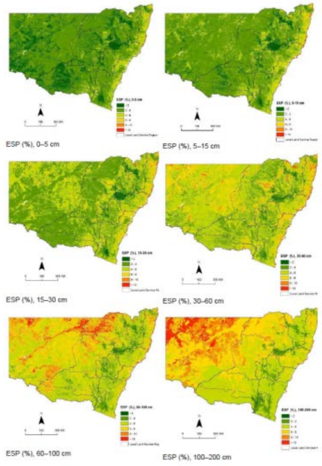
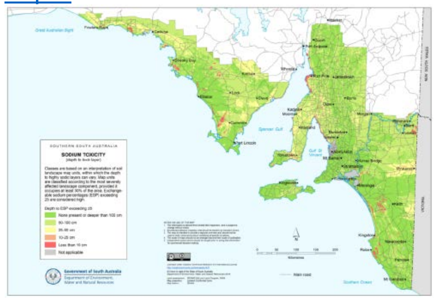
Subsoil carbonate

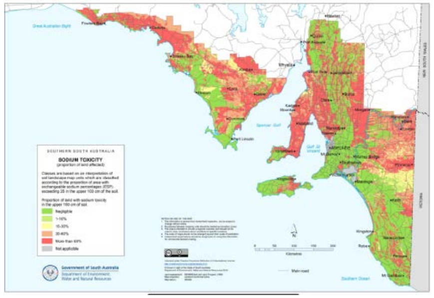
Soils containing carbonates of calcium, and to a lesser extent magnesium, are widespread across southern South Australia and western Victoria, particularly in the less than 400 mm rainfall zone. They can occur as finely divided segregations mixed with sand and clay particles; as hard nodules or concretions (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. See Table 9.

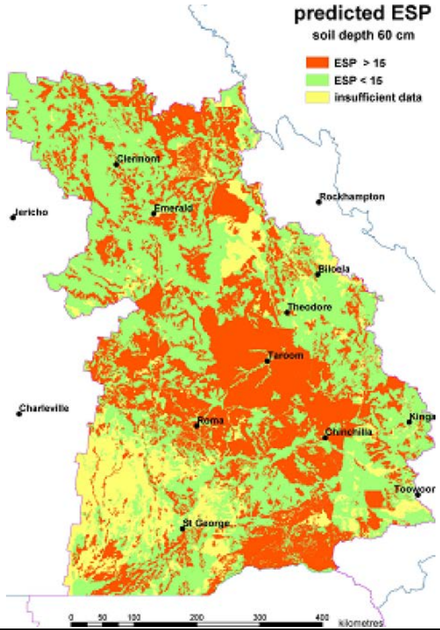
Table 8 Soil sodicity

Soil constraint	Scope (e.g. state, regional, national)	Methodology	Scale	Utility and availability of data	Map Product and Reference
ESP (GRDC)	Australian grains region	Multi-stage approach: (i) *Define active-cropping areas* (ii) *Disaggregate yield to soil data locations* (iii) *Extract soil data and harmonize soil depths* (iv) *Define optimal ranges for soil constraints* (v) *Pre-process climate data* (vi) *Fit a model that represents yield as a function of soil constraints* (vii) *Apply the model to estimate yield gaps due to soil constraints at soil data locations* (viii) *Interpolate values to 1-km grid over entire cropping area* (ix) *Aggregate predictions to SA2 level* (x) *Apply economic analysis at SA2 level* 0-10, 10-50, 50-200 cm	National – aggregated to Statistical Area 2 (SA2) level.	Data and report not released at this stage (GRDC). Provides estimates of yield gaps; gross value of yield gap per constraint; % cropping area affected, and area affected (Mha). CONFIDENTIAL	
Upper subsoil sodicity (Victoria)	Victorian (private land)	Provides a broad state-wide overview of upper subsoil sodicity levels across Victoria. Created from soil site observations within the Victorian Soil Information System (VSIS) and interpretation of existing legacy soil and landscape mapping in Victoria. Should not be used to indicate subsoil sodicity at the local scale, but instead as a generalised indication of likely	1:500,000	Available on request through Agriculture Victoria (DEDJTR) http://vro.agriculture.vic.gov.au/dpi/vro/vrosite.nsf/pages/soil_soil-sodicity	

Soil constraint	Scope (e.g. state, regional, national)	Methodology	Scale	Utility and availability of data	Map Product and Reference
		ESP classes at regional to state-wide scale.			
Sodicity (soil profile)	Tasmania (state)	V1.0 80 m resolution DSM (2015), followed by draft v2.0 30 m resolution DSM (2018), using newly collected (400 sites) and Tasmanian Legacy Soil Site data (6500 sites, DPIPWE) and local, state-derived sodicity hazard rulesets based on ESP% and depths. Rulesets available on DPIPWE website post June 2018. DSM based on a regression tree approach, for multiple depths and soil attributes, using k-fold cross validation to determine modelling diagnostics and uncertainties.	80 m, 30 m resolution	Creative Commons, data on request and available on LISTmap post June 2018. ESP R^2 Calibration 0.72, Validation 0.46	
Sodicity (NSW)	NSW	Unsure at this stage: may have been based on a combination of land systems mapping and soil-landscape mapping with expert opinion to classify map units	>1:1M	Unclear if available, potentially superseded by Sodicity map generated as part of NSW Digital Soil Maps.	Included in New South Wales State of the Environment (2006) report.  DLWC (2003)

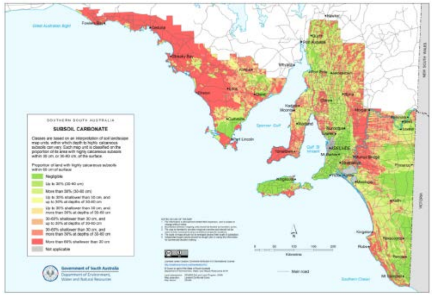
Soil constraint	Scope (e.g. state, regional, national)	Methodology	Scale	Utility and availability of data	Map Product and Reference
ESP	NSW (State)	Digital soil mapping (DSM) using multiple linear regression or Cubist decision tree modelling approaches. Original models were developed from a dataset of approximately 6000 soil profiles across NSW, divided into training and validation data sets at an 80:20% ratio. The models were applied against 17 environmental covariates representing the various soil forming factors to develop the final maps. 0-5, 5-15, 15-30, 30-60, 60-100, 100-200. Lin's concordance values are low: 0-5 cm (0.22), 5-15 cm (0.22), 15-30 cm (0.20), 30-60 cm (0.17), 60-100 cm (0.14), 100-200 cm (0.07).	100 m raster resolution	Provides continuous data on soil properties/constraints across NSW for a range of purposes, including assisting in sustainable land management, ecological modelling and hydrological modelling. Digital maps for all depth intervals can be downloaded through OEH data portal. http://data.environment.nsw.gov.au/dataset/digital-soil-maps-for-key-soil-properties-over-nsw Maps for six depth intervals down to 2 m and 90% confidence level maps are also available on request via: data.broker@environment.nsw.gov.au	
Sodium toxicity (depth to toxic layer)	Southern SA	Estimates of ESP based on extrapolation of laboratory analyses between similar soil materials and soils. Five (plus not applicable) estimated 'Depth to Sodium Toxicity' analysis data classes have been supplied, as percentage values of Soil Landscape Map Units to be used for the calculation of spatial data statistics. Five (plus not applicable) legend categories (TOX_NA_D) have been determined by rating the most severely affected landscape component, provided it occupies at least 30% of the area of the Soil Landscape Map Unit.	Accuracy to scale of mapping (50 m at 1:50K and 300 m at 1:100K scale). SE, Kangaroo Is., Lofty Ranges and lower Yorke Peninsula mapped at 1:50K. Eyre Peninsula, main part of Yorke	Data available through Creative Commons Attribution 4.0 via: https://data.sa.gov.au/data/dataset/sodium-depth	https://data.sa.gov.au/data/dataset/sodium-depth 

Soil constraint	Scope (e.g. state, regional, national)	Methodology	Scale	Utility and availability of data	Map Product and Reference
			Peninsula, Murray Mallee and Northern Agricultural Districts mapped at 1:100K.		
Sodium toxicity (proportion of land affected)	Southern SA	Estimates of ESP based on extrapolation of laboratory analyses between similar soil materials and soil types. Affected land has toxic levels of sodium within 100 cm of the surface. Three Sodium Toxicity (proportion of land affected) analysis data classes (including not applicable) have been supplied, as percentage values of Soil Landscape Map Units to be used for the calculation of spatial data statistics. Five (plus not applicable) legend categories (TOX_NA_P) determined by rating the most severely affected landscape component, provided it occupies at least 30% of the area of the Soil Landscape Map Unit.	Accuracy to scale of mapping (50 m at 1:50K and 300 m at 1:100K scale). SE, Kangaroo Is., Lofty Ranges and lower Yorke Peninsula mapped at 1:50K. Eyre Peninsula, main part of Yorke Peninsula, Murray Mallee and Northern Agricultural Districts mapped at 1:100K.	Data available through Creative Commons Attribution 4.0 via: https://data.sa.gov.au/data/dataset/sodium-proportion	https://data.sa.gov.au/data/dataset/sodium-proportion 
ESP (60 cm)	Qld grain cropping region	Spatial estimation of subsoil constraints in Queensland has been derived using soil site data in the NRM Soil and Land Information (SALI) database system, and the best available land resource mapping. Polygons (from land resource survey			Dang et al (2004).

Soil constraint	Scope (e.g. state, regional, national)	Methodology	Scale	Utility and availability of data	Map Product and Reference
		maps) overlayed with point data (site information) and values (or attributes) allocated to the polygons according to a hierarchical system of 'attribution' based on the method of Smith and Grundy (2000).			
ESP	Regional – e.g. Burdekin	Raster surfaces describing ESP (15N1 - Rayment and Lyons, 2011) of soils in the Burdekin River basin. Study area covers approximately 13.4 million hectares in Central and North Queensland. Mapped in five depth slices to a maximum depth of one metre. Upper and lower uncertainty limits accompany each depth slice. Developed using datasets held in the SALI (Soil and Land Information) database (DSITI & DNRM). The maps were made by using spatial modelling and digital soil mapping (DSM; McBratney et al., 2003) techniques to produce a fine-resolution 3-arc-second grid of soil attribute values and their uncertainties, across entire Burdekin	90 m and 30 m raster grid	Available through Creative Commons 3.0 via: https://data.qld.gov.au/dataset/soil-and-landscape-grid-digital-soil-attribute-maps-for-queensland-series/resource/ce1ce6cd-6732-4825-ba34-eda246ca809c	http://qldspatial.information.qld.gov.au/catalogue/custom/search.page?q="Queensland digital soil attributes - Burdekin River basin - exchangeable sodium" O'Brien, L.E. and Thomas, E. 2018. Soil constraints mapping to inform nutrient management in the cropping industries. RP155C. Soil Constraints Report. Department of Environment and Science, Queensland Government – awaiting publication.

Soil constraint	Scope (e.g. state, regional, national)	Methodology	Scale	Utility and availability of data	Map Product and Reference
		River Basin (130 000 sq km). ESP (15N1 - Rayment and Lyons, 2011) determined using the most appropriate method based on soil pH and method uncertainty (where results exist for more than one method). Methods used include exchangeable cations (15Ax, 15C1, 15D3, 15F1 - Rayment and Lyons, 2011), Mehlich 3 extractable elements (18F1 - Rayment and Lyons, 2011) and MIR reflectance spectroscopy (CEC only).			

Table 9 Subsoil carbonate

Soil constraint	Scope (e.g. state, regional, national)	Methodology	Scale	Utility and availability of data	Map Product and Reference
Subsoil carbonate	Southern SA	Three Subsoil Carbonate analysis data classes (depth to very highly calcareous material i.e. strong reaction to 1M HCl) have been supplied, as percentage values of Soil Landscape Map Units. Depth to highly calcareous subsoils (i.e. fine carbonate in the soil matrix) may vary significantly across the landscape. Each Soil Landscape Map Unit is categorised into legend categories (CARB_SUB) according to the proportion of its area with highly calcareous subsoils within 30 cm of the surface. A further subdivision is made to highlight land where highly calcareous subsoils occur within 60 cm of the surface. A total of eight legend categories (including not applicable) have been supplied – e.g. up to 30% (30-60 cm), >60% shallower than 30 cm.	Accuracy to scale of mapping (50 m at 1:50K and 300 m at 1:100K scale). SE, Kangaroo Is., Lofty Ranges and lower Yorke Peninsula mapped at 1:50K. Eyre Peninsula, main part of Yorke Peninsula, Murray Mallee and Northern Agricultural Districts mapped at 1:100 K.	Data is accessible under a Creative Commons 4.0 via: https://data.sa.gov.au/data/dataset/subsoil-carbonate	https://data.sa.gov.au/data/dataset/subsoil-carbonate 

4.4.2 Soil acidity

Soil acidity

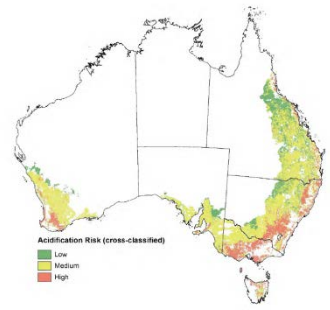
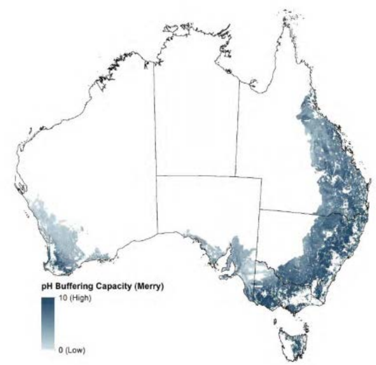
Soil acidity mapping highlights land where acidification due to normal farming practices is, or could become, a significant problem. Buffering Capacity indicates capacity of soil to resist acidification. The predicted potential benefits of ameliorating soil acidity would be $428 million/annum (Dang et al 2017). Amelioration below 30 cm is difficult.

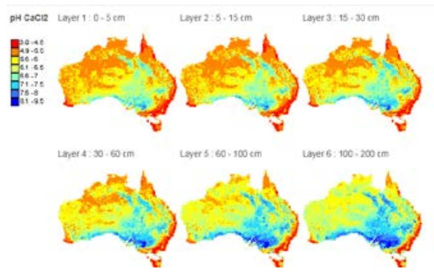
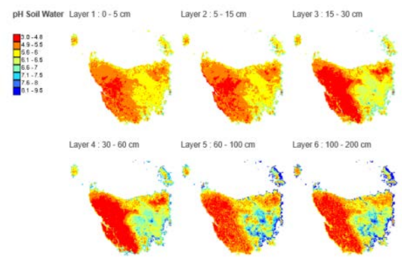
NLP prioritisation process (McKenzie et al 2017) identified acidity as having very large and widespread impacts on agricultural production in many districts of Australia. Impacts are occurring now and likely to increase substantially over next decade. Experience in some jurisdictions indicates that problems can be solved by supplying improved information on acidification risk and appropriate responses – but identification of where such investments are best made is needed. See Table 10.

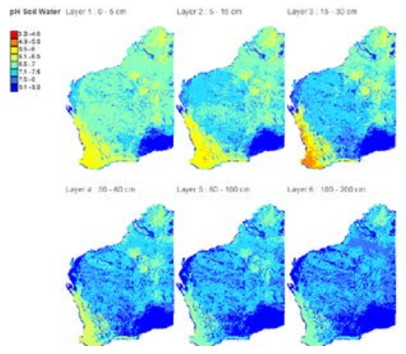
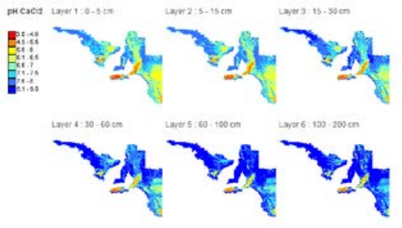
Aluminium

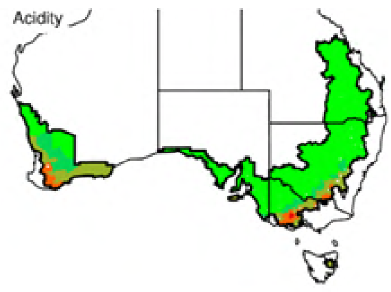
Many plants are sensitive to aluminium at even small concentrations. Aluminium occurs in most soils, but its availability to plants is highly pH dependent. Although there is some evidence to suggest that aluminium availability increases in strongly alkaline soils, most aluminium toxicity is reported in strongly acidic soils. As a general rule, correction of soil acidity will alleviate aluminium toxicity symptoms. See Table 11.

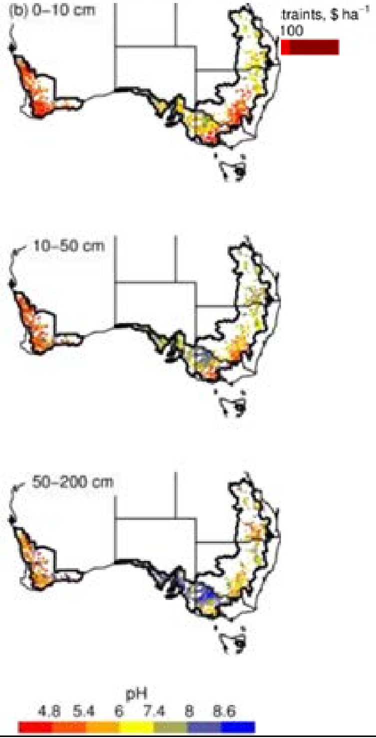
Table 10 Soil acidity

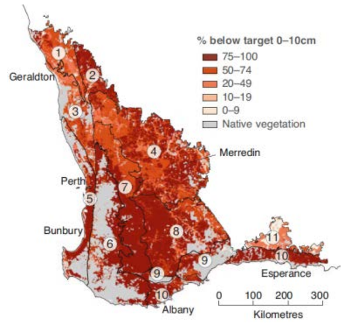
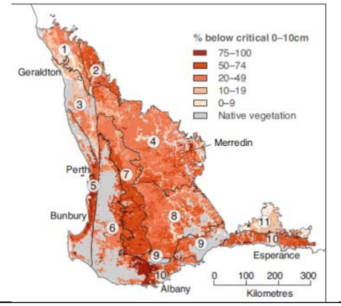
Soil constraint	Scope (e.g. state, regional, national)	Methodology	Scale	Utility and availability of data	Map Product and Reference
Soil acidification risk	National	<u>NLP2 prioritisation</u> Estimated acidification risk (low, medium, high) based on estimation of lime requirements and net acid addition rates of current land uses. These data were used with other inputs to derive the summary of priorities for addressing acidification by management unit (e.g. NRM region) Index of the risk of soil acidification, based only on soil characteristics and current land use, calculated using the following indicators: 1. Lime requirements (LR, 5 classes) – calculated using the current pH and buffering capacity (see Figure 2.4). 2. Likely NAAR – estimated using the classes defined by the provisional NAAR ranking (see Table 2.3) and mapped using the Australian Land Use and Management Classification (Table 2.4) (5 classes) (see Figure 2.5) Spatial layer is the result of combining these two indices according to Table 2.4. Soil acidification is likely to be a problem in areas with a high-risk ranking. This important consideration is much harder to determine. Risk of Acidification values: 1 = Low, 2 = Medium, 3 = High risk <u>New data sources</u>: Improved National Soil Grid (pH and pH buffering capacity); improved land management data; new datasets for some regions (e.g. WA and SA)	I km raster	National prioritisation -useful for framing priorities for interventions but provides no information on effectiveness of current land management. Creative Commons Attribution 4.0 International Public License	McKenzie NJ, Hairsine PB, Gregory LJ, Austin J, Baldock JA, Webb MJ, Mewett J, Cresswell HP, Welti N, Thomas M (2017). Priorities for improving soil condition across Australia's agricultural landscapes. CSIRO, Australia. <u>Acidification Risk</u>  gure 2.6: Areas where soil acidification is likely to be a problem based on the cross-classification in Table 2.4 of estimated lime requirements and net acid addition rates of current land uses. <u>Buffering Capacity</u> 

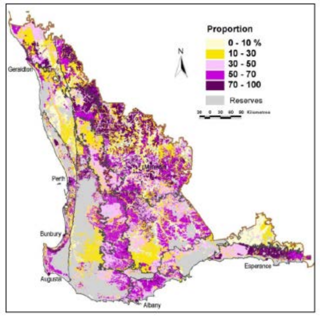
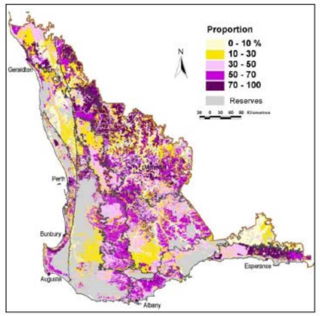
Soil constraint	Scope (e.g. state, regional, national)	Methodology	Scale	Utility and availability of data	Map Product and Reference
		Type of analysis: Continental analysis vis GIS with improved spatial datasets; incorporation of results from district-scale studies on current extent and severity of acidification.			
pH – $CaCl_2$	National (Soil and landscape Grid of Australia)	Soil and Landscape Grid of Australia's, Australia-wide Soil Attribute Maps generated (2014) using measured soil attribute data from existing databases in the national soil site data collation and spectroscopic estimates made with the CSIRO's National spectroscopic database (Viscarra Rossel & Webster, 2012). Spatial modelling performed using decision trees with piecewise linear models and kriging of residuals. 50 environmental covariates, representing climate, biota, terrain, and soil and parent material, used in the modelling. Uncertainty derived using a bootstrap (Monte Carlo-type) approach to derive, for each pixel, a probability density function (pdf), from which were derived 90% confidence limits. Approach described in Viscarra Rossel et al. (2015a). Soil attribute levels estimated for depth intervals: 0-5 cm, 5-15 cm, 15-30 cm, 30-60 cm, 60-100 cm and 100-200 cm.	Predicted at 90 m raster resolution.	Creative Commons Attribution 4.0 International License. Data accessible via: http://www.clw.csiro.au/aclep/soilandlandscapegrid/	
pH – water	Tasmania – from Soil and landscape Grid of Australia	Soil attributes modelled using decision trees with piecewise linear models using local scale input data and covariates.	Predicted at 90 m raster resolution.	Creative Commons Attribution 4.0 International License	

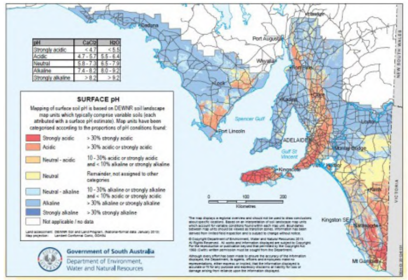
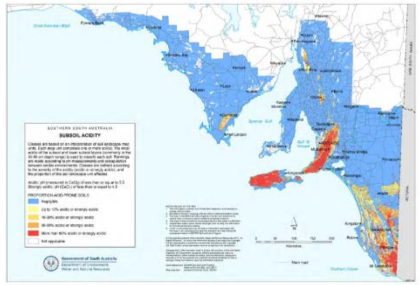
Soil constraint	Scope (e.g. state, regional, national)	Methodology	Scale	Utility and availability of data	Map Product and Reference
pH (water)	WA – from Soil and Landscape Grid of Australia	Polygon map unit disaggregation technique 'DSMART' used (Odgers et al., 2014). In these regions the disaggregation is based on the best contiguous soil polygon maps that were available for these areas.	Predicted at 90 m raster resolution.	Creative Commons Attribution 4.0 International License	
pH (water)	SA – from Soil and Landscape Grid of Australia	Polygon map unit disaggregation technique 'DSMART' used (Odgers et al., 2014). In these regions the disaggregation is based on the best contiguous soil polygon maps that were available for these areas.	Predicted at 90 m raster resolution.	Creative Commons Attribution 4.0 International License	
Acidity		Multi-stage approach: (i) *Define active-cropping areas* (ii) *Disaggregate yield to soil data locations* (iii) *Extract soil data and harmonize soil depths* (iv) *Define optimal ranges for soil constraints* (v) *Pre-process climate data*		Data and report not released at this stage (GRDC). Provides estimates of yield gaps; gross value of yield gap per constraint; % cropping area affected, and area affected (Mha). CONFIDENTIAL	Reference: Cost of Edaphic Stress to the Australian Grains Industry (UQ00081) 2017. Yash Dang (UQ) et al.

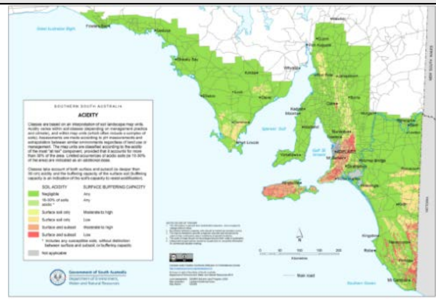
Soil constraint	Scope (e.g. state, regional, national)	Methodology	Scale	Utility and availability of data	Map Product and Reference
		(vi) *Fit a model that represents yield as a function of soil constraints* (vii) *Apply the model to estimate yield gaps due to soil constraints at soil data locations* (viii) *Interpolate values to 1-km grid over entire cropping area* (ix) *Aggregate predictions to SA2 level* (x) *Apply economic analysis at SA2 level* 0-10, 10-50, 50-200 cm			

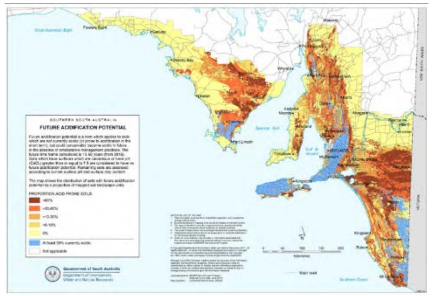
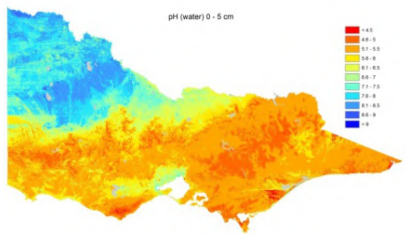
Soil constraint	Scope (e.g. state, regional, national)	Methodology	Scale	Utility and availability of data	Map Product and Reference
					
Acidity	SW Western Australia	Geo-located soil samples were collected across the agricultural areas of south-west WA during 2005–12 by Precision SoilTech (Andrew et al. 2007), a federal government funded Caring for our Country project in conjunction with smaller datasets including resampling of Weaver and Reed (1998) and Summers and Weaver (2006) sites. A total of 161 000 samples, including about 67 000 samples taken from subsurface (10–20 and 20–30 cm layers), were collected from over 93 000 sites and used (anonymously) to determine soil pH	Aggregated to Agricultural Soil Zones (Ag Soil Zones).	Regional benchmarking. Does not assist with farm management. Data available via DPIRD (contact: Tim Overheu).	Reference: Gazey C, Andrew J and Griffin E (2013). In: *Report card on sustainable natural resource use in agriculture in WA*. DAFWA.

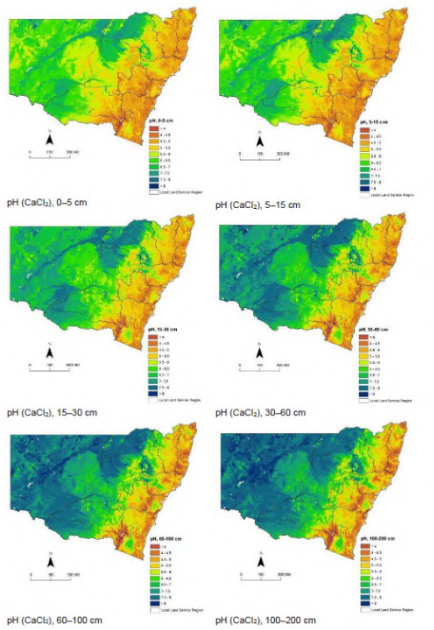
Soil constraint	Scope (e.g. state, regional, national)	Methodology	Scale	Utility and availability of data	Map Product and Reference
		status and trend. The data set used is unique in Australia. % of sites sampled (2005-12) with soil pH at 0-10 cm below the DAFWA target of pH_{Ca} 5.5 and critical pH (pH_{Ca} 5.0). For each Ag Soil zone in SW WA.			 
Subsoil acidity (proportion of area < pH 5.6 water)	SW WA	Susceptibility ranges (proportions of map units) likely be soil pH limiting to wheat growth (van Gool 2016).	Various input scales – 1:50K to 1:250K.	Data available via the Western Australia government data service: https://catalogue.data.wa.gov.au/dataset/soil-landscape-land-quality-subsurface-acidification	van Gool, D 2016, 'Identifying soil constraints that limit wheat yield in South-West Western Australia', *Resource management technical report 399.* Department of Agriculture and Food, Western Australia, Perth.

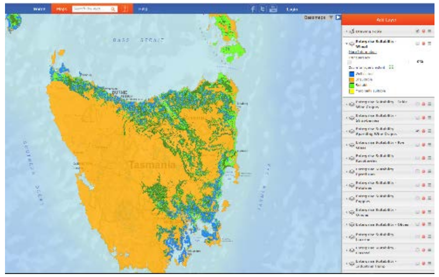
Soil constraint	Scope (e.g. state, regional, national)	Methodology	Scale	Utility and availability of data	Map Product and Reference
					 Figure 4.7.1b Area where subsoil acidity is one of few (1–3) constraints
Surface soil acidity (proportion of area < pH 5.6 water)	SW WA grain region	The map of topsoil acidity shows where pHw in the topsoil is less than 5.6 (or pHCa <4.5), considered to be less restrictive than subsoil pH, as it is readily ameliorated using surface application of lime. The pH values were edited for entire soil groups within each soil-landscape zone after collation of information for the *Report card on sustainable natural resource use in agriculture* (DAFWA 2013). However, topsoil pH varies with management (fertiliser use, lime, cultivation, rainfall). The values represent a mean, but there will be considerable variation within individual paddocks and between farms. Shows that it is a significant yield-limiting constraint on the edge of the Wheatbelt around Mullewa and Morawa, but occurs in most cropping zones.	Various input scales – 1:50K to 1:250K.	Data available via the Western Australia government data service: https://catalogue.data.wa.gov.au/dataset/soil-landscape-land-quality-zones	van Gool, D 2016, 'Identifying soil constraints that limit wheat yield in South-West Western Australia', *Resource management technical report 399.* Department of Agriculture and Food, Western Australia, Perth.  Figure 4.7.1b Area where subsoil acidity is one of few (1–3) constraints

Soil constraint	Scope (e.g. state, regional, national)	Methodology	Scale	Utility and availability of data	Map Product and Reference
Acidity (Surface and subsurface)	Agricultural zone SA	The acidity of each component of each Soil Landscape Map Unit is assessed. All land that is known to be acidic (or similar to land known to be acidic), is classified regardless of land use or management.17 Acidity attribute (or 'analysis data') classes have been supplied as percentage (areal extent) values of each Soil Landscape Map Unit. Note: the sum of all percentage values for each map unit totals 100%. This analysis data is to be used for the calculation of spatial data statistics. Acidity attribute (analysis data) classes account for both surface (0-10 cm) and subsoil (30-80 cm) acidity, as well as surface soil buffering capacity. Respective pH values for soil acidity classes are: 'Strongly acidic': pH_{CaCl2} <4.5 or pH_{H2O} <5.5; 'Acidic': pH_{CaCl2} 4.5-5.4 or pH_{H2O} 5.5-6.4; 'Neutral': pH_{CaCl2} 5.5-6.9 or pH_{H2O} 6.5-7.9; 'Alkaline': pH_{CaCl2} >=7 or pH_{H2O} >=8. For map display purposes, Soil Landscape Map Units are categorised into 7 legend categories (ACID), including not applicable, designed to highlight the acidity of the most 'at risk' component(s), occupying at least 30% of the map unit area. Map units with limited occurrences of acidic soils (10-30% of area) are shown as an additional legend category.	Accuracy to scale of mapping (50 m at 1:50K and 300 m at 1:100K scale). SE, Kangaroo Is., Lofty Ranges and lower Yorke Peninsula mapped at 1:50K. Eyre Peninsula, main part of Yorke Peninsula, Murray Mallee and Northern Agricultural Districts mapped at 1:100K.	Data available through Creative Commons Attribution 4.0 via: https://data.sa.gov.au/data/dataset/acidity	Soil acidity and buffering capacity (AgInsight SA)   
Acidity	Southern SA	This assessment highlights where acidity is, or could become, a significant problem. Based on limited field pH measurements and extrapolation	Accuracy to scale of mapping (50 m at	Data available through Creative Commons Attribution 4.0 via: https://data.sa.gov.au/data/dataset/acidity	https://data.sa.gov.au/data/dataset/acidity

Soil constraint	Scope (e.g. state, regional, national)	Methodology	Scale	Utility and availability of data	Map Product and Reference
		between similar environments. The acidity of each component of each Soil Landscape Map Unit is assessed. All land that known to be acidic, or similar to land known to be acidic, is classified regardless of land use or management. 17 Acidity attribute (or 'analysis data') classes have been supplied as percentage (areal extent) values of each Soil Landscape Map Unit. Acidity attribute (analysis data) classes account for both surface (0-10 cm) and subsoil (30-80 cm) acidity, as well as surface soil buffering capacity (which indicates a soil's capacity to resist acidification). Respective pH values for soil acidity classes are: 'Strongly acidic': pHCaCl2 <4.5 or pHH2O <5.5; 'Acidic': pHCaCl2 4.5-5.4 or pHH2O 5.5-6.4; 'Neutral': pHCaCl2 5.5-6.9 or pHH2O 6.5-7.9; 'Alkaline': pHCaCl2 >=7 or pHH2O >=8. For map display purposes, Soil Landscape Map Units are categorised into 7 legend categories (ACID), including not applicable, designed to highlight the acidity of the most 'at risk' component(s), occupying at least 30% of the map unit area. Map units with limited occurrences of acidic soils (10-30% of area) are shown as an additional legend category.	1:50K and 300 m at 1:100K scale). SE, Kangaroo Is., Lofty Ranges and lower Yorke Peninsula mapped at 1:50K. Eyre Peninsula, main part of Yorke Peninsula, Murray Mallee and Northern Agricultural Districts mapped at 1:100K.		
Future Acidification Potential (SA)	State – southern SA	Mapping based on SA Agricultural landscape mapping. Future acidification potential is where soils could conceivably become acidic in future, in the absence of ameliorative management practices. 'Future' implies a time frame of 10-50 years from 2015.	Accuracy to scale of mapping (50 m at 1:50K and 300 m at 1:100K	Data available through Creative Commons Attribution 4.0 via: https://data.sa.gov.au/data/dataset/acid-potential-asris	

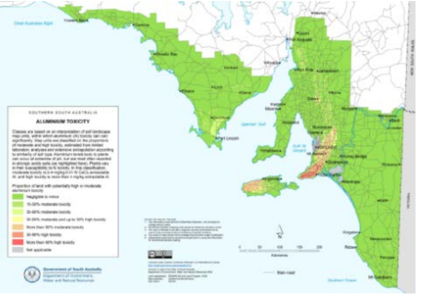
Soil constraint	Scope (e.g. state, regional, national)	Methodology	Scale	Utility and availability of data	Map Product and Reference
		Soils classified as already acidic (i.e. surface pHCaCl2 < 5.5) are excluded from the calculation. Soils with calcareous surfaces (or have pHCaCl2 > 7.5) are considered to have no future acidification potential. Remaining soils assessed according to current surface pH, surface clay content and rainfall zone.	scale). SE, Kangaroo Is., Lofty Ranges and lower Yorke Peninsula mapped at 1:50K. Eyre Peninsula, main part of Yorke Peninsula, Murray Mallee and Northern Agricultural Districts mapped at 1:100K.		
pH (acidity) DSM (pH water and pH $CaCl_2$)	Victoria	Digital soil mapping - pH (water and $CaCl_2$) Grids of 10 soil properties produced for Victoria. These grids, in raster format, provide prediction and confidence interval values for key soil properties at a 90 m grid resolution for six set depths meet the specifications created by GlobalSoilMap; 0 – 5 cm, 5 – 15 cm, 15 – 30 cm, 30 – 60 cm, 60 - 100 cm and 100 – 200 cm, across Victoria. Methodology used to develop the Soil Grids of Victoria was based on that refined by the Australian Soil and Landscape Grid (Viscarra Rossel et al. 2015). Data and knowledge embedded into existing soil related datasets, e.g.	Predicted at 90 m raster resolution.	Data is accessible via: http://www.ozdsm.com.au/ozdsm_map.php or DEDJTR. Prediction accuracy: 0-5 cm (R^2 = 0.68) 5-15 cm (R^2 = 0.72) 15-30 cm (R^2 = 0.74) 30-80 cm (R^2 = 0.74) 100-200 cm (R^2 = 0.72)	Agriculture Victoria Research Report: Soil Grids of Victoria (Hopley et al 2017) - unpublished. 

Soil constraint	Scope (e.g. state, regional, national)	Methodology	Scale	Utility and availability of data	Map Product and Reference
		soil profile and land mapping collections, have been key inputs. 170 gridded environmental datasets were used. The supporting database contains more than one million measurements for over 18,000 geo-referenced soil sites. Over 6,000 of these sites have soil property predictions derived from samples analysed using MIR spectroscopy.			
pH (acidity) $CaCl_2$	NSW	Digital soil mapping (DSM) using multiple linear regression or Cubist decision tree modelling approaches. Original models were developed from a dataset of approximately 5830 soil profiles across NSW, divided into training and validation data sets at an 80:20% ratio. The models were applied against 17 environmental covariates representing the various soil forming factors to develop the final maps. 0-5, 5-15, 15-30, 30-60, 60-100, 100-200. Lin's concordance: 0.59, 0.64, 0.73, 0.76, 0.79, 0.77	100 m raster resolution	Provides continuous data on soil properties/constraints across NSW for a range of purposes, including assisting in sustainable land management, ecological modelling and hydrological modelling Digital and jpeg maps for 0-30 and 30-100 cm depth intervals can be downloaded through OEH data portal. http://data.environment.nsw.gov.au/dataset/digital-soil-maps-for-key-soil-properties-over-nsw Maps for six depth intervals down to 2 m and 90% confidence level maps are also available on request via: data.broker@environment.nsw.gov.au	Office of Environment and Heritage, Sydney. http://data.environment.nsw.gov.au/dataset/digital-soil-maps-for-key-soil-properties-over-nsw 

Soil constraint	Scope (e.g. state, regional, national)	Methodology	Scale	Utility and availability of data	Map Product and Reference
Tasmania		Digital Soil Mapping (DSM) has formed the basis of an Enterprise Suitability Mapping (ESM) program for 20 different crops (36 in development) at 80 m resolution. DSM is based on a regression tree approach, for multiple depths and soil attributes pH, EC, SOC%, Clay%, Sand%, Silt%, Depth, Sodicity, Salinity, Drainage, Permeability, AWC, Ksat. Calibration sites are based on existing and newly collected soils data, approximately 6500 sites. ESM rulesets use DSM and climate data for each crop, using a most-limiting factor approach, and identifying major soil and climate constraints for each crop. Each crop has a clickable query in LISTmap, showing all economically feasible constraints that might be managed. It would be very easy to develop maps of crop-specific soil constraints e.g. pH, salinity, drainage etc. for Tasmania.	80 m raster resolution	Data is available via: https://maps.thelist.tas.gov.au/listmap/app/list/map?bookmarkId=217804#.Wp9gK-hBW3U	Program: http://dpipwe.tas.gov.au/agriculture/investing-in-irrigation DSM Layers: https://maps.thelist.tas.gov.au/listmap/app/list/map?bookmarkId=217804#.Wp9gK-hBW3U.email ESM Layers: https://maps.thelist.tas.gov.au/listmap/app/list/map?bookmarkId=217892#.Wp9gQARirKA.email 
Acidity & Rapid acidification	**Qld:** Selected mapping areas	Data developed using mass preserving spline across averaged soil profile data for each soil profile class. (0-5 cm, 5-15	Raster grid (approx. 30 m x 30 m).	Suited for regional decision making to sub-farm scale. Data available in raster format pending release. Will also be available in vector format.	O'Brien, L.E. and Thomas, E. 2018. Soil constraints mapping to inform nutrient management in the cropping industries. RP155C. Soil Constraints

Soil constraint	Scope (e.g. state, regional, national)	Methodology	Scale	Utility and availability of data	Map Product and Reference
	adjacent to GBR: Mary-Burnett, Townsville, Burdekin, Wet Tropics, Atherton, Mackay-Whitsunday	cm, 15-30 cm, 30-60 cm, 60-100 cm, 100-200 cm). pH data derived from direct measurement (laboratory or Soil and Land Resource Assessment Field Manual code). Rapid acidification is defined as the time in years for pH of a soil layer to decrease by a pH unit. It is modelled using pH, clay and organic carbon content data.	Vector map 1:100 000.		Report. Department of Environment and Science, Queensland Government – awaiting publication.
Acidity (& others)	Queensland sugar cane cropping areas	Collation of existing soil mapping that has been updated to include soil constraint data for sugar cane cropping regions in Queensland.	Various	Department of Environment and Science. Available under Creative Commons 4.0 at: http://qldspatial.information.qld.gov.au/catalogue/custom/detail.page?fid={3A49B68F-25D3-4AD3-968E-E8F55803C1FE}. From project RP155C 'Sub-soil constraints mapping to inform nutrient management in cropping industries'.	

Table 11 Aluminium

Soil constraint	Scope (e.g. state, regional, national)	Methodology	Scale	Utility and availability of data	Map Product and Reference
Aluminium toxicity	Southern SA	Assessment based on critical levels for aluminium sensitive plants such as lucerne. Four Aluminium Toxicity analysis data classes (including not applicable) supplied as percentage values for each Soil Landscape Map Unit to be used for the calculation of spatial data statistics. Note: the sum of all percentage values for each map unit totals 100%. Toxicity potential can vary significantly within a Soil Landscape Map Unit which is categorised into eight (plus 'not applicable') legend categories (TOX_AL) according to the proportion of high and moderate toxicity. Because aluminium toxicity is so highly pH dependent, and pH in turn is highly management dependent, legend categories are generalised. Dataset derived from the Soil Landscape Map Units spatial dataset.	Accuracy to scale of mapping (50 m at 1:50K and 300 m at 1:100K scale). SE, Kangaroo Is., Lofty Ranges and lower Yorke Peninsula mapped at 1:50K. Eyre Peninsula, main part of Yorke Peninsula, Murray Mallee and Northern Agricultural Districts mapped at 1:100K.	Aluminium Toxicity dataset can be viewed at NatureMaps (>Soils>Soil Chemistry Attributes). Spatial data downloads available via: https://data.sa.gov.au/data/dataset/aluminium	https://data.sa.gov.au/data/dataset/aluminium Creative Commons Attribution 4.0 
Exch aluminium	Victoria (State)	Map was generated by Brown and Johnston from surface and sub-surface submitted samples. Exchangeable aluminium greater than 50 mg/kg (extractant 1M KCl) was determined with about 25% of all samples tested having aluminium values greater than 50 mg/kg (Brown and Johnston 1982).	1:5M	Currently not available as a spatial dataset. Could be revised using soil analysis data from more recent soil laboratory assessments.	Brown, A.J. and Johnston, J.A. (1982). Exchangeable aluminium in Victorian soils. In "Trace Element Review papers, 1982". Agricultural Services Library, Department of Agriculture, Victoria.

Soil constraint	Scope (e.g. state, regional, national)	Methodology	Scale	Utility and availability of data	Map Product and Reference
					

4.4.3 Salinity and soil physical constraints

Salinity

Non-watertable salinity (also known as 'dry saline land') is land where soils contain elevated levels of soluble salts which are not associated with a watertable. The salts have presumably accumulated in the soil either from aeolian accessions and subsequent leaching, marine aerosols, or via saline groundwaters which are no longer influencing the land surface. Salts generally occur as subsoil 'bulges', which possibly reflect either the extent of leaching (i.e. salt cannot be leached any further than the depth of the seasonal wetting front), or an impermeable deep subsoil layer which prevents flushing of the salts into substrate materials. Many map units have components of contrasting land types, with variable soil salinity. See Table 12.

Soil salinity is estimated to cost growers $270 million/annum and affect 9.3 million ha, mainly in Western Australia (Dang et al 2017).

Waterlogging

Waterlogging occurs when all or part of the soil profile is saturated with water. Some soils are effectively never waterlogged, 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. See Table 13.

Compaction

Soil compaction can have a detrimental effect on root growth when bulk density exceeds 1.6 g cm^{-3}. Soil compaction is estimated to cost growers $205 million/annum and affect 3.4 million ha (Dang et al 2017). An independent survey of subsoil constraints to plant growth in the higher rainfall cropping areas of WA (Evans et al. 2007) did not often encounter soil compaction on soils predicted by the methodology described by van Gool et al (2005). This difference may be because many areas have been cropped only recently (and hence compaction had not developed) and the use of smaller machinery. See Table 14.

Ca:Mg ratio

High levels of magnesium in soil can increase dispersion, and this can be indicated by the Ca:Mg ratio. For a given exchangeable sodium percentage, a low Ca:Mg ratio (<1) will exacerbate dispersion. See Table 15.

Bulk density (BD)

Bulk density is the weight of soil in a given volume. Soils with a BD greater than 1.6 g/cm^3 may restrict root growth. Bulk density increases with compaction and typically increases with depth. See Table 16.

Soil physical condition

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, in particular, varies significantly across the landscape and is affected by management practice as well as by inherent properties of the soil. See Table 17.

Soil structural decline and surface soil condition

Surface soil condition varies significantly across the landscape and is affected by management practice as well as by inherent properties of the soil. The assessment only indicates where soil structural problems could potentially be significant, and does not define specific occurrences within particular conditions. The most significant surface soil physical limitation in South Australia is the condition known as hard setting. Surface seals which develop on hard setting soils have low infiltration rates (leading to surface ponding of water, or excessive runoff/erosion); have a narrow moisture range for effective working, which can result in patchy emergence. Hard setting soils generally have high proportions of fine sand and silt, and insufficient swelling clay content to allow for internal volume changes. The clay particles may be dispersive, and organic matter levels may be low, but the latter are not prerequisite for hardsetting. See Table 18 (soil structural decline) and 19 (surface soil condition).

Subsoil structure

Soil structure in many assessments 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. Poor subsoil structure is commonly attributable to sodic or dispersive clay, 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 limitation than those which are deeper in the profile; therefore the assessment of subsoil structure is an integration of structure type and depth. Poorly structured but non-dispersive subsoils have coarse blocky or prismatic aggregates, or are massive and hard (AgInsight SA).

Hardpan is defined as material which is too hard to dig with hand tools, and at shallow depth, influences the effective root zone of plants and impacts on engineering uses of land. Hardpans (including calcrete, ferricrete and silcrete) are generally relatively young materials cemented or indurated, in or below the soil, developed as part of soil forming processes. Calcrete is by far the most common, being widespread on Eyre and Yorke Peninsulas, Murraylands, the South East and Gulf Plains. 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. See Table 20.

Workability

Workability combines the ability to cultivate the topsoil and the land quality for machinery trafficability; for example, where access might be required to spray plants. Workability can be a constraint because heavy soils or steep land increase fuel use, time and wear and tear on machinery, increasing production costs. Very poor land, such as rock outcrop, or steep land with more than 30% slope, is generally considered to be non-cropping land. (Van Gool 2016). See Table 21.

Drainage

Drainage is influenced by soil texture, soil structure, porosity and soil type, which ultimately influence the rate of infiltration and hydraulic conductivity. These factors also inform the nature of water flow (i.e. lateral and vertical) in soil. See Table 22.

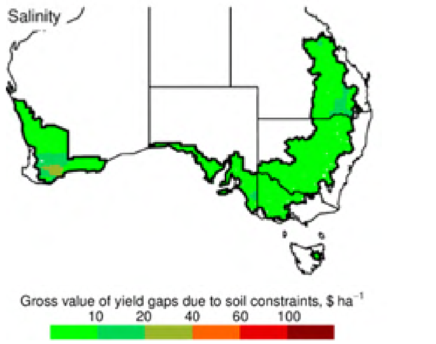
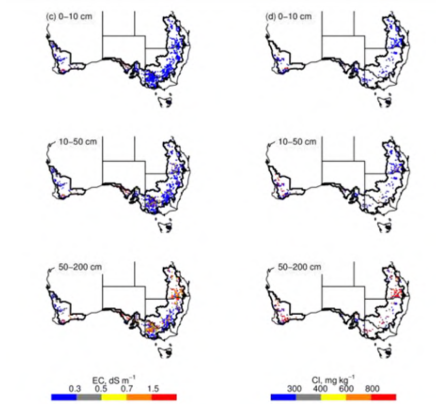
Permeability

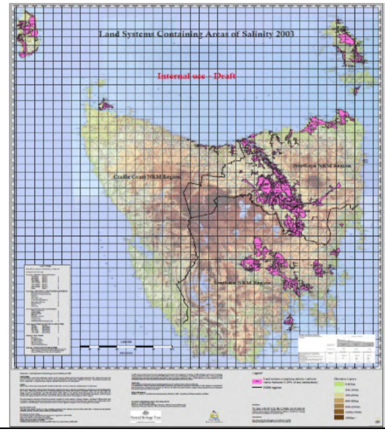
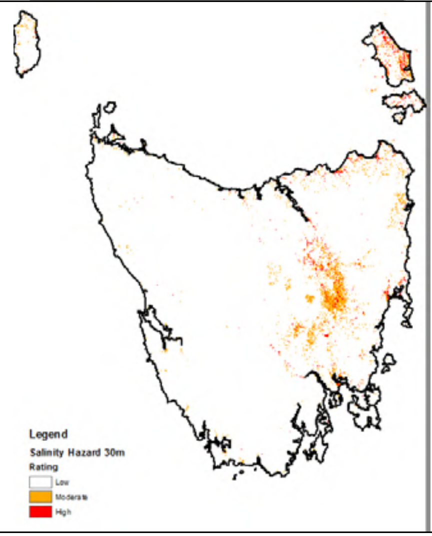
Permeability (also known as hydraulic conductivity) relates to the soils ability to conduct water. It is largely influenced by particle size distribution, pore space, pore size and the continuity of the spaces. Permeability can vary with soil layer. See Table 23.

Available Water Capacity

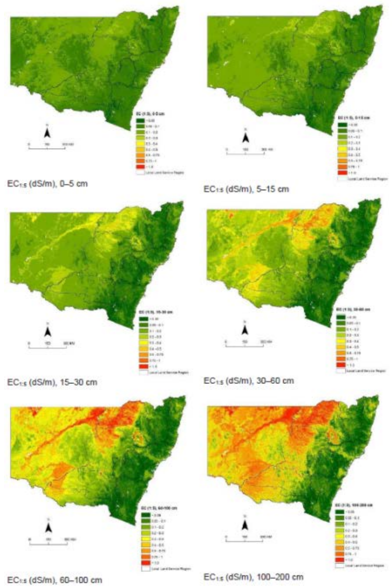
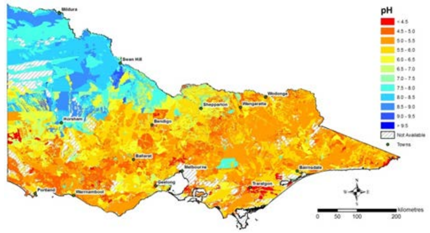
Available Water Holding Capacity (AWHC) of the soil profile is determined by the effective depth of a soil (i.e. physical and chemical barriers to root growth, which can vary by plant species); and how much water within that depth is potentially available to plants. In SA AWHC rankings have been estimated from soil texture, structure and stone content within the potential root zone of a wheat plant. See Table 24.

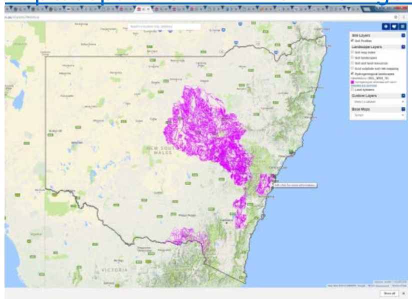
Table 12 Salinity

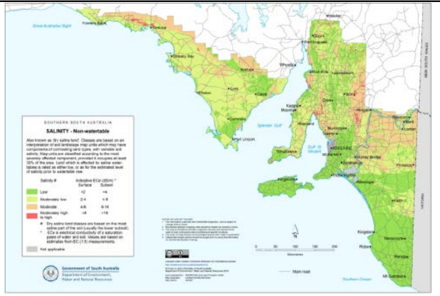
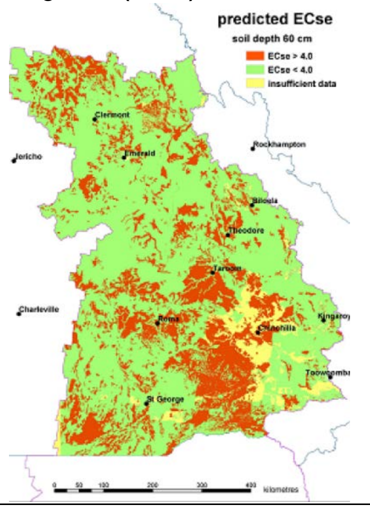
Soil constraint	Scope (e.g. state, regional, national)	Methodology	Scale	Utility and availability of data	Map Product and Reference
Salinity (Grains regions)	Australian grains region	National maps that quantify forfeited grain yields due to specific soil constraints of sodicity, acidity, salinity and compaction at the level of Statistical Area Level 2 (SA2). Data obtained from a number of diverse sources: wheat yield data at the SA2 level (ABS), remote sensing data on 30 m and 250 m pixels (Landsat and MODIS satellites), climate data on a 5 km grid across Australia from SILO database hosted by Queensland Government, and soil data from soil profiles across Australia's cropping land, predominantly from the National Soil Site Collation (Searle, 2014). Information from these diverse sources has been combined, with careful consideration of the different spatial scales, in such a way as to allow the formulation of models that can predict the lost yield due to soil constraints. Saline soils are characterised by an electrical conductivity of > 0.3 dS m^{-1} in the 0–10 cm soil depth or > 0.7 dS m^{-1} in subsoils. They are also characterised by a chloride concentration of > 300 mg kg^{-1} in the 0–10 cm soil depth or > 600 mg kg^{-1} in subsoil, which provides toxic conditions for many crop species.	National – aggregated to Statistical Area 2 (SA2) level.	Data and report not released at this stage (GRDC). Provides estimates of yield gaps; gross value of yield gap per constraint; % cropping area affected, and area affected (Mha). CONFIDENTIAL	Reference: Cost of Edaphic Stress to the Australian Grains Industry (UQ00081) 2017. Yash Dang (UQ) et al.  
Salinity - Tasmania	Regional – Tasmanian NAP Area	Undertaken for 2003 NAP Salinity Audit. Used Land Systems to develop a salinity map of the state, as well as indicate regions where salinity was	1:250,000	Creative Commons. Data packages available as ArcGIS geodatabases and associated scanned pdf reports via	Bastick, C., Lynch, S. (2003). Land Systems Containing Areas of Salinity in 2003. DPIPWE

Soil constraint	Scope (e.g. state, regional, national)	Methodology	Scale	Utility and availability of data	Map Product and Reference
		likely to exist given observations by field staff. The existing Salinity Land Degradation map by Sue Grice, 1995 was used as a starting point. Known errors and inconsistencies were corrected. A coverage of regions where salinity is likely to occur was derived from the map of known regions of salinity.		DPIPWE and the NRM data library.	
Salinity	Tasmania (state)	V1.0 80 m resolution Digital Soil Mapping (DSM) (2015), followed by draft v2.0 30 m resolution DSM (2018), using newly collected (400 sites) and Tasmanian Legacy Soil Site data (6500 sites, DPIPWE) and local, state-derived salinity hazard rulesets based on ESP% and depths. Rulesets available on DPIPWE website post June 2018. DSM based on a regression tree approach, for multiple depths and soil attributes, using k-fold cross validation to determine modelling diagnostics and uncertainties. Derived ECse using PTF based on Clay % and EC 1:5 in water.	80 m, 30 m resolution	Creative Commons, data on request and available on LISTmap post June 2018. EC R^2 Calibration 0.42, Validation 0.26. Clay R^2 Calibration 0.82, Validation 0.66	
Salinity Hazard -	NSW (State)	Land and Soil Capability (LSC) mapping identifies the most limiting	1:100 000-1:500 000	Available for viewing on eSPADE spatial viewer	Dataset reference: Office of Environment and Heritage, 2017, Land and Soil

Soil constraint	**Scope (e.g. state, regional, national)**	**Methodology**	**Scale**	**Utility and availability of data**	**Map Product and Reference**
Land and Soil Capability (LSC) Mapping for NSW		class of 8 LSC hazards including topsoil acidification, salinity, water erosion, wind erosion, mass movement, shallow soils/rock outcrop, soil structure decline and waterlogging. These hazards are accessed for the dominant facet (sub-landscape) of map units across NSW using the best available soil information products. This information is sourced from the compilation of over 65 soil map products. Each hazard is given a rating between 1 (best, highest capability land) and 8 (worst, lowest capability land). The classification is assigned to each hazard using a ruleset published in OEH 2012, "*The land and soil capability assessment scheme – second approximation*".	Compilation of many soil mapping datasets of various scales. For more information see LSC metadata on the OEH Data Portal.	(http://espade.environment.nsw.gov.au) and can be downloaded from the OEH Data Portal at http://data.environment.nsw.gov.au/dataset/land-and-soil-capability-mapping-for-nsw4bc12	Capability Mapping for NSW, NSW Office of Environment and Heritage, Sydney. Mapping ruleset: Office of Environment and Heritage, 2012, The land and soil capability assessment scheme – second approximation. NSW Office of Environment and Heritage, Sydney. Available for download at http://www.environment.nsw.gov.au/soils/20120394lsc2spubslandingpage.htm

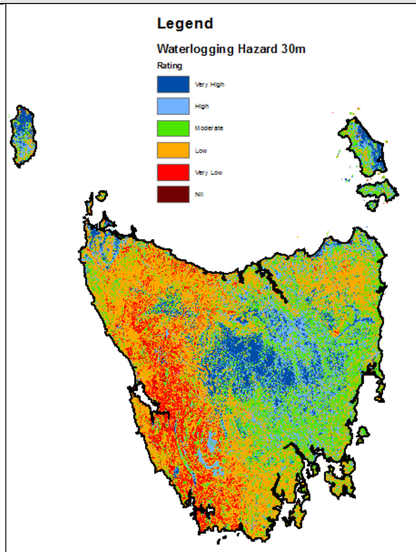
Soil constraint	Scope (e.g. state, regional, national)	Methodology	Scale	Utility and availability of data	Map Product and Reference
EC 1:5 (log dS/m)	NSW (State)	Digital soil mapping (DSM) using multiple linear regression or Cubist decision tree modelling approaches. Original models were developed from a dataset of approximately 6000 soil profiles across NSW, divided into training and validation data sets at an 80:20% ratio. The models were applied against 17 environmental covariates representing the various soil forming factors to develop the final maps. 0-5, 5-15, 15-30, 30-60, 60-100, 100-200 depths assessed. Lin's concordance values low for surface horizons: 0.18, 0.24, 0.37, 0.51, 0.58, 0.56	100 m raster resolution	Provides continuous data on soil properties/constraints across NSW for a range of purposes, including assisting in sustainable land management, ecological modelling and hydrological modelling. Digital maps for all depth intervals can be downloaded through OEH data portal. http://data.environment.nsw.gov.au/dataset/digital-soil-maps-for-key-soil-properties-over-nsw Maps for six depth intervals down to 2 m and 90% confidence level maps are also available on request via: data.broker@environment.nsw.gov.au	
EC 1:5	Victoria	Soil point data stored in the Victorian Soil Information System (VSIS) from over 6,000 sites has been standardised to the set depths (using equal area splines or a value weighting derived from the proportional contribution of each sample to the depth class). This processed data was used to attribute soil land units from a collection of surveys (mapped at 1:100k or better) collated to provide the best map unit coverage across the State. Only data from sites that match the soil type of the dominant soil within the land unit being attributed were used. Sites and land units were	1:250,000	Data available under Creative Commons 4.0 via: https://www.data.vic.gov.au/data/dataset/victorian-soil-electrical-conductivity-mapping-vicdsmv1	 Robinson et al (2013) Digital Soil Map of Victoria, v.1.0. Department of Economic Development, Jobs, Transport and Resources.

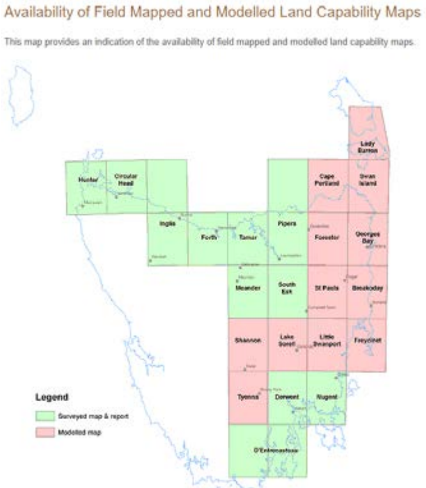
Soil constraint	Scope (e.g. state, regional, national)	Methodology	Scale	Utility and availability of data	Map Product and Reference
		assigned an Australian Soil Classification (to the Suborder level) to aid this process. This dataset comprises soil property mapping across the whole State of Victoria at 6 prescribed depths. The set depths are 0 to 5 cm, 5 to 15 cm, 15 to 30 cm, 30 to 60 cm, 60 to 100 cm and 100 to 200 cm.			
Salinity (Hydrogeological Landscapes – HGL)	NSW (Regional)	The Hydrogeological Landscapes (HGL) concept provides a structure for the understanding of how salinity manifests itself in the landscape and how differences in salinity are expressed across the landscape. A HGL spatially defines areas of similar salt stores and pathways for salt mobilisation. Process of HGL determination relies on the integration of several factors: geology, soils, slope, regolith depth, and climate; an understanding of the differences in salinity development; and the impacts (land salinity/salt load/water electrical conductivity) in landscapes. Information sources such as soil maps, site characterisation, salinity site mapping, hydrogeological conditions and surface and groundwater data are combined to develop standard descriptions for each HGL unit.	Various, generally 1:100K – 1:250K	Tool for targeting actions to appropriate areas for salinity management. Creative Commons. Data packages available as ArcGIS geodatabases and associated reports via OEH Data Portal. Products can also be viewed and downloaded via eSPADE.	Hydrogeological Landscapes of NSW and ACT (overview and links to all available products) – http://data.environment.nsw.gov.au/dataset/hydrogeological-landscapes-nsw-act Available HGLs also available as a Custom Layer on eSPADE - http://espade.environment.nsw.gov.au 
Non-watertable salinity	Southern SA	Non-watertable salinity (or dry saline land) is where soil contains elevated levels of soluble salts that are not associated with a watertable. Mapping shows the degree of non-watertable salinity, based on the most saline part	Accuracy to scale of mapping (50 m at 1:50K and 300 m at 1:100K scale).	Spatial data to be used at regional, subregional and catchment level, and can be used to provide property overviews; however, cannot be used at the paddock level.	Creative Commons Attribution https://data.sa.gov.au/data/dataset/9cfed822-c50e-4963-98d6-8205697d7ae2

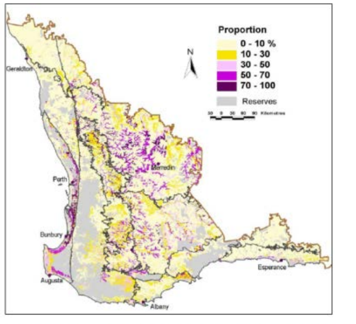
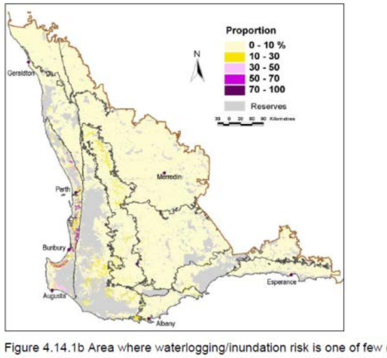
Soil constraint	Scope (e.g. state, regional, national)	Methodology	Scale	Utility and availability of data	Map Product and Reference
		of the map unit (provided it occupies at least 30%), while detailed proportion data are supplied for calculating respective areas of each non-watertable salinity class (spatial data statistics). Six Salinity - Non-watertable attribute (or 'analysis data') classes have been supplied as percentage (areal extent) values of each Soil Landscape Map Unit (SLU). Classes are based on indicative ECe assessments of the most saline part of the soil (usually the lower subsoil). ECe is electrical conductivity of a saturation paste of water and soil; and values have been estimated from EC(1:5) measurements.	SE, Kangaroo Is., Lofty Ranges and lower Yorke Peninsula mapped at 1:50K. Eyre Peninsula, main part of Yorke Peninsula, Murray Mallee and Northern Agricultural Districts mapped at 1:100K.	Data can be accessed via: https://data.sa.gov.au/data/dataset/salinity-nwt	
ECse (60 cm)	**Qld (grain cropping region)**	Spatial estimation of subsoil constraints in Queensland has been derived using soil site data in the NRM Soil and Land Information (SALI) database system, and the best available land resource mapping. Polygons (from land resource survey maps) overlayed with point data (site information) and values (or attributes) allocated to the polygons according to a hierarchical system of ‘attribution’ based on the method of Smith and Grundy (2000).			Dang et al (2004) 

Soil constraint	Scope (e.g. state, regional, national)	Methodology	Scale	Utility and availability of data	Map Product and Reference
EC/NA = EC/Exch Na	**Qld:** Selected mapping areas adjacent to Great Barrier Reef: Mary-Burnett, Townsville, Burdekin, Wet Tropics, Atherton, Mackay-Whitsunday	Data developed using mass preserving spline across averaged soil profile data for each soil profile class. (0-5 cm, 5-15 cm, 15-30 cm, 30-60 cm, 60-100 cm, 100-200 cm) EDPK = ([Naexch.]+0.556[Kexch.])/CEC*100% (Bennett et al 2016)	Raster grid (approx. 30 m x 30 m). Vector map 1:100 000.	Suited for regional decision making to sub-farm scale. Data available in raster format pending release. Will also be available in vector format.	O'Brien, L.E. and Thomas, E. 2018. Soil constraints mapping to inform nutrient management in the cropping industries. RP155C. Soil Constraints Report. Department of Environment and Science, Queensland Government – awaiting publication.
Electro-chemical Stability Index (ESI)	**Qld:** Selected mapping areas adjacent to Great Barrier Reef: Mary-Burnett, Townsville, Burdekin, Wet Tropics, Atherton, Mackay-Whitsunday	Data developed using mass preserving spline across averaged soil profile data for each soil profile class. (0-5 cm, 5-15 cm, 15-30 cm, 30-60 cm, 60-100 cm, 100-200 cm). Electro-chemical Stability Index (ESI) – calculated directly as EC/CEC where EC is Electrical Conductivity (1:5 water) (Blackwell et al 1991).	Raster grid (approx. 30 m x 30 m). Vector map 1:100 000.	Suited for regional decision making to sub-farm scale. Data available in raster format pending release. Will also be available in vector format.	O'Brien, L.E. and Thomas, E. 2018. Soil constraints mapping to inform nutrient management in the cropping industries. RP155C. Soil Constraints Report. Department of Environment and Science, Queensland Government – awaiting publication.

Table 13 Waterlogging

Soil constraint	Scope (e.g. state, regional, national)	Methodology	Scale	Utility and availability of data	Map Product and Reference
Waterlogging Hazard - Tasmania	State	V1.0 80 m resolution Digital Soil Mapping (DSM) (2015), followed by draft v2.0 30 m resolution DSM (2018), using newly collected (400 sites) and Tasmanian Legacy Soil Site data (6500 sites, DPIPWE) and a combination of drainage and permeability DSM indices. Rulesets available on DPIPWE website post June 2018. DSM based on a regression tree approach, for multiple depths and soil attributes, using k-fold cross validation to determine modelling diagnostics and uncertainties.	80 m, 30 m	Creative Commons, data on request and available on LISTmap post June 2018. See validation diagnostics for DSM drainage and permeability indices	
Potential waterlogging	Grains regions of Australia	DPIPWE has been tasked by TIA (Tasmanian Institute of Agriculture) and GRDC to map areas of potential waterlogging in wetter months (April-October), for each month. The analysis uses the DSM Soil and Landscape Grids of Australia with applied saturated hydraulic conductivity (K-sat) pedotransfer functions to subsoil layers. SILO generated annual rainfall and evaporation grids are generated for each month (30 years of data) – excess rainfall (after evaporation) is then applied to the K-sat values to determine where excess rainfall cannot physically move through the subsoil in a given month, leading to waterlogging	90 m resolution	Data and report not released at this stage (TIA/ GRDC) CONFIDENTIAL	Not complete.

Soil constraint	Scope (e.g. state, regional, national)	Methodology	Scale	Utility and availability of data	Map Product and Reference
		within the root-zone. Transpiration was considered minimal in winter months, and not considered in this analysis. The process is planned for completion by late March, 2018 (maps and report).			
Land capability - waterlogging	Tasmania	DPIPWE uses the Land Capability Classification System (LCCS) to assess, classify and map land according to its ability to support a range of crops on a long term sustainable basis. The evaluation is based on the degree of limitation imposed on that land by a variety of physical factors which include erosion, soils, wetness and climate. Land is evaluated based on range of potential crops, productivity, ease of management and risk of degradation. Only broadacre agricultural crops and pastoral activities considered, and only where they occur on private freehold and leased Crown land. Mapping is a combination of field mapped and modelled processes.	1:100 000	Creative Commons. Data packages available as ArcGIS geodatabases and associated scanned pdf reports via DPIPWE and the NRM data library. Also available for display and download online at www.theLIST.tas.gov.au	Map Link: https://maps.thelist.tas.gov.au/listmap/app/list/map?bookmarkId=263595 Further Information: http://dpipwe.tas.gov.au/agriculture/land-management-and-soils/land-and-soil-resource-assessment/land-capability 
Waterlogging risk	SW WA grain region	Waterlogging Risk mapping derived from land quality attribution associated with soil-landscape mapping at the subsystem/phase level. Waterlogging risk estimates are based on ratings for soil (e.g. permeability) and landscape position for the different rainfall districts. The assessment is based on	Various input scales – 1:50 K to 1:250 K.	Data available through Creative Commons 4.0 via the Western Australia government website: https://catalogue.data.wa.gov.au/dataset/soil-landscape-land-quality-waterlogging-risk	van Gool, D 2016, 'Identifying soil constraints that limit wheat yield in South-West Western Australia', *Resource Management Technical Report 399*, Department of Agriculture and Food, Western Australia, Perth.

Soil constraint	Scope (e.g. state, regional, national)	Methodology	Scale	Utility and availability of data	Map Product and Reference
		the duration of waterlogging during the growing season.			 Figure 4.14.1a Total area with moderate or greater waterlogging/inundation risk  Figure 4.14.1b Area where waterlogging/inundation risk is one of few (1–3) constraints
Waterlogging susceptibility	Southern SA	Soil Landscape Map Units assessed according to period of time that all, or part, of the soil profile is waterlogged. Assessment is an estimate based on observable soil and landscape features, and on opportunistic recordings of soil wetness following rainfall events. Map units typically contain variable waterlogging characteristics. Eight Waterlogging	Accuracy to scale of mapping (50 m at 1:50K and 300 m at 1:100K scale). SE, Kangaroo Is., Lofty Ranges and lower Yorke	Data is accessible under a Creative Commons 4.0 via: https://data.sa.gov.au/data/dataset/waterlogging	https://data.sa.gov.au/data/dataset/waterlogging

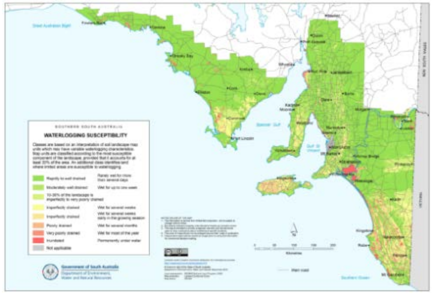
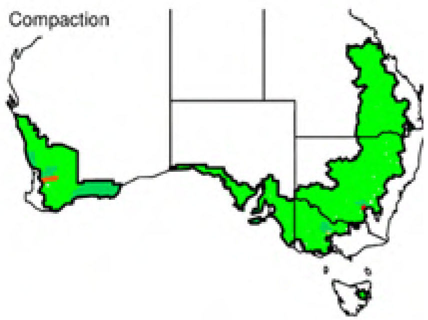
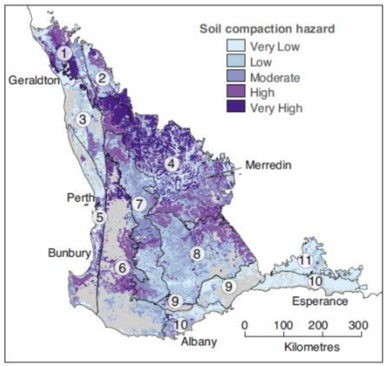
Soil constraint	Scope (e.g. state, regional, national)	Methodology	Scale	Utility and availability of data	Map Product and Reference
		Susceptibility attribute (or 'analysis data') classes have been supplied as percentage (areal extent) values of each Soil Landscape Map Unit. As a general rule, classes W4 through to W8 are non-arable. For map display purposes, Map Units have been categorised into nine legend categories (WATERLOG), including not applicable, designed to highlight the most limiting or susceptible component(s), provided this accounts for at least 30% of the map unit. Map units with limited occurrences of imperfectly to very poorly drained soils (10 - 30% of area) shown as additional legend category. Dataset derived from the [Soil Landscape Map Units] spatial dataset to be used for map creation or the calculation of spatial data statistics.	Peninsula mapped at 1:50K. Eyre Peninsula, main part of Yorke Peninsula, Murray Mallee and Northern Agricultural Districts mapped at 1:100K.		

Table 14 Compaction

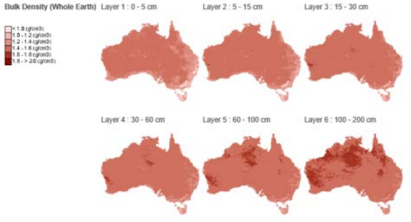
Soil constraint	Scope (e.g. state, regional, national)	Methodology	Scale	Utility and availability of data	Map Product and Reference
Compaction (GRDC)		Multi-stage approach: (i) *Define active-cropping areas* (ii) *Disaggregate yield to soil data locations* (iii) *Extract soil data and harmonize soil depths* (iv) *Define optimal ranges for soil constraints* (v) *Pre-process climate data* (vi) *Fit a model that represents yield as a function of soil constraints* (vii) *Apply the model to estimate yield gaps due to soil constraints at soil data locations* (viii) *Interpolate values to 1-km grid over entire cropping area* (ix) *Aggregate predictions to SA2 level (note: 2,310 SA2 regions in Australia).* (x) *Apply economic analysis at SA2 level* 0-10, 10-50, 50-200 cm	National – aggregated to Statistical Area 2 (SA2) level.	Data and report not released at this stage (GRDC). Provides estimates of yield gaps; gross value of yield gap per constraint; % cropping area affected, and area affected (Mha). CONFIDENTIAL	Reference: Cost of Edaphic Stress to the Australian Grains Industry (UQ00081) 2017. Yash Dang (UQ) et al. 
Compaction hazard	WA	Methodology for assessing compaction hazard using soil-landscape mapping is described in van Gool et al (2005). Predicts compaction hazard but not based on actual measurements. Hazard assessment is based on a combination of particle size distribution and presence or absence of soil structure and organic matter. Soils with a wide range of particle sizes, low organic matter and limited or no soil structure are particularly susceptible to compaction. Susceptibility of soils to subsurface compaction based on field texture, arrangement, coarse	Various input scales – 1:50K to 1:250K.	Regional benchmarking. Does not assist with farm management. Data available via DPIRD (contact: Tim Overheu) and via the Western Australia government data service: https://catalogue.data.wa.gov.au/dataset/soil-landscape-land-quality-subsurface-compaction	Reference: Carter D, Davies S and Schoknecht N (2013). 'Soil organic carbon' In: *Report card on sustainable natural resource use in agriculture in WA*. DAFWA. 

Soil constraint	Scope (e.g. state, regional, national)	Methodology	Scale	Utility and availability of data	Map Product and Reference
		fragments and organic matter (adapted from Needham et al. 1998b)			
Compaction Risk	**Qld:** Selected mapping areas adjacent to Great Barrier Reef: Mary-Burnett, Townsville, Burdekin, Wet Tropics, Atherton, Mackay-Whitsunday	Data developed using mass preserving spline across averaged soil profile data for each soil profile class. (0-5 cm, 5-15 cm, 15-30 cm, 30-60 cm, 60-100 cm, 100-200 cm).	Raster grid (approx. 30 m x 30 m). Vector map 1:100 000.	Suited for regional decision making to sub-farm scale. Data available in raster format pending release. Will also be available in vector format.	O'Brien, L.E. and Thomas, E. 2018. Soil constraints mapping to inform nutrient management in the cropping industries. RP155C. Soil Constraints Report. Department of Environment and Science, Queensland Government – awaiting publication.
Plastic Limit	**Qld:** Selected mapping areas adjacent to Great Barrier Reef: Mary-Burnett, Townsville, Burdekin, Wet Tropics, Atherton, Mackay-Whitsunday	Data developed using mass preserving spline across averaged soil profile data for each soil profile class. Plastic Limit (PL) estimated using a pedotransfer function (Keller and Dexter 2012).	Raster grid (approx. 30 m x 30 m). Vector map 1:100 000.	Suited for regional decision making to sub-farm scale. Data available in raster format pending release. Will also be available in vector format.	TBA

Table 15 Calcium to Magnesium ratio (Ca:Mg)

Soil constraint	Scope (e.g. state, regional, national)	Methodology	Scale	Utility and availability of data	Map Product and Reference
Ca:Mg	Burdekin Catchment (Qld)	Contains raster surfaces describing the calcium to magnesium ratio of soils in the Burdekin River basin. Study area covers approximately 13.4 million hectares in Central and North Queensland. This attribute is mapped in five depth slices to a maximum depth of one metre. Upper and lower uncertainty limits accompany each depth slice.			

Table 16 Bulk Density (BD)

Soil constraint	Scope (e.g. state, regional, national)	Methodology	Scale	Utility and availability of data	Map Product and Reference
Bulk Density – whole earth (g/cm^3)	Australia (Soil and Landscape Grid of Australia)	Soil and Landscape Grid of Australia's, Australia-wide Soil Attribute Maps generated (2014) using measured soil attribute data from existing databases in the national soil site data collation and spectroscopic estimates made with the CSIRO's National spectroscopic database (Viscarra Rossel & Webster, 2012). Spatial modelling performed using decision trees with piecewise linear models and kriging of residuals. 50 environmental covariates, representing climate, biota, terrain, and soil and parent material,	Predicted at 90 m raster resolution.	Creative Commons Attribution 4.0 International License. Data accessible via: http://www.clw.csiro.au/aclep/soilandlandscapegrid/	

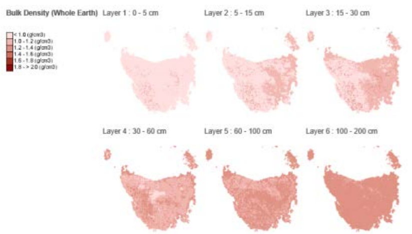
Soil constraint	Scope (e.g. state, regional, national)	Methodology	Scale	Utility and availability of data	Map Product and Reference
		used in the modelling. Uncertainty derived using a bootstrap (Monte Carlo-type) approach to derive, for each pixel, a probability density function (pdf), from which were derived 90% confidence limits. Approach is described in Viscarra Rossel et al. (2015). Soil attribute levels estimated for depth intervals: 0-5 cm, 5-15 cm, 15-30 cm, 30-60 cm, 60-100 cm and 100-200 cm.			
Bulk Density – whole earth (g/cm^3)	Tasmania (Soil and Landscape Grid of Australia)				

Table 17 Soil physical condition

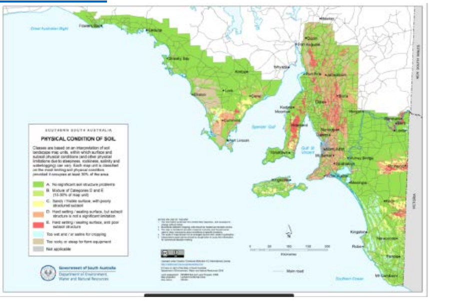
Soil constraint	Scope (e.g. state, regional, national)	Methodology	Scale	Utility and availability of data	Map Product and Reference
Soil physical condition	Southern SA	The 'Physical Condition of Soil' dataset is an integration of 'Structure of Subsoil' and 'Physical Condition of Surface Soil' datasets. The assessment only indicates where soil structural problems could potentially be significant, and does not define specific occurrence of particular conditions. The purpose of this assessment is to identify potential soil structure limitations on arable land, by using four simplified categories: 'no significant problems'; 'surface soil only'; 'subsoil only'; 'surface and subsoil'. Each Soil Landscape Map Unit is categorised into seven (plus not applicable) legend categories according to its most limiting soil physical condition, provided that it occupies at least 30% of the map unit. Subsoil structure limitations of moderate, high and very high define 'poor subsoil structure' in this assessment. Land which is non-arable due to one or more of waterlogging, salinity, rockiness or steepness is not considered. There is no analysis data associated with this attribute.	Accuracy to scale of mapping (50 m at 1:50 K and 300 m at 1:100 K scale). SE, Kangaroo Is., Lofty Ranges and lower Yorke Peninsula mapped at 1:50 K. Eyre Peninsula, main part of Yorke Peninsula, Murray Mallee and Northern Agricultural Districts mapped at 1:100 K.	Data is accessible under a Creative Commons 4.0 via: https://data.sa.gov.au/data/dataset/soil-condition	https://data.sa.gov.au/data/dataset/soil-condition 

Table 18 Soil structural decline

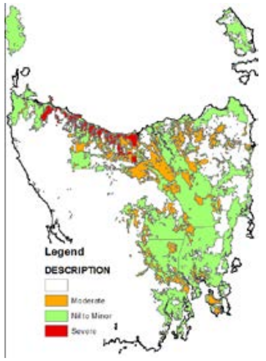
Soil constraint	Scope (e.g. state, regional, national)	Methodology	Scale	Utility and availability of data	Map Product and Reference
Soil Structure Decline	State – Tasmanian Freehold Land	1:250 000 Land System boundaries on private (freehold) land were used as units for identifying areas containing a range of soil constraints land degradation hazards. Constraints were identified using a combination of existing site data and DPIPWE field officer knowledge via a questionnaire. The methodology followed the national approach proposed by Graham (1989).	1:500 000	Creative Commons. Data packages available as ArcGIS geodatabases and associated scanned pdf reports via DPIPWE and the NRM data library.	Grice, M.S. (1995). Assessment of Soil and Land Degradation on Private Freehold Land in Tasmania. Dept of Primary Industries & Fisheries, Tasmania. Accompanying 1:500 000 maps. 

Table 19 Surface soil condition

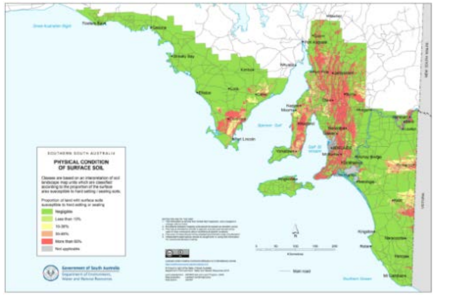
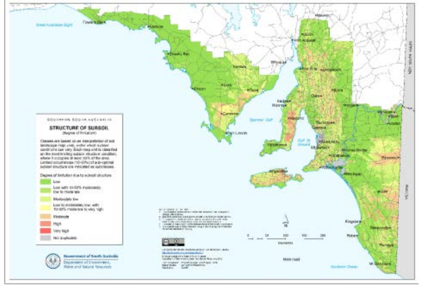
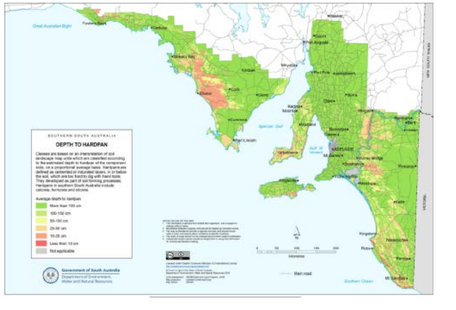
Soil constraint	Scope (e.g. state, regional, national)	Methodology	Scale	Utility and availability of data	Map Product and Reference
Physical condition of surface soil	Southern SA	Five Physical Condition of Surface Soil analysis data classes (proportion of land with surface soils susceptible to hardsetting or sealing – negligible, <10%, 10-30%, 30-60%, >60%) supplied as percentage values of Soil Landscape Map Units to be used for the calculation of spatial data statistics. Soil Landscape Map Units are categorised into five legend categories (plus not applicable) according to the proportion of land with surface soils susceptible to hard setting and/or sealing. Derived from the Soil Landscape Map Units spatial dataset to be used for map creation or the calculation of spatial data statistics.	Accuracy to scale of mapping (50 m at 1:50 K and 300 m at 1:100 K scale). SE, Kangaroo Is., Lofty Ranges and lower Yorke Peninsula mapped at 1:50 K. Eyre Peninsula, main part of Yorke Peninsula, Murray Mallee and Northern Agricultural Districts mapped at 1:100 K.	Data is accessible under a Creative Commons 4.0 via: https://data.sa.gov.au/data/dataset/surface-condition	https://data.sa.gov.au/data/dataset/surface-condition 

Table 20 Subsoil structure

Soil constraint	Scope (e.g. state, regional, national)	Methodology	Scale	Utility and availability of data	Map Product and Reference
Degree of limitation due to subsoil structure	Southern SA	Six Structure of Subsoil analysis data classes (including not applicable) supplied as percentage values of Soil Landscape Map Units to be used for the calculation of spatial data statistics. Note: sum of all percentage values for each map unit totals 100%. Soil Landscape Map Units categorised into five (plus not applicable) legend categories (low, moderately low, moderate, high, very high) according to the most limiting subsoil structure condition, provided it accounts for more than 30% of the area. Two additional legend categories identify land where there are limited occurrences (i.e. 10 - 30%) of soil structure limitation.	1:100 000	Structure of Subsoil (degree of limitation) dataset can be viewed on NatureMaps (>Soils>Soil Physical Condition Attributes). Spatial data downloads are available from: https://data.sa.gov.au/data/dataset/subsoil-structure https://data.environment.sa.gov.au/NatureMaps/Pages/default.aspx https://data.sa.gov.au/data/dataset/subsoil-structure	
Depth to hardpan	Southern SA	Mapping shows the average estimated depth to hardpan, while detailed proportion data are supplied for calculating respective areas of each depth to hardpan class (spatial data statistics). Depth to hard material is routinely measured during field survey where it occurs within a metre or so of the surface. Seven Hardpan Depth analysis data classes (including not applicable) have been supplied as percentage values of Soil Landscape Map Units to be used for the calculation of spatial data statistics. Note: the sum of all percentage values for each map unit totals 100%. Soil Landscape Map Units are categorised into six (plus not applicable) legend categories (PAN_DEPTH) according to	Accuracy to scale of mapping (50 m at 1:50K and 300 m at 1:100K scale). SE, Kangaroo Is., Lofty Ranges and lower Yorke Peninsula mapped at 1:50K. Eyre Peninsula, main part of Yorke Peninsula, Murray Mallee and Northern Agricultural	Data can be accessed via: https://data.sa.gov.au/data/dataset/hard-rock	https://data.sa.gov.au/data/dataset/c50a9833-46c3-47ef-9627-c7534632a852 

Soil constraint	Scope (e.g. state, regional, national)	Methodology	Scale	Utility and availability of data	Map Product and Reference
		the estimated average depth to hardpan. There is often significant variation from the assigned category within a map unit. Dataset is based on an interpretation of 1:40 000 stereo colour aerial photography and limited field inspection of landscapes and soils by soil scientists. Soil Landscape Map Unit boundaries were determined after an integration of field observations and recordings; laboratory analyses; stereoscopic examination of aerial photographs; understanding of regional landscape processes and stratigraphy; existing soil and geological mapping data.	Districts mapped at 1:100K.		

Table 21 Workability

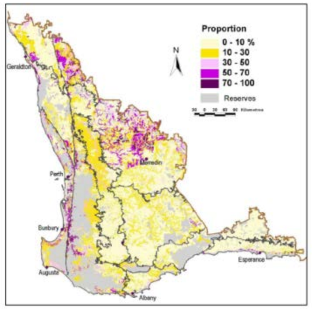
Soil constraint	Scope (e.g. state, regional, national)	Methodology	Scale	Utility and availability of data	Map Product and Reference
Workability	WA	Workability is a qualitative estimate of soils and landscapes that are fair to poor for production purposes. Workability combines the ability to cultivate the topsoil and the land quality for machinery trafficability; for example, where access might be required to spray plants.	Various input scales – 1:50K to 1:250K.	Data available via WA government, DPIRD (contact: Tim Overheu)	 Figure 4.17.1a Total area of very poor to fair workability van Gool, D 2016, 'Identifying soil constraints that limit wheat yield in South-West Western Australia', *Resource Management Technical Report 399,* Department of Agriculture and Food, Western Australia, Perth.

Table 22 Drainage

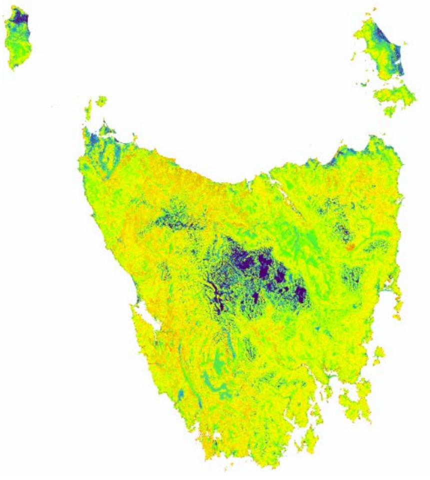
Soil constraint	Scope (e.g. state, regional, national)	Methodology	Scale	Utility and availability of data	Map Product and Reference
Drainage	Tasmania (state)	Digital Soil Mapping (DSM) has formed the basis of an Enterprise Suitability Mapping (ESM) program for 20 different crops (36 in development) at 80 m and 30m resolution. DSM based on regression tree approach, for multiple depths and soil attributes (i.e. pH, EC, SOC%, Clay%, Sand%, Silt%, depth, sodicity, salinity, drainage, permeability, AWC, Ksat). Calibration sites based on existing and newly collected soils data (approximately 6500 sites. Note: crop-specific soil constraint maps e.g. pH, salinity, drainage etc. are quite feasible for Tasmania.	80 m, 30 m	Creative Commons. Data packages available as ArcGIS rasters and associated scientific publications via DPIPWE. Mapping available on LISTmap post June 2018 Validation R^2 0.56	
Drainage	**Qld:** Selected mapping areas adjacent to Great Barrier Reef: Mary-Burnett, Townsville, Burdekin, Wet Tropics, Atherton, Mackay-Whitsunday	Data developed using mass preserving spline across averaged soil profile data for each soil profile class. pH data derived from direct measurement (laboratory or Soil and Land Resource Assessment Field Manual code).	Raster grid (approx. 30 m x 30 m). Vector map 1:100 000.	Suited for regional decision making to sub-farm scale. Data available in raster format pending release. Will also be available in vector format.	Soil constraints mapping to inform nutrient management in the cropping industries. RP155C. Department of Environment and Science 2018 – unpublished.

Table 23 Permeability

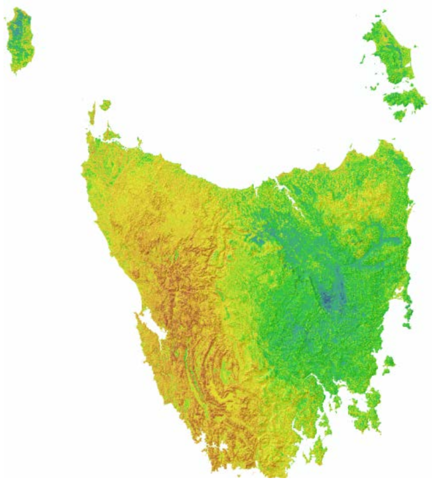
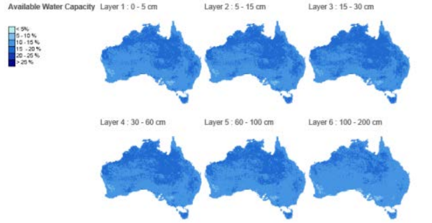
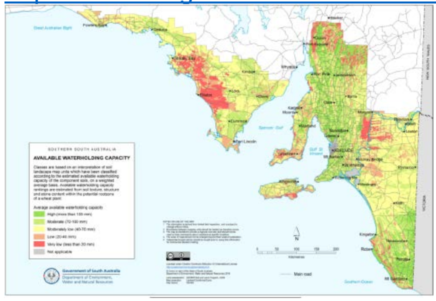
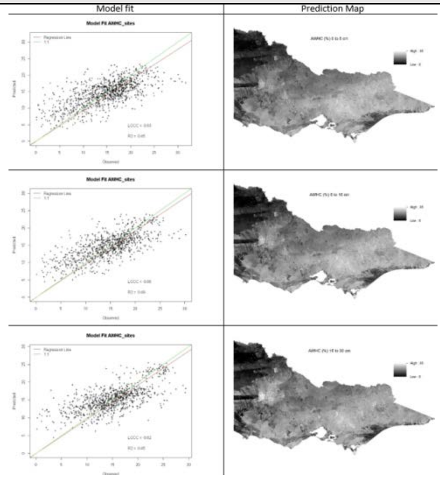
Soil constraint	Scope (e.g. state, regional, national)	Methodology	Scale	Utility and availability of data	Map Product and Reference
Permeability	Tasmania (state)	Digital Soil Mapping (DSM) has formed the basis of an Enterprise Suitability Mapping (ESM) program for 20 different crops (36 in development) at 80 m and 30 m resolution. DSM based on regression tree approach, for multiple depths and soil attributes (i.e. pH, EC, SOC%, Clay%, Sand%, Silt%, depth, sodicity, salinity, drainage, permeability, AWC, Ksat). Calibration sites based on existing and newly collected soils data (approximately 6500 sites. Note: crop-specific soil constraint maps e.g. pH, salinity, drainage etc. are quite feasible for Tasmania.	80 m, 30 m resolution	Creative Commons. Data packages available as ArcGIS rasters and associated scientific publications via DPIPWE. Mapping available on LISTmap post June 2018 Validation R^2 = 0.48.	
Permeability	**Qld:** Selected mapping areas adjacent to Great Barrier Reef: Mary-Burnett, Townsville, Burdekin, Wet Tropics, Atherton, Mackay-Whitsunday	Data developed using mass preserving spline across averaged soil profile data for each soil profile class. pH data derived from direct measurement (laboratory or Soil and Land Resource Assessment Field Manual code).	Raster grid (approx. 30 m x 30 m). Vector map 1:100 000.	Suited for regional decision making to sub-farm scale. Data available in raster format pending release. Will also be available in vector format.	TBA

Table 24 Available Water Capacity

Soil constraint	Scope (e.g. state, regional, national)	Methodology	Scale	Utility and availability of data	Map Product and Reference
Available Water Capacity (%)	Australia (Soil and Landscape Grid of Australia)	Soil and Landscape Grid of Australia's, Australia-wide Soil Attribute Maps generated (2014) using measured soil attribute data from existing databases in the national soil site data collation and spectroscopic estimates made with the CSIRO's National spectroscopic database (Viscarra Rossel & Webster, 2012). Spatial modelling performed using decision trees with piecewise linear models and kriging of residuals. 50 environmental covariates, representing climate, biota, terrain, and soil and parent material, used in the modelling. Uncertainty derived using a bootstrap (Monte Carlo-type) approach to derive, for each pixel, a probability density function (pdf), from which were derived 90% confidence limits. Approach is described in Viscarra Rossel et al. (2015). Soil attribute levels estimated for depth intervals: 0-5 cm, 5-15 cm, 15-30 cm, 30-60 cm, 60-100 cm and 100-200 cm.	Predicted at 90 m raster resolution.	Creative Commons Attribution 4.0 International License. Data accessible via: http://www.clw.csiro.au/aclep/soilandlandscapegrid/	
Available Water Capacity	Tasmania (state)	Digital Soil Mapping (DSM) has formed the basis of an Enterprise Suitability Mapping (ESM) program for 20 different crops (36 in development) at 80 m resolution. DSM based on regression tree approach, for multiple depths and soil attributes (i.e. pH, EC, SOC%, Clay%, Sand%, Silt%, depth, sodicity, salinity, drainage, permeability, AWC, Ksat).	80 m resolution (30 m currently being developed)	Creative Commons. Data packages available as ArcGIS rasters and associated scientific publications via DPIPWE.	

Soil constraint	Scope (e.g. state, regional, national)	Methodology	Scale	Utility and availability of data	Map Product and Reference
		Calibration sites based on existing and newly collected soils data (approximately 6500 sites. Note: crop-specific soil constraint maps e.g. pH, salinity, drainage etc. are quite feasible for Tasmania.			
AWHC	Southern SA	AWHC rankings estimated from soil texture, structure and stone content within the potential root zone of a wheat plant. Waterholding capacities for characteristic soils of Soil Landscape Map Units estimated from morphological properties, not laboratory analyses, and can vary substantially across the landscape. For map display purposes, each Soil Landscape Map Unit is categorised into six legend categories (AWHC), including not applicable, according to the estimated average Available Waterholding Capacity of its soils, on a proportional basis. In other words, map units often contain variable soils and these are summarised using a weighted average AWHC ranking.	Accuracy to scale of mapping (50 m at 1:50 K and 300 m at 1:100 K scale). SE, Kangaroo Is., Lofty Ranges and lower Yorke Peninsula mapped at 1:50K. Eyre Peninsula, main part of Yorke Peninsula, Murray Mallee and Northern Agricultural Districts mapped at 1:100K.	Data is accessible under a Creative Commons 4.0 via: https://data.sa.gov.au/data/dataset/awhc	https://data.sa.gov.au/data/dataset/awhc 
Available Water Holding capacity (AWHC)	Victoria	Digital soil mapping – Available Water Holding capacity Grids of 10 soil properties have been produced for Victoria. These grids, in raster format, provide prediction and confidence interval values for key soil properties at a 90 m grid resolution for six set depths meet the specifications created by GlobalSoilMap; 0 – 5 cm, 5 – 15 cm,	Predicted at 90 m raster resolution.	Prediction accuracy: (0-5 cm) R^2 0.45 (5-15 cm) R^2 0.49 (15-30 cm) R^2 0.45 (30-60 cm) R^2 0.45 (60-100 cm) R^2 0.46 (100-200 cm) R^2 0.4	Agriculture Victoria Research Report: Soil Grids of Victoria (Hopley et al 2017) - unpublished.

Soil constraint	Scope (e.g. state, regional, national)	Methodology	Scale	Utility and availability of data	Map Product and Reference
		15 – 30 cm, 30 – 60 cm, 60 - 100 cm and 100 – 200 cm, across Victoria. Methodology used to develop the Soil Grids of Victoria was based on that refined by the Australian Soil and Landscape Grid (Viscarra Rossel et al. 2015). Data and knowledge embedded into existing soil related datasets, e.g. soil profile and land mapping collections, have been key inputs. 170 gridded environmental datasets were used. The supporting database contains more than one million measurements for over 18,000 geo-referenced soil sites. Over 6,000 of these sites have soil property predictions derived from samples analysed using MIR spectroscopy.			
PAWC (dryland and irrigated)	**Qld:** Selected mapping areas adjacent to Great Barrier Reef: Mary-Burnett, Townsville, Burdekin, Wet Tropics, Atherton, Mackay-Whitsunday	Data developed using mass preserving spline across averaged soil profile data for each soil profile class.	Raster grid (approx. 30 m x 30 m). Vector map 1:100 000.	Suited for regional decision making to sub-farm scale. Data available in raster format pending release. Will also be available in vector format.	TBA

4.4.4 Nutrient constraints

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. 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 are considered representative of South Australia's most chemically fertile soils, while highly leached sands are the least fertile. See Table 25.

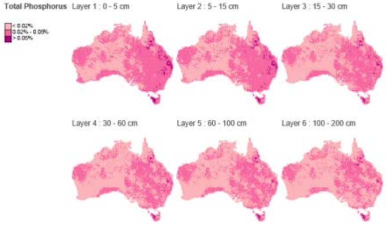
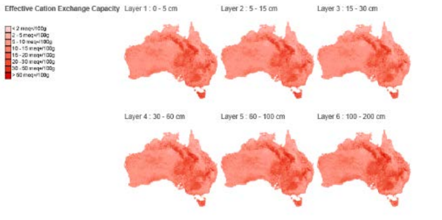
Soil fertility is a complex and highly variable property to assess. However, for ‘big picture’ modelling such as regional crop yields, an estimate of inherent soil fertility is valuable. Poor sands have low inherent fertility. These soils have other constraints that limit yields such as water repellence, low soil water storage, rapid soil permeability, acidic topsoil and subsoil and wind erosion (van Gool 2016).

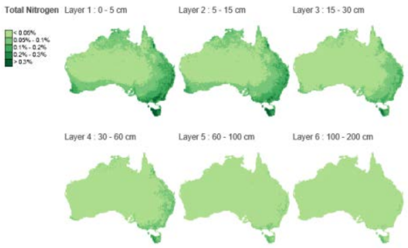
NLP prioritisation (McKenzie at al 2017) noted that nutrient decline can occur as a widespread and chronic problem that can threaten viability (e.g. central Queensland cropping lands). Nutrient excesses are often more localised and associated with high input systems (e.g. dairy, sugar cane, intensive 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.

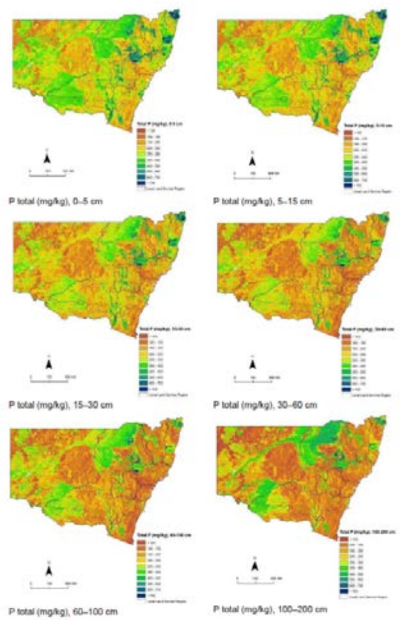
Boron

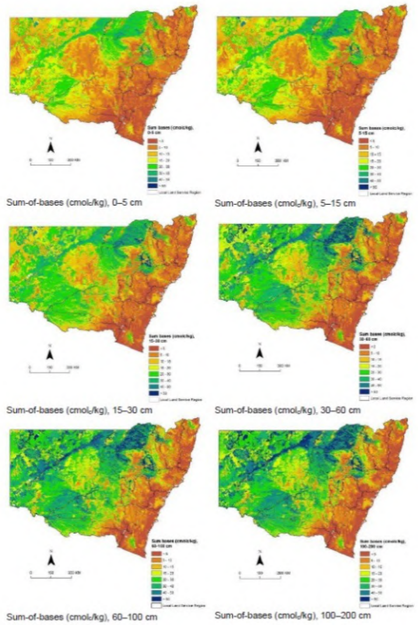
Boron is an essential trace element which occurs naturally in most soils, although at high concentrations it is toxic to many agricultural plants. High concentrations of boron tend to occur where marine sediments have influenced soil formation. Because boron salts are slightly soluble, they are leached out of the root zone in higher rainfall areas. However, in lower rainfall areas or where impermeable subsoil clay layers prevent leaching, boron concentrations can be high. Work by CSIRO has established that concentrations of >15 mg/kg are toxic to cereals. Other work suggests that the tolerance of horticultural crops is significantly lower. Toxic effects are more marked in dry seasons when roots penetrate deeper into the soil. Excess boron cannot be removed from soil or treated in any way under dryland farming conditions. Accidental or deliberate breeding for boron tolerance has produced a range of cultivars which are appropriate for affected soils. See Table 26.

Table 25 Nutrient Status

Soil constraint	Scope (e.g. state, regional, national)	Methodology	Scale	Utility and availability of data	Map Product and Reference
Total P	Australia – Soil and Landscape Grid of Australia	Soil and Landscape Grid of Australia's, Australia-wide Soil Attribute Maps generated (2014) using measured soil attribute data from existing databases in the national soil site data collation and spectroscopic estimates made with the CSIRO's National spectroscopic database (Viscarra Rossel & Webster, 2012). Spatial modelling performed using decision trees with piecewise linear models and kriging of residuals. 50 environmental covariates, representing climate, biota, terrain, and soil and parent material, used in the modelling. Uncertainty derived using a bootstrap (Monte Carlo-type) approach to derive, for each pixel, a probability density function (pdf), from which were derived 90% confidence limits. Approach is described in Viscarra Rossel et al. (2015a). Soil attribute levels estimated for depth intervals: 0-5 cm, 5-15 cm, 15-30 cm, 30-60 cm, 60-100 cm and 100-200 cm.	Predicted at 90 m raster resolution.	Creative Commons Attribution 4.0 International License. Data accessible via: http://www.clw.csiro.au/aclep/soilandlandscapegrid/	
Effective Cation Exchange Capacity (ECEC)	Australia – Soil and Landscape Grid of Australia	Soil and Landscape Grid of Australia's, Australia-wide Soil Attribute Maps generated (2014) using measured soil attribute data from existing databases in the national soil site data collation and spectroscopic estimates made with the CSIRO's National spectroscopic database (Viscarra Rossel & Webster, 2012). Spatial modelling performed using decision trees with piecewise linear models and kriging of residuals. 50 environmental covariates, representing climate, biota,	Predicted at 90 m raster resolution.	Creative Commons Attribution 4.0 International License. Data accessible via: http://www.clw.csiro.au/aclep/soilandlandscapegrid/	

Soil constraint	Scope (e.g. state, regional, national)	Methodology	Scale	Utility and availability of data	Map Product and Reference
		terrain, and soil and parent material, used in the modelling. Uncertainty derived using a bootstrap (Monte Carlo-type) approach to derive, for each pixel, a probability density function (pdf), from which were derived 90% confidence limits. Approach is described in Viscarra Rossel et al. (2015a). Soil attribute levels estimated for depth intervals: 0-5 cm, 5-15 cm, 15-30 cm, 30-60 cm, 60-100 cm and 100-200 cm.			
Total N	Australia – Soil and Landscape Grid of Australia	Soil and Landscape Grid of Australia's, Australia-wide Soil Attribute Maps generated (2014) using measured soil attribute data from existing databases in the national soil site data collation and spectroscopic estimates made with the CSIRO's National spectroscopic database (Viscarra Rossel & Webster, 2012). Spatial modelling performed using decision trees with piecewise linear models and kriging of residuals. 50 environmental covariates, representing climate, biota, terrain, and soil and parent material, used in the modelling. Uncertainty derived using a bootstrap (Monte Carlo-type) approach to derive, for each pixel, a probability density function (pdf), from which were derived 90% confidence limits. Approach is described in Viscarra Rossel et al. (2015). Soil attribute levels estimated for depth intervals: 0-5 cm, 5-15 cm, 15-30 cm, 30-60 cm, 60-100 cm and 100-200 cm.	Predicted at 90 m raster resolution.	Creative Commons Attribution 4.0 International License. Data accessible via: http://www.clw.csiro.au/aclep/soillandscapegrid/	

Soil constraint	Scope (e.g. state, regional, national)	Methodology	Scale	Utility and availability of data	Map Product and Reference
Nutrient status (P)	SW WA	Available records (140 000 samples from 1982–2012) assessed to determine nutrient status for P, K, S, and soil acidity for arable and pasture soils in the south-west of WA. Proportion of samples above or below critical soil test values was used to determine the extent of a nutrient excess or deficit. A soil P fertility index (P90) was derived from the ratio of measured soil test P to critical soil test P values. This index is an indicator of the severity of soil P excess or deficit to achieve 90% of maximum production of pastures or crops. Based on this index, values of 1 are optimum, and those greater than or less than 1 are in excess or deficient respectively.			
Total P	NSW (State)	Digital soil mapping (DSM) using multiple linear regression or Cubist decision tree modelling approaches. Original models were developed from a dataset of approximately 6000 soil profiles across NSW, divided into training and validation data sets at an 80:20% ratio. The models were applied against 17 environmental covariates representing the various soil forming factors to develop the final maps. Lin's concordance: 0.57, 0.60, 0.63, 0.62, 0.63, 0.54	100 m raster resolution	Provides continuous data on soil properties/constraints across NSW for a range of purposes, including assisting in sustainable land management, ecological modelling and hydrological modelling. Digital maps for all depth intervals can be downloaded through OEH data portal. http://data.environment.nsw.gov.au/dataset/digital-soil-maps-for-key-soil-properties-over-nsw Maps for six depth intervals down to 2 m and 90% confidence level maps are also available on request via:	

Soil constraint	Scope (e.g. state, regional, national)	Methodology	Scale	Utility and availability of data	Map Product and Reference
				data.broker@environment.nsw.gov.au	
CEC – sum of bases (log $cmol_c$/kg)	NSW	Digital soil mapping (DSM) using multiple linear regression or Cubist decision tree modelling approaches. Original models were developed from a dataset of approximately 6000 soil profiles across NSW, divided into training and validation data sets at an 80:20% ratio. The models were applied against 17 environmental covariates representing the various soil forming factors to develop the final maps. Lin's concordance: 0.44, 0.49, 0.47, 0.59, 0.61, 0.74)	100 m raster resolution	Provides continuous data on soil properties/constraints across NSW for a range of purposes, including assisting in sustainable land management, ecological modelling and hydrological modelling. Digital maps for all depth intervals can be downloaded through OEH data portal. http://data.environment.nsw.gov.au/dataset/digital-soil-maps-for-key-soil-properties-over-nsw Maps for six depth intervals down to 2 m and 90% confidence level maps are also available on request via: data.broker@environment.nsw.gov.au	

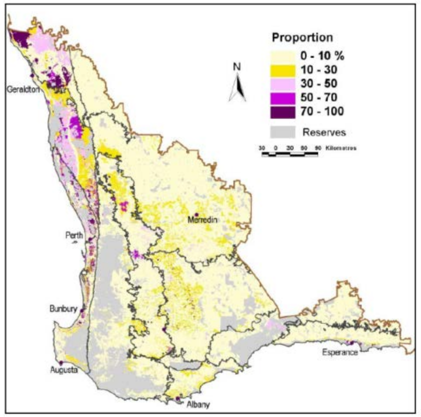
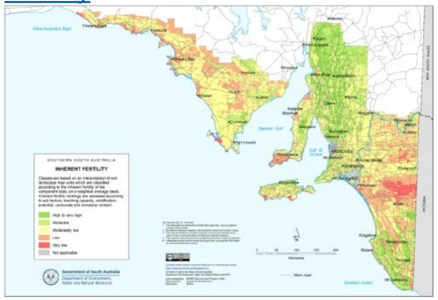
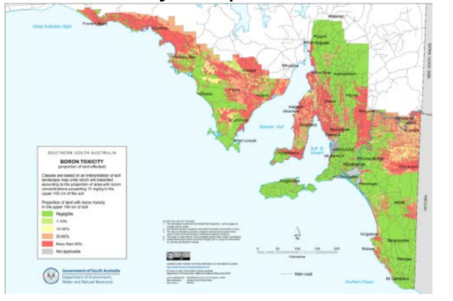
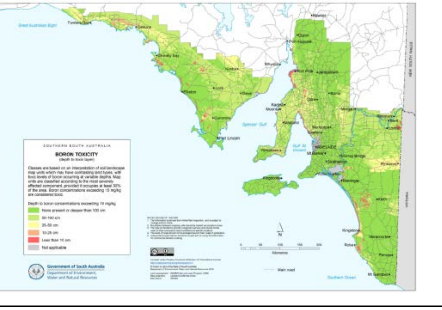
<table>
<tr><th>Soil constraint</th><th>Scope (e.g. state, regional, national)</th><th>Methodology</th><th>Scale</th><th>Utility and availability of data</th><th>Map Product and Reference</th></tr>
<tr><td>Low Inherent Fertility</td><td></td><td>Uses information for organic carbon, phosphorus retention index and clay percentage. Organic carbon considered to be major indicator of inherent soil fertility, and strongly affected by climate. Sands have a low inherent fertility with other constraints including water repellence, low soil water storage, rapid soil permeability, acidic topsoil and subsoil and wind erosion.
<table>
<tr><th>Soil property</th><th>Calculation</th></tr>
<tr><td>Organic carbon %</td><td>multiply value by 5</td></tr>
<tr><td>Phosphorus retention index</td><td>divide value by 2</td></tr>
<tr><td>Clay %</td><td>multiply value by 2</td></tr>
<tr><td></td><td>calculate the average score (as an integer)</td></tr>
</table></td><td>Various input scales – 1:50K to 1:250K.</td><td>Data available via the Western Australia government, DPIRD (contact: Tim Overheu)</td><td>

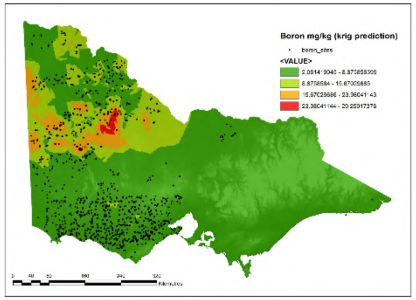
Figure 4.3.1 Total area of very low inherent fertility

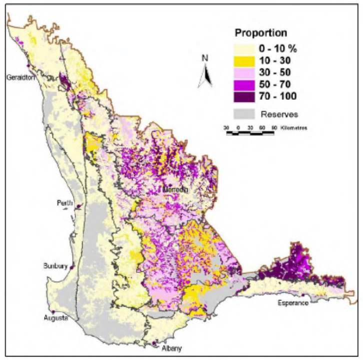
van Gool, D 2016, ‘Identifying soil constraints that limit wheat yield in South-West Western Australia’, Resource Management Technical Report 399, Department of Agriculture and Food, Western Australia, Perth.</td></tr>
<tr><td>Inherent fertility</td><td>Southern SA</td><td>Each of the 61 soils representative of the range found across SA's agricultural zone has been given an inherent fertility ranking (score) on a scale from 1 to 5 (these are tabulated in the document <u>Assessing Agricultural Land</u> (Maschmedt 2002). Six Inherent Fertility attribute (or 'analysis data') classes have been supplied as percentage (areal extent) values of each Soil Landscape Map Unit – i.e. ‘high to very high, ‘moderate’, ‘moderately low’, ‘low’, ‘very low’. For map display purposes, a weighted average Inherent Fertility score is calculated to summarise the variable</td><td>Accuracy to scale of mapping (50 m at 1:50K and 300 m at 1:100K scale). SE, Kangaroo Is., Lofty Ranges and lower Yorke Peninsula mapped at 1:50K. Eyre Peninsula, main part of Yorke</td><td>Data accessible under a Creative Commons 4.0 via: https://data.sa.gov.au/data/dataset/inherent-fertility</td><td>https://data.sa.gov.au/data/dataset/inherent-fertility
</td></tr>
</table>

Soil constraint	Scope (e.g. state, regional, national)	Methodology	Scale	Utility and availability of data	Map Product and Reference
		soils typically found within each map unit. These area-weighted average scores have been categorised into six (including not applicable) Inherent Fertility legend categories.	Peninsula, Murray Mallee and Northern Agricultural Districts mapped at 1:100K.		
Nutrient Holding Capacity (CEC or ECEC)	**Qld:** Selected mapping areas adjacent to Great Barrier Reef: Mary-Burnett, Townsville, Burdekin, Wet Tropics, Atherton, Mackay-Whitsunday	Data developed using mass preserving spline across averaged soil profile data for each soil profile class. CEC (cmolec/kg) – direct measurement (laboratory or Soil and Land Resource Assessment Field Manual Code)	Raster grid (approx. 30 m x 30 m). Vector map 1:100 000.	Suited for regional decision making to sub-farm scale. Data available in raster format pending release. Will also be available in vector format.	O'Brien, L.E. and Thomas, E. 2018. Soil constraints mapping to inform nutrient management in the cropping industries. RP155C. Soil Constraints Report. Department of Environment and Science, Queensland Government – awaiting publication.

Table 26 Boron toxicity

Soil constraint	Scope (e.g. state, regional, national)	Methodology	Scale	Utility and availability of data	Map Product and Reference
Boron toxicity (proportion of land affected)	Southern SA	Each component within each Soil Landscape Map Unit assessed according to the average estimated depth to toxic boron concentration. Affected land has boron concentrations exceeding 15 mg/kg within 100 cm of the surface. Three Boron Toxicity (proportion of land affected) analysis data classes (including not applicable) have been supplied, as percentage values of Soil Landscape Map Unit to be used for the calculation of spatial data statistics. Five (plus not applicable) legend categories (TOX_B_P) determined by rating the most severely affected proportion of the landscape, provided it occupies at least 30% of the area of the Soil Landscape Map Unit.	Accuracy to scale of mapping (50 m at 1:50K and 300 m at 1:100K scale). SE, Kangaroo Is., Lofty Ranges and lower Yorke Peninsula mapped at 1:50K. Eyre Peninsula, main part of Yorke Peninsula, Murray Mallee and Northern Agricultural Districts mapped at 1:100K.		https://data.sa.gov.au/data/dataset/boron-proportion Boron Toxicity: Proportion of land affected 
Boron toxicity (depth to toxic layer)	Southern SA	This assessment is intended to highlight areas where boron toxicity may affect plant growth, at least in some seasons. Assessments made from soil test results and extrapolation between similar soil materials and environments. Each component of each Soil Landscape Map Unit is assessed according to the average estimated depth to toxic boron concentration. Six Boron Toxicity (depth to toxic layer) attribute (or 'analysis data') classes, including not	Accuracy to scale of mapping (50 m at 1:50 K and 300 m at 1:100 K scale). SE, Kangaroo Is., Lofty Ranges and lower Yorke Peninsula mapped at 1:50 K. Eyre		Boron toxicity – depth to toxic layer https://data.sa.gov.au/data/dataset/boron-depth 

<table>
<tr><th>Soil constraint</th><th>Scope (e.g. state, regional, national)</th><th>Methodology</th><th>Scale</th><th>Utility and availability of data</th><th>Map Product and Reference</th></tr>
<tr><td></td><td></td><td>applicable, supplied as percentage (areal extent) values of each Soil Landscape Map Unit. For map display purposes, six legend categories (TOX_B_D), including not applicable, have been established which highlight the most severely affected component(s) of each Soil Landscape Map Unit, provided this accounts for at least 30% of the map unit area</td><td>Peninsula, main part of Yorke Peninsula, Murray Mallee and Northern Agricultural Districts mapped at 1:100 K.</td><td></td><td></td></tr>
<tr><td>Boron</td><td>Victoria</td><td>Initial kriged prediction of Boron (mg/kg) using MIR spectroscopy from legacy soil samples in the Victorian Soil Archive (VSA) [unpublished].</td><td>1:1 M</td><td>Map produced in 2013 as part of the Understanding Soils and Farming Systems project. Internal (unpublished) dataset available from Agriculture Victoria upon request.</td><td>
</td></tr>
<tr><td>Boron toxicity</td><td>SW Western Australia</td><td>This map assessment includes soils to 80cm deep, which includes many deep texture-contrast soils. The applied method states that other constraints may also be restricting to plant growth. The map is based on the following ruleset to determine
<table>
<tr><th>Indicator</th><th>Nil
(if any criterion is met)</th><th>Moderate
(must meet all criteria)</th></tr>
<tr><td>Clay (%)</td><td><20</td><td>≥20</td></tr>
<tr><td>Exchangeable sodium percentage (%)</td><td>≤6</td><td>>6</td></tr>
<tr><td>pH_w</td><td><7.5</td><td>≥7.5</td></tr>
<tr><td>Soil depth (cm)</td><td><30</td><td>30–80</td></tr>
<tr><td>Rainfall (mm)</td><td>≥600 or high rainfall zone</td><td><600 or the low or medium rainfall zone</td></tr>
</table>
proportion of area (e.g. 0-10%, 10-30%, 30-50%, 50-70%, 70-100%) with</td><td>Various input scales – 1:50K to 1:250K.</td><td>Data available via WA government , DPIRD (contact: Tim Overheu)</td><td>van Gool, D 2016, ‘Identifying soil constraints that limit wheat yield in South-West Western Australia’, Resource Management Technical Report 399, Department of Agriculture and Food, Western Australia, Perth.</td></tr>
</table>

Soil constraint	Scope (e.g. state, regional, national)	Methodology	Scale	Utility and availability of data	Map Product and Reference
		moderate or greater boron toxicity susceptibility.			 Figure 4.1.1 Total area of moderate or greater boron toxicity susceptibility

4.4.5 Sandy soils

Soil texture

Surface soil texture refers to the approximate clay content of the surface soil. Texture influences many soil qualities including water holding capacity, wilting point moisture levels, nutrient retention, erodibility, permeability, workability and seedling emergence. In heterogeneous landscapes, map units often contain a range of surface soil textures. See Table 27.

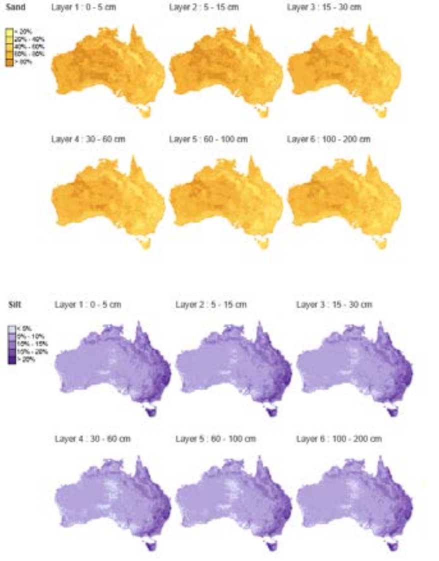
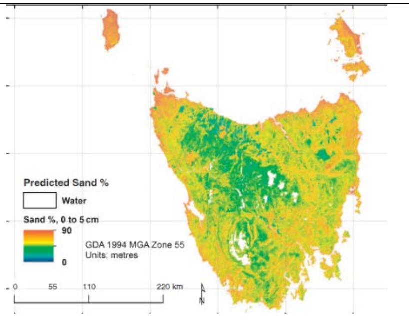
Water Repellence

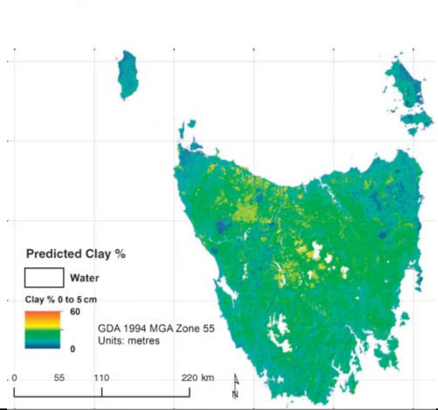
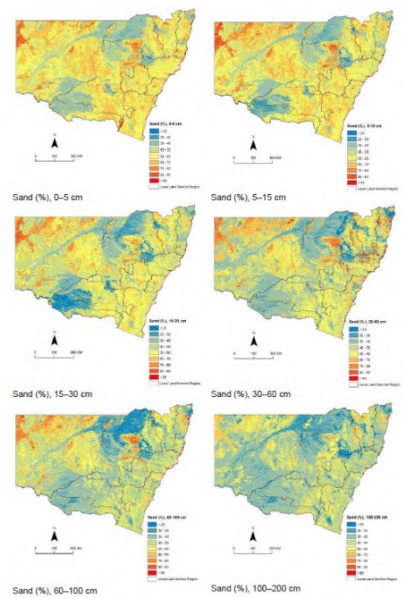
Water Repellence is caused by hydrophobic organic materials, mainly waxes, contained in plant remains within the soil. The waxes coat the soil particles causing water to bead on the surface. This causes uneven wetting of the upper part of the soil profile, with large masses of soil remaining dry. Patchy 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 loamier 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. See Table 28.

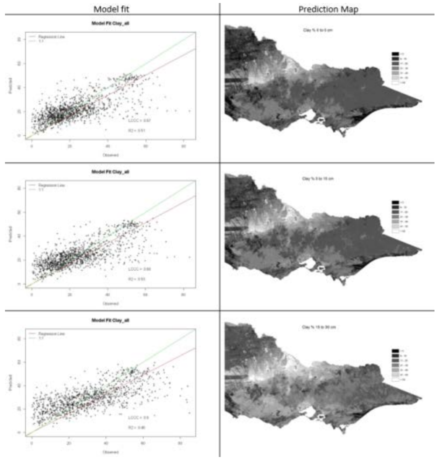
A high proportion of WA wheat-growing areas are subject to this constraint and areas where it is most important are much less because it is commonly associated with other constraints of sandy soils such as low water storage, low fertility, acidity and wind erosion (van Gool 2016). Although water repellence 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 WA from water repellence is estimated at $251 million.

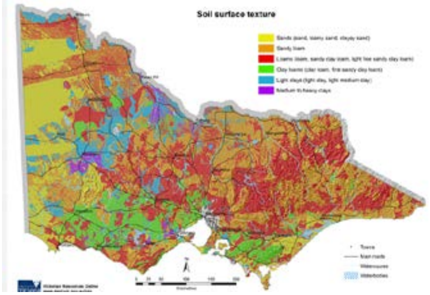
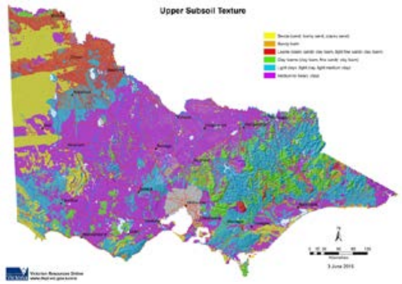
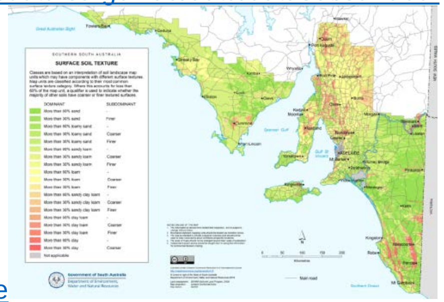
Farmer surveys in several areas of the south-west of WA indicate that water repellence is widespread, increasing, and significantly affects agricultural production (Davies et al. 2013). A survey of 28 farmers in the West Midlands in 2010 indicated water repellence as their top constraint to production (46%) ahead of soil water holding capacity and soil acidity. About 85% of these farmers indicated that the water repellent soils on their property were increasing in both area and severity. These results are not surprising given that sandy surfaced soils of low clay content dominate this area and the move to minimum tillage leaves more organic residues in the soil.

Table 27 Soil texture

Soil constraint	Scope (e.g. state, regional, national)	Methodology	Scale	Utility and availability of data	Map Product and Reference
% clay, % silt, % sand	Australia (Soil and Landscape Grid of Australia)	Soil and Landscape Grid of Australia's, Australia-wide Soil Attribute Maps generated (2014) using measured soil attribute data from existing databases in the national soil site data collation and spectroscopic estimates made with the CSIRO's National spectroscopic database (Viscarra Rossel & Webster, 2012). Spatial modelling performed using decision trees with piecewise linear models and kriging of residuals. 50 environmental covariates, representing climate, biota, terrain, and soil and parent material, used in the modelling. Uncertainty derived using a bootstrap (Monte Carlo-type) approach to derive, for each pixel, a probability density function (pdf), from which were derived 90% confidence limits. Approach is described in Viscarra Rossel et al. (2015). Soil attribute levels estimated for depth intervals: 0-5 cm, 5-15 cm, 15-30 cm, 30-60 cm, 60-100 cm and 100-200 cm.	Predicted at 90 m raster resolution.	Creative Commons Attribution 4.0 International License. Data accessible via: http://www.clw.csiro.au/aclep/soilandlandscapegrid/	
%clay, % sand, %silt (profile)	Tasmania (state)	Digital Soil Mapping (DSM) has formed the basis of an Enterprise Suitability Mapping (ESM) program for 20 different crops (36 in development) at 80 m resolution. DSM based on regression tree approach, for multiple depths (0-5, 5-15, 15-30, 30-60, 60-100, 100-200 cm) and soil attributes (i.e. pH, EC, SOC%, Clay%, Sand%, Silt%, depth, sodicity, salinity, drainage, permeability, AWC, Ksat). Calibration sites based on existing and newly collected soils data	80 m resolution (30 m currently being developed)	Creative Commons. Data packages available as ArcGIS rasters and associated scientific publications via DPIPWE. Sand Validation R^2: 0.68, 0.63, 0.56, 0.52, 0.38	

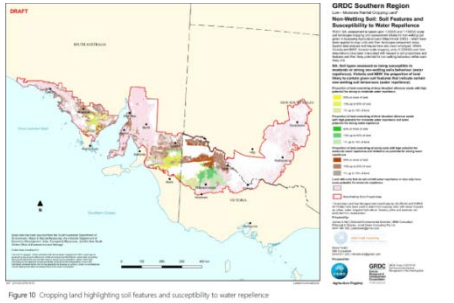
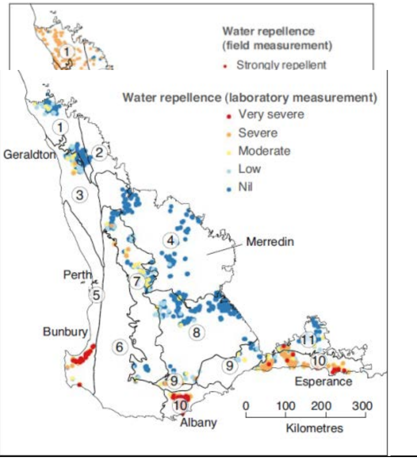
Soil constraint	Scope (e.g. state, regional, national)	Methodology	Scale	Utility and availability of data	Map Product and Reference
		(approximately 6500 sites. Silt was derived as difference from 100% and sand/clay % totals.		Clay Validation R^2: 0.63, 0.62, 0.56, 0.51, 0.41	
%clay, % silt, % sand	NSW	Digital soil mapping (DSM) using multiple linear regression or Cubist decision tree modelling approaches. Original models were developed from a dataset of approximately 6000 soil profiles across NSW, divided into training and validation data sets at an 80:20% ratio. The models were applied against 17 environmental covariates representing the various soil forming factors to develop the final maps. 0-5, 5-15, 15-30, 30-60, 60-100, 100-200. Lin's concordance: % clay: 0.55, 0.58, 0.55, 0.48, 0.42, 0.32 % silt: 0.26, 0.31, 0.28, 0.27, 0.33, 0.21 % sand: 0.39, 0.46, 0.46, 0.42, 0.44, 0.51	100 m raster resolution	Provides continuous data on soil properties/constraints across NSW for a range of purposes, including assisting in sustainable land management, ecological modelling and hydrological modelling. Digital maps for all depth intervals can be downloaded through OEH data portal. http://data.environment.nsw.gov.au/dataset/digital-soil-maps-for-key-soil-properties-over-nsw Maps for six depth intervals down to 2 m and 90% confidence level maps are also	

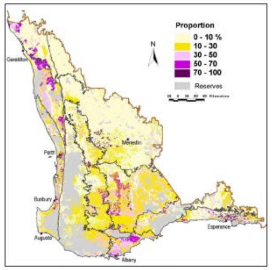
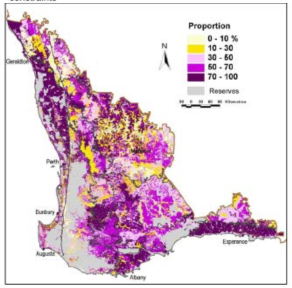
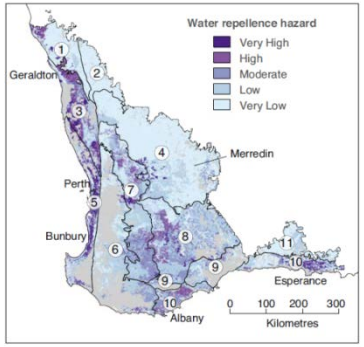
Soil constraint	Scope (e.g. state, regional, national)	Methodology	Scale	Utility and availability of data	Map Product and Reference
				available on request via: data.broker@environment.nsw.gov.au	
% clay, % silt, % sand	Victoria	Digital soil mapping: Grids of 10 soil properties have been produced for Victoria. These grids, in raster format, provide prediction and confidence interval values for key soil properties at a 90 m grid resolution for six set depths meet the specifications created by GlobalSoilMap; 0 – 5 cm, 5 – 15 cm, 15 – 30 cm, 30 – 60 cm, 60 - 100 cm and 100 – 200 cm, across Victoria. Methodology used to develop the Soil Grids of Victoria was based on that refined by the Australian Soil and Landscape Grid (Viscarra Rossel et al. 2015). Data and knowledge embedded into existing soil related datasets, e.g. soil profile and land mapping collections, have been key inputs. 170 gridded environmental datasets were used. The supporting database contains more than one million measurements for over 18,000 geo-referenced soil sites. Over 6,000 of these sites have soil property predictions derived from samples analysed using MIR spectroscopy.	Predicted at 90 m raster resolution.	Predicted accuracy (R^2): Clay: (0-5 cm) 0.51; (5-15 cm) 0.53; (15-30 cm) 0.46; (30-60 cm) 0.41; (60-100 cm) 0.38; (100-200 cm) 0.32 Silt: (0-5 cm) 0.54; (5-15 cm) 0.57; (15-30 cm) 0.56; (30-60 cm) 0.49; (60-100 cm) 0.43; (100-200 cm) 0.46 sand: (0-5 cm) 0.41; (5-15 cm) 0.41; (15-30 cm) 0.37; (30-60 cm) 0.29; (60-100 cm) 0.31; (100-200 cm) 0.24	Soil Grids of Victoria. Hopley et al 2017. 

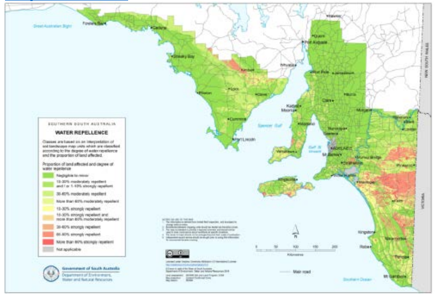
Soil constraint	Scope (e.g. state, regional, national)	Methodology	Scale	Utility and availability of data	Map Product and Reference
Surface and upper subsoil texture class	Victoria	Soil texture maps (surface and upper subsoil) created using soil data observations within the Victorian Soil Information System (VSIS) and existing soil mapping from surveys conducted over the past 50 years. Considerable variation in soil texture is likely within a region, depending on factors such as soil type, landform and landscape process.	1:500 000	Available on request through Agriculture Victoria (DEDJTR) http://vro.agriculture.vic.gov.au/dpi/vro/vrosite.nsf/pages/soil_soil-texture	 
Surface soil texture	Southern SA	Nine Surface Soil Texture attribute (or 'analysis data') classes supplied (e.g. more than 60% sand; more than 30% sand; more than 60% clay; more than 30% clay etc) as percentage (areal extent) values of each Soil Landscape Map Unit. Note: sum of all percentage values for each map unit totals 100%. This analysis data is to be used for the calculation of spatial data statistics. For map display purposes, Soil Landscape Map Units have been categorised (i) according to the most common Surface Soil Texture class, provided this occupies at least 30% of the area; and (ii) where the	Accuracy to scale of mapping (50 m at 1:50 K and 300 m at 1:100 K scale). SE, Kangaroo Is., Lofty Ranges and lower Yorke Peninsula mapped at 1:50 K. Eyre Peninsula, main part of Yorke Peninsula, Murray Mallee and Northern Agricultural Districts mapped at 1:100 K.	Data is accessible under Creative Commons 4.0 via: https://data.sa.gov.au/data/dataset/surface-texture	https://data.sa.gov.au/data/dataset/surface-  texture

Soil constraint	Scope (e.g. state, regional, national)	Methodology	Scale	Utility and availability of data	Map Product and Reference
		aforementioned accounts for less than 60% of the map unit, a qualifier* indicates whether the majority of remaining soil components have coarser (i.e. more sandy) or finer (i.e. more clayey) textured surfaces. Dataset has been derived from the Soil Landscape Map Units spatial dataset to be used for map creation or the calculation of spatial data statistics.			

Table 28 Water repellence

Soil constraint	Scope (e.g. state, regional, national)	Methodology	Scale	Utility and availability of data (including limitations)	Map Product and Reference
Water repellence for south-eastern Non-wetting sands (for GRDC)	GRDC Southern region – Low-Moderate Rainfall zone (SA, Vic, NSW).	<u>SA</u>: Soil types assessed as being susceptible to moderate-strong non-wetting soils behaviour (i.e. water repellence) – as per Assessing Agricultural Land (Maschmedt 2002). Applied to map units and landscape component areas. <u>Vic and NSW</u>: Proportion of land likely to contain given features that indicate certain non-wetting soil behaviours (water repellence). Land System descriptions have been interpreted with respect to soil proportions and features and their likely potential for non-wetting behaviour.	<u>SA</u>: 1:50K to 1:100K scale soil/landscape mapping. <u>Vic and NSW</u>: Broader Land System (1:250 000) scale mapping.	Data provided by James Hall (Juliet Creek Consulting) for use in CRC (with acknowledgement). Based on expert interpretation of key soil properties influencing non-wetting. Very limited data available for Victoria and NSW.	 Reference: The Nature, Extent and Distribution of Non-Wetting Soils in the Low-Moderate Rainfall Cropping Areas of GRDC Southern region. (2015). Juliet Creek Consulting.
Water repellence (WA) based on field and lab test sites	Regional WA	<u>Laboratory measurements</u>: The degree of water repellence is determined using the laboratory MED test (King 1981; Carter 2002). MED categories are shown in Table 2.6.4. Limited unpublished data from 1,863 topsoil samples from the soil quality and DAFF soil carbon program (Daniel Murphy, UWA and Frances Hoyle, DAFWA) and DAFWA (Derk Bakker, David Hall and Paul Blackwell). <u>Field measurements</u>: The surface of 8800 sites from the DAFWA regional soils survey program were field tested for water repellence. Results indicate that water repellence is widespread throughout the south-west of WA. An analysis of these data with soil type (WA Soil Groups) demonstrates a strong correlation	Point scale	Data available via DPIRD (contact: Tim Overheu). Based on extensive field and laboratory data.	<u>Reference</u>: Carter D, Davies, Blackwell P and Schoknecht N (2013). 'Water repellence' In: *Report card on sustainable natural resource use in agriculture in WA*. DAFWA. 

Soil constraint	Scope (e.g. state, regional, national)	Methodology	Scale	Utility and availability of data (including limitations)	Map Product and Reference
		between water repellence and sand content in the topsoil.			
Water repellence hazard (WA)	SW WA	Spatial extent of water repellence was derived from the soils and their properties described in DAFWA's soil-landscape mapping of the south-west of WA. Assessing water repellence hazard using the soil-landscape mapping is described in van Gool et al. (2005). The resultant hazard map is a prediction of the likelihood of water repellence occurring and is not based on actual measurements.	Various input scales – 1:50K to 1:250K.	Data available via the Western Australia government data service: https://catalogue.data.wa.gov.au/dataset/soil-landscape-land-quality-water-repellence. Report is available from: https://researchlibrary.agric.wa.gov.au/rmtr/280/	 Figure 4.15.1b Area where water repellence susceptibility is one of few (1–3) constraints  Figure 4.15.1a Total area with moderate or greater water repellence susceptibility 

Soil constraint	Scope (e.g. state, regional, national)	Methodology	Scale	Utility and availability of data (including limitations)	Map Product and Reference
					van Gool, D 2016, 'Identifying soil constraints that limit wheat yield in South-West Western Australia', *Resource Management Technical Report 399,* Department of Agriculture and Food, Western Australia, Perth.
Water repellence	Southern SA	Four Water Repellence attribute (or 'analysis data') classes supplied, including not applicable) as percentage (areal extent) values of each Soil Landscape Map Unit. For map display purposes, Soil Landscape Map Units have been categorised into 10 legend categories (WATERREPEL), including 'not applicable', 'negligible to minor' '10-30% moderately repellent', '10-30% moderately repellent', '30-60% strongly repellent' etc; according to the proportion of the land at risk of water repellence (based on the extent of susceptible soils) as well as the degree of repellence. For NatureMaps, the standard legend categories have been simplified to a minor extent.	Accuracy to scale of mapping (50 m at 1:50K and 300 m at 1:100K scale). SE, Kangaroo Is., Lofty Ranges and lower Yorke Peninsula mapped at 1:50K. Eyre Peninsula, main part of Yorke Peninsula, Murray Mallee and Northern Agricultural Districts mapped at 1:100K.	Data available from: https://data.sa.gov.au/data/dataset/water-repellence and shared under a creative commons license.	https://data.sa.gov.au/data/dataset/water-repellence 

4.4.6 Other

Soil Organic Carbon

NLP prioritisation (McKenzie at al 2017) noted the importance of SOC in maintaining soil health and addressing climate change. Results from NSCP and related studies highlighted major constraints and trade-offs involved in maintaining or increasing SOC. See Table 29.

Erosion

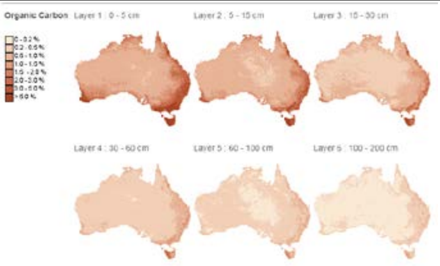
Wind Erosion Potential indicates where wind erosion could be a problem under particular soil disturbance and weather conditions (not where wind erosion has been or is currently a problem). The assessment is based on inherent soil and land characteristics such as surface texture, thickness of erodible 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. Erosion potential can vary greatly within a map unit and much of the wind erosion prone land in SA occurs in complex landscapes of susceptible sandhills and more stable flats.

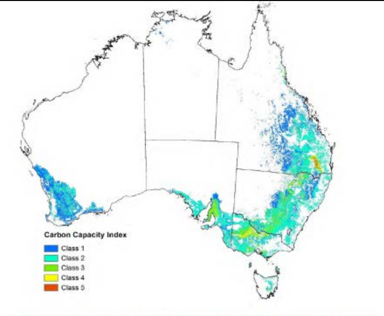
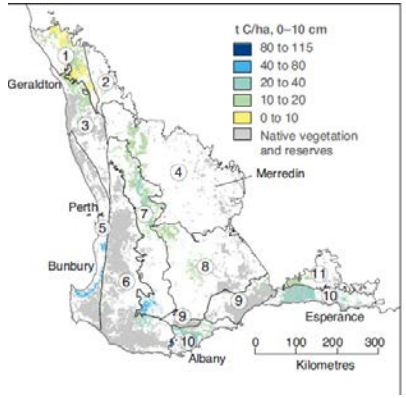
Wind erosion hazard occurs on exposed land with loose topsoil. Because wind erosion is typically associated with sandy soils that often have other major constraints, such as acidity, non-wetting and low soil water storage (van Gool 2016). See Table 30.

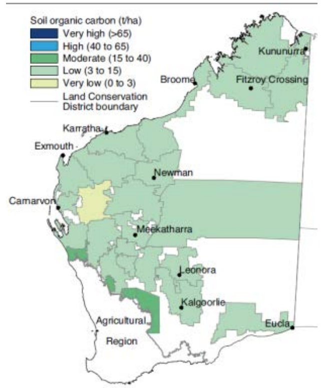
Soil Type

Understanding soil types provides appropriate context for many soil constraints and can be useful for broad assessment of likely constraints in many areas. See Table 31.

Table 29 Soil organic carbon (SOC)

Soil constraint	Scope (e.g. state, regional, national)	Methodology	Scale	Utility and availability of data	Map Product and Reference
Soil Organic Carbon (%)	National (Soil and landscape Grid of Australia)	Soil and Landscape Grid of Australia's, Australia-wide Soil Attribute Maps generated (2014) using measured soil attribute data from existing databases in the national soil site data collation and spectroscopic estimates made with the CSIRO's National spectroscopic database (Viscarra Rossel & Webster, 2012). Spatial modelling performed using decision trees with piecewise linear models and kriging of residuals. 50 environmental covariates, representing climate, biota, terrain, and soil and parent material, used in the modelling. Uncertainty derived using a bootstrap (Monte Carlo-type) approach to derive, for each pixel, a probability density function (pdf), from which were derived 90% confidence limits. Approach is described in Viscarra Rossel et al. (2015a). Soil attribute levels estimated for depth intervals: 0-5 cm, 5-15 cm, 15-30 cm, 30-60 cm, 60-100 cm and 100-200 cm.	Predicted at 90 m raster resolution.	Creative Commons Attribution 4.0 International License. Data accessible via: http://www.clw.csiro.au/aclep/soillandscapegrid/	
Carbon Capacity Index	National	NLP2 prioritisation The maps were developed for agricultural lands, rangelands and managed forests. The mapping process involved developing three indices from existing spatial layers. The indices (capacity, gains and retention) were applied to calculate an estimate of the potential for enhancing soil organic carbon content.	I km raster	National prioritisation -useful for framing priorities for interventions but provides no information on effectiveness of current land management. Creative Commons Attribution 4.0 International Public License	McKenzie NJ, Hairsine PB, Gregory LJ, Austin J, Baldock JA, Webb MJ, Mewett J, Cresswell HP, Welti N, Thomas M (2017). Priorities for improving soil condition across Australia's agricultural landscapes. CSIRO, Australia.

Soil constraint	Scope (e.g. state, regional, national)	Methodology	Scale	Utility and availability of data	Map Product and Reference
					 Figure 3.4: Carbon Capacity Index (Class 1 has the smallest capacity to store carbon and Class 5 the largest)
Soil organic carbon (t Ca/ha) 0-10 cm	SW Western Australia	Five primary data sources were used in this assessment with samples procured between 1999 and 2012. SCaRP (2009-11) 1456 samples (0-10 cm) – LECO measured; Soil Quality Program (2006-09) 512 samples (0-10 cm) – WB measured; Lower Swan Coastal Plain survey (2007-08) 317 samples (10-10 cm) – WB measured; Albany catchments (2007-08) 192 samples – WB measured; DAFWA soils database (1999-2012) 214 samples – WB measured. Only 25% of data has BD to allow stock (t C/ha) to be measured. Due to spatial distribution of samples, available data in this format remains highly clumped. Only 7% of the soil-landscape units contained the 2490 samples measured for SOC at 0–10 cm. About half of these subsystems had only 1 or 2 samples, which are not reliable. Therefore, even modestly reliable estimates are available for just a small percentage of south-west WA. These contribute to low confidence in aggregate statistics at a	Aggregated to Agricultural Soil Zones (Ag Soil Zones).	Regional benchmarking. Does not assist with farm management. Data available via DPIRD (contact: Tim Overheu).	Reference: Griffin E, Hoyle F and Murphy D (2013). 'Soil organic carbon' In: *Report card on sustainable natural resource use in agriculture in WA*. DAFWA. 

Soil constraint	Scope (e.g. state, regional, national)	Methodology	Scale	Utility and availability of data	Map Product and Reference
		regional scale (e.g. Ag Soil Zones) and for entire south-west of WA.			
Soil carbon	WA rangelands	The units for the mapping is the land conservation district. As there were very few soil sites with SOC observations available, this site data was compared with modelled approaches from the NLWRA (Raupach et al. 2001) where a modest correlation was observed. This gives some confidence to modelled predictions.	1:5M	Data produced as part of scorecards in 2017 as part of the 'Report card on sustainable natural resource use in the rangelands: status and trend in the pastoral rangelands of Western Australia' by Department of Agriculture and Food, Western Australia is licensed under a Creative Commons Attribution 4.0. Data should be available from DAFWA.	"Report card on sustainable natural resource use in the rangelands of Western Australia" https://www.agric.wa.gov.au/rangelands/report-card-sustainable-natural-resource-use-rangelands-western-australia  Figure 3.5.6 Modelled SOC stocks (t/ha) for the top 30cm of the soil profile by modal level within each LCD (adapted from Raupach et al. 2001)

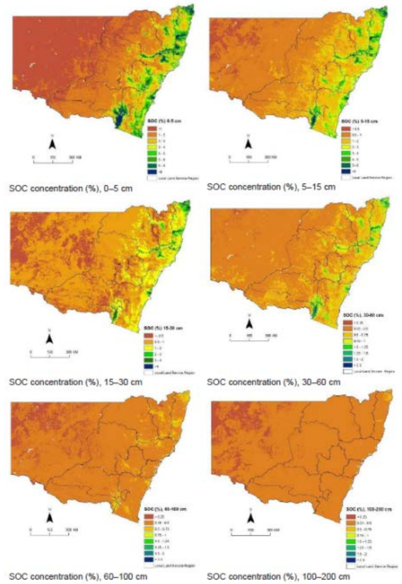
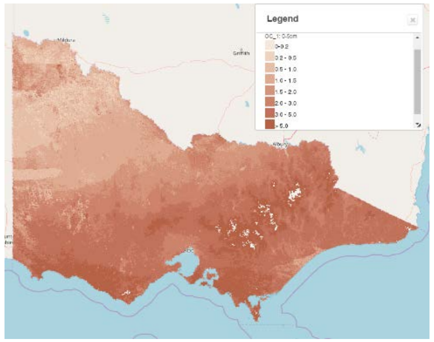
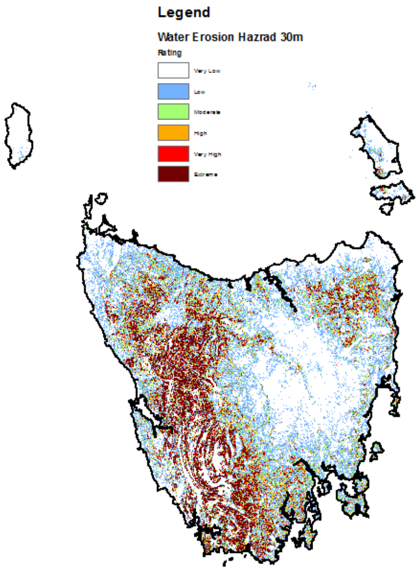
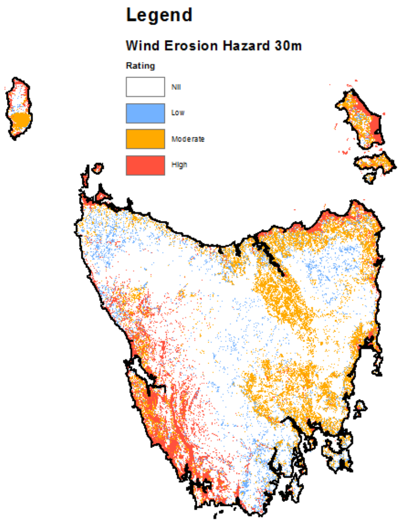
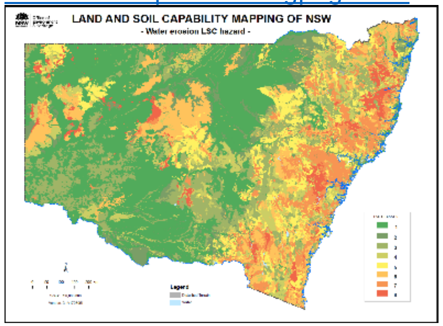
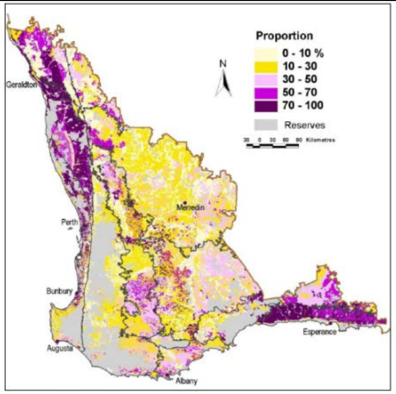
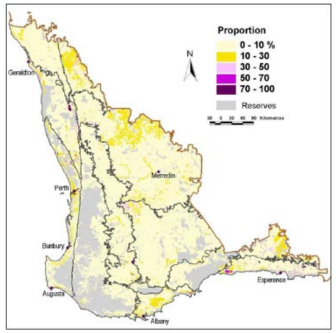
Soil constraint	Scope (e.g. state, regional, national)	Methodology	Scale	Utility and availability of data	Map Product and Reference
Soil organic carbon (log %, log kg/m³ and SOC stocks (log t/ha)	NSW	Digital soil mapping (DSM) using multiple linear regression or Cubist decision tree modelling approaches. Original models were developed from a dataset of approximately 6000 soil profiles across NSW, divided into training and validation data sets at an 80:20% ratio. The models were applied against 17 environmental covariates representing the various soil forming factors to develop the final maps. 0-5, 5-15, 15-30, 30-60, 60-100, 100-200. Lin's concordance: SOC (log%) 0.65, 0.58, 0.43, 0.23, 0.14, 0.02	100 m raster resolution	Provides continuous data on soil properties/constraints across NSW for a range of purposes, including assisting in sustainable land management, ecological modelling and hydrological modelling. Digital maps for all depth intervals can be downloaded through OEH data portal. http://data.environment.nsw.gov.au/dataset/digital-soil-maps-for-key-soil-properties-over-nsw Maps for six depth intervals down to 2 m and 90% confidence level maps are also available on request via: data.broker@environment.nsw.gov.au	
Soil Organic Carbon (%)	Victoria	Digital soil mapping – SOC grids have been produced for Victoria for the depth intervals of 0 – 5 cm, 5 – 15 cm, 15 – 30 cm. These grids, in raster format, provide prediction and confidence interval values for key soil properties at a 90 m grid resolution The methodology used to develop the Soil Grids of Victoria was based on that refined by the Australian Soil and Landscape Grid (Viscarra Rossel et al. 2015). Data and knowledge embedded into existing soil related datasets, e.g. soil profile and land mapping collections, have been key inputs.	Predicted at 90 m raster resolution .	Data accessible via: http://www.ozdsm.com.au/ozdsm_map.php or Agriculture Victoria (DEDJTR). Prediction accuracy: 0-5 cm (R2 = 0.61) 5-15 cm (R2 = 0.62) 15-30 cm (R2 = 0.47)	

Table 30 Erosion

Soil constraint	Scope (e.g. state, regional, national)	Methodology	Scale	Utility and availability of data	Map Product and Reference
Wind erosion & water erosion	Tasmania (state)	Digital Soil Mapping (DSM) has formed the basis of an Enterprise Suitability Mapping (ESM) program for 20 different crops (36 in development) at 80 m resolution. DSM based on regression tree approach, for multiple depths and soil attributes (i.e. pH, EC, SOC%, Clay%, Sand%, Silt%, depth, sodicity, salinity, drainage, permeability, AWC, Ksat). Calibration sites based on existing and newly collected soils data (approximately 6500 sites. Water erosion is based on RUSLE calculations of DSM for clay, sand, silt, SOC%, coarse fragments, permeability, topsoil structure and slope-length. Wind Erosion based on DSM values for Sand, SOC% and coarse fragments using in-house erosion hazard ratings.	80 m, 30 m	Creative Commons. Data packages available as ArcGIS rasters and associated scientific publications via DPIPWE. Validation Diagnostics available for each separate DSM parameter.	

Soil constraint	Scope (e.g. state, regional, national)	Methodology	Scale	Utility and availability of data	Map Product and Reference
					
Sheet & Rill Erosion Gull Erosion Mass Movement Tunnel Erosion Wind Erosion	Tasmania (Freehold Land)	1:250 000 Land System boundaries on private (freehold) land were used as units for identifying areas containing a range of soil constraints land degradation hazards. Constraints were identified using a combination of existing site data and DPIPWE field officer knowledge via a questionnaire. The methodology followed the national approach proposed by Graham (1989).	1:500 000	Creative Commons. Data packages available as ArcGIS geodatabases and associated scanned pdf reports via DPIPWE and the NRM data library.	Grice, M.S. (1995). Assessment of Soil and Land Degradation on Private Freehold Land in Tasmania. Dept of Primary Industries & Fisheries, Tasmania. Accompanying 1:500 000 maps. Maps available in print only, or as GIS layers on request.
Water erosion LSC hazard	NSW (State)	One of the eight Land and Soil Capability (LSC) hazards. The hazard is accessed for the dominant facet (sub-landscape) of map units across NSW using the best available soil	1:100 000-1:500 000 Map layer is a compilation of	GIS dataset is available on request from OEH at soils@environment.nsw.gov.au	Mapping ruleset: Office of Environment and Heritage, 2012, The land and soil capability assessment scheme – second approximation. NSW

Soil constraint	Scope (e.g. state, regional, national)	Methodology	Scale	Utility and availability of data	Map Product and Reference
		information products. This information is sourced from the compilation of over 65 soil map products. Each hazard is given a rating between 1 (best, highest capability land) and 8 (worst, lowest capability land). The classification is assigned to each hazard using a ruleset published OEH 2012, "*The land and soil capability assessment scheme – second approximation*".	many soil mapping datasets of various scales. For more information see LSC metadata on the OEH Data Portal		Office of Environment and Heritage, Sydney. Available for download at: http://www.environment.nsw.gov.au/soils/20120394lsc2spubslandingpage.htm 
Wind erosion hazard	WA grain cropping regions	Wind Erosion risk mapping derived from land quality attribution associated with soil-landscape mapping at the subsystem/phase level.	Various input scales – 1:50K to 1:250K.	Data is accessible under a Creative Commons 4.0 via: https://catalogue.data.wa.gov.au/dataset/soil-landscape-land-quality-wind-erosion-risk	van Gool, D 2016, 'Identifying soil constraints that limit wheat yield in South-West Western Australia', *Resource Management Technical Report 399,* Department of Agriculture and Food, Western Australia, Perth.

Soil constraint	Scope (e.g. state, regional, national)	Methodology	Scale	Utility and availability of data	Map Product and Reference
					 Figure 4.16.1a Total area of high to extreme wind erosion hazard  Figure 4.16.1b Area where wind erosion hazard is one of few (1–3) constraints
Wind erosion potential	Southern SA	Seven Wind Erosion Potential attribute classes supplied as percentage (areal extent) values of each Soil Landscape Map Unit – low, moderately low, moderate, mod-high, high to extreme. For map display purposes, Soil Landscape Map Units have been categorised to (i) highlight the most limiting Wind Erosion Potential class, provided this occupies at least 30% of the area; and (ii) account for variability	Accuracy to scale of mapping (50 m at 1:50 K and 300 m at 1:100 K scale). SE, Kangaroo Is., Lofty Ranges and lower Yorke Peninsula	Data is accessible under a Creative Commons 4.0 via: https://data.sa.gov.au/data/dataset/wind-erosion-grid	https://data.sa.gov.au/data/dataset/wind-erosion

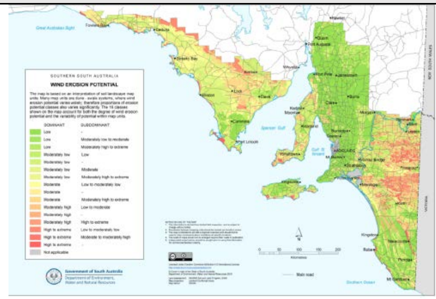
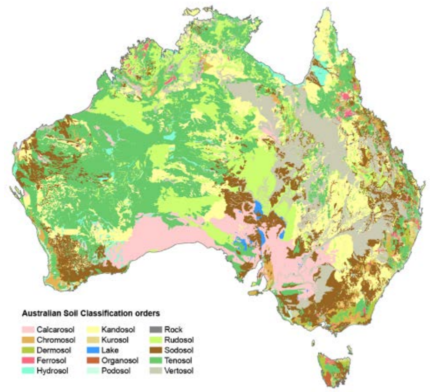
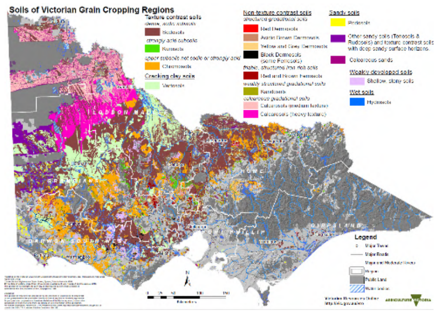
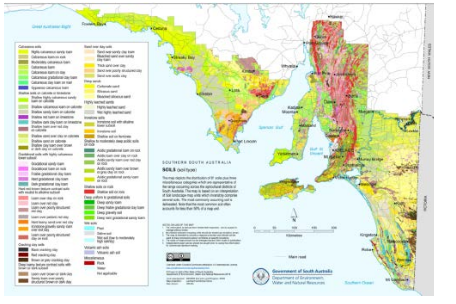
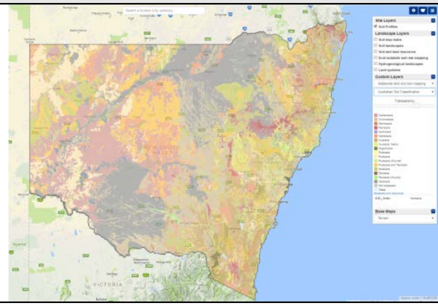
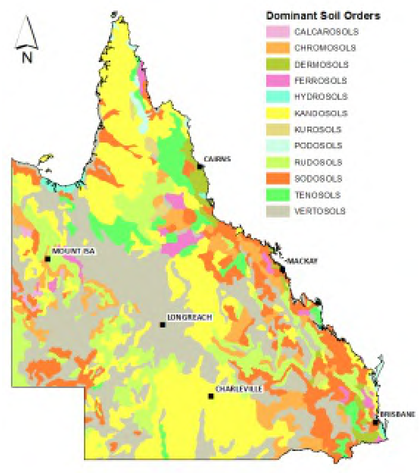
Soil constraint	Scope (e.g. state, regional, national)	Methodology	Scale	Utility and availability of data	Map Product and Reference
		in remaining subdominant classes. This system produces 17 map legend categories (EROS_WIND), including not applicable.	mapped at 1:50K. Eyre Peninsula, main part of Yorke Peninsula, Murray Mallee and Northern Agricultural Districts mapped at 1:100 K.		

Table 31 Soil type

Soil constraint	Scope (e.g. state, regional, national)	Methodology	Scale	Utility and availability of data	Map Product and Reference
ASC	National	Atlas of Australian Soils mapping units was transformed into an Australian Soil Classification (ASC) soil order map. Compiled to aid the production of Concepts and Rationale of Australian Soil Classification (1997).	1:2 Million	Data available from: http://www.asris.csiro.au/themes/Atlas.html	Ashton and McKenzie, 2001 
Broad soil types	Victorian grain cropping region	Consistent broadscale statewide overview that displays dominant Soil Orders, according to the Australian Soil Classification (Isbell, 2002). The map was produced using all available mapping and site data as well as expert interpretation. Gain cropping areas are based on data from the Victorian Land Use Information System (VSIS) and may not include all cropped areas. Also, not all these soils are used for cropping. Although many of these soils are well suited, there are some that present significant limitations such as shallow depth, poor drainage, salinity or stoniness. Landscape qualities can also present constraints, e.g. steep slopes, accessibility.	1:500K		 http://vro.agriculture.vic.gov.au/dpi/vro/vrosite.nsf/pages/grains_vic_soils

Soil constraint	Scope (e.g. state, regional, national)	Methodology	Scale	Utility and availability of data	Map Product and Reference
Soil type	Southern SA	61 soils identified, representative of the range occurring across southern SA, based on an interpretation of Soil Landscape Map Units. These Soils (soil type) classes are also termed 'subgroup soils' in the reference text Hall et al. 2009, 'The Soils of Southern South Australia', where they are described in detail. Each of these soils has a two-character alphanumeric code. The first character (letter) represents the relevant Soil Group; the second character (number) represents a particular soil within the Soil Group. Three additional miscellaneous classes (rock, water, not applicable) are also provided. Hence, 64 attribute (or 'analysis data') classes have been supplied, as percentage (areal extent) values of each possible soil type within each Soil Landscape Map Unit. For map display purposes, the most commonly occurring Soil (SOIL_SUBGR legend category) is defined, however, it should be noted that this often accounts for less than 50% of a Soil Landscape Map Unit.	Accuracy to scale of mapping (50 m at 1:50K and 300 m at 1:100K scale). SE, Kangaroo Is., Lofty Ranges and lower Yorke Peninsula mapped at 1:50K. Eyre Peninsula, main part of Yorke Peninsula, Murray Mallee and Northern Agricultural Districts mapped at 1:100 K.	Data is accessible under a Creative Commons 4.0 via: https://data.sa.gov.au/data/dataset/soil-type	https://data.sa.gov.au/data/dataset/soil-type 
Soil Types (ASC)	NSW	Provides soil types across NSW using the Australian Soils Classification at Order level. Uses the best available soils natural resource mapping coverage developed for the Land and Soil Capability (LSC) dataset. Derived from a lookup table system linking a Great Soil Group classification soil type to a most appropriate ASC class for each mapping unit. Individual map units have been grouped and	1:250 000	Data is accessible under a Creative Commons 4.0 via: http://data.environment.nsw.gov.au/dataset/australian-soil-classification-asc-soil-type-map-of-nsweaa10	Reference: Office of Environment and Heritage, 2017, Australian Soil Classification (ASC) Soil Type map of NSW, NSW Office of Environment and Heritage, Sydney.

Soil constraint	Scope (e.g. state, regional, national)	Methodology	Scale	Utility and availability of data	Map Product and Reference
		dissolved according to the Soil Type field to produce the final map.			
Dominant ASC Soil Orders	Qld				https://www.qld.gov.au/environment/land/soil/soil-testing/types# 

4.5 Needs assessment for Program 3 related to soil amelioration products and technology (Activity 5)

Activity 5 had two components, Part A was an economic analysis of investing in soil constraint amelioration, and Part B was the development of a short document (presented as the Executive Summary in this Final Report) that was informed by the Scoping Study 3.3.01 findings in consultation with a (pre-identified) panel from the Soil CRC (including Program Leaders 2, 3 and 4, and the Scoping Study Leader for 3.1.0.1). Part A is presented in this section (4.5).

Part A: Economic Analysis of Investing in Ameliorating Soil Constraints

This activity was led by Dr Bill Malcolm (The Agricultural Economics Group) with support from Tristan Wardley (University of Melbourne), and input from Dr Roger Armstrong, Dr Susan Orgill and 'theme' leaders.

The aim of this activity was to apply a farm economics approach to analysing the potential benefits and costs of interventions in soil management to lift constraints to production in cropping and grazing systems.

Role and importance of economic analysis in the context of soil amelioration

A major area of research in Australian agriculture is investigating the options for ameliorating soil constraints to crop and pasture production. An important component of this work is determining the benefits and costs of managing such soil constraints.

The goal of farmers is to use the resources they control to create choices by building wealth. Profit is a means to these ends. Output of grain and dry matter for livestock from farmland is the means to making profit from the land that is managed. Farmers need information about the potential for investments of capital and management into ameliorating the effects of constraints on crop and pasture land to be a good investment. Good investments earn a return on the extra capital invested that have a good chance of being better than alternative investments, on-farm and off, and considering the risks involved in such investments. Once a technical/management innovation has been demonstrated to overcome a soil constraint to production, the economic merit of the change has to be evaluated. This involves identifying the extra costs, extra benefits, net benefits and the risk. Risk here is defined as; expected variability of extra yields and income around the mean over the life of the amelioration or innovation.

Conducting economic analysis of amelioration or technical innovations in farming systems is challenging due to the detailed information required about the system and the changes in output from the changes in inputs (response functions). Scientific research done well produces response functions that are required by economic analysis and which can be used in the analysis of representative farming systems (e.g. soils of defined characteristics and constraints). However, much of this detail often remains unknown and making decisions about investing in farming systems remains a challenge, with well-informed 'best bets' often the result. Often there is uncertainty surrounding how a well-researched innovation will perform in a farming system context. Farm economic analysis can overcome this uncertainty and inform next- and end-users of research (i.e. decision-makers). To this end, various techniques are used: partial, whole farm budgets and farm investment budgets incorporating risk analysis. In the face of uncertainty about how an innovation might perform in a farming system, ‘Threshold Analysis’ is recommended. This is where for a given innovation with well-established costs, the benefits that would be required for this investment to be a good investment are defined. That is, the benefits that represent a return on capital that exceeds alternative uses of the extra capital invested and with acceptable risk.

Farm economic analysis also has a role in screening investments in agricultural Research, Development and Extension (R, D & E) according to the likely net benefits of the investment overcoming problem (e.g. the soil constraint). As with the analysis of investment at the farm level, budgets and threshold analysis can be used to estimate potential industry-wide and public benefits of investing in science to solve problems in agriculture. In this report, case studies are used to demonstrate the methods of analysing innovations to ameliorate soil constraints, specifically, (i) the marginal activity gross margin and threshold analysis method, (ii) investing in a liming strategy to reduce soil acidity, and (iii) investing in clay addition to sandy soils incorporating a risk budgeting technique.

Key outputs included in this section

- Criteria for judging whether an investment in soil constraint R, D & E is justified
- Detail the farm economic approach to analysing investing in R, D & E to ameliorate soil constraints (including the Threshold method when costs are known and benefits are unknown, as well as the Marginal Gross Margin concept)
- Provide three case studies: soil amelioration in a high rainfall zone, liming soil to overcome acidity and clay incorporation on sandy soils.

Evaluating proposed investments in agricultural Research, Development and Extension

One way of evaluating proposals to invest in agricultural R, D & E is for a small group of people with science, extension, economics and farm systems disciplinary expertise to work separately and collectively to form a view about the worth of a proposed investment.

Information about the magnitude of the proposed investment will largely determine the extent of formal analysis that may be warranted. An investment that is relatively small in the context of the whole portfolio of investments will not warrant the same level of ‘resources’ in analysing the investment as an investment that is much larger. Relatively small investments will be done mostly qualitatively; relatively large investments will warrant considerable quantitative analysis of expected benefits and costs.

Step 1 Fit with Strategy and Right Agency

The proposed research must fit with the ‘Strategy’ of the organisation, and the organisation must be the ‘Right Agency’ to address the problem. Step one would be determined by organisation management.

Step 2 Market Failure Narrative

This step involves establishing the reasons why inadequate quantities are supplied of the good or service that the investment proposes to deliver. The case that markets are not supplying the required quantities of the good or service in question is based on the characteristics of the good or service and of the relevant markets that cause the market to fail. The characteristic of market failure implying a possible role for government is that from the private perspective the costs of supplying the good or service exceed the benefits, such as in the case of public goods, unintended spill over effects from an economic activity, asymmetric information between agents, and economies of size and scale effects on producing the good or service.

The details of each case are presented to establish that without investment there will be insufficient quantities of the good or service in question supplied. If this is the case, then the justification for the CRC and partners investing in this area is established on the basis that the benefits of this investment are likely to exceed the cost, including the opportunity cost of the resources, and considering risks involved. This is done in Steps 3-10. Step 2 would be mostly informed by economics expertise.

Step 3 Science Test

Scientists and extension specialists form a judgement that the proposed R,D or E activity is sound in terms of their disciplines. That is, the research problem is genuine and important; the research questions are appropriate; the research design and method is sound. Step 3 would be fully informed by science and extension expertise.

Step 4 Adoption, Benefits, Costs, Risks

Steps 4 would be a collective effort, though individual members of the research appraisal team may do quantitative analysis if it is warranted.

<u>Industry</u>

This question concerns the size of the industry. The aim is to establish the significance of the relevant industry in the Australian economy, to give a sense of perspective. An agricultural industry that constitutes a large Gross Value of Agricultural Product compared with many other agricultural industries signifies this is an industry in which producers have had and currently have a comparative advantage. An estimate of the total population of producers in the industry, and of the proportion of these producers to whom the R,D or E may be relevant is useful as this forms the basis for considering potential adoption and size of benefits (for example, scale (area), amount of marketable ‘yield’, value of production (increase in $) etc).

<u>Benefits</u>

The form of the benefits of the innovation that is the subject of the R,D or E investment needs to be defined well. This involves setting out in considerable detail how the innovation would change the farm system in which the innovation is to be adopted. From this, the beneficial changes are identified. Only the primary (direct) extra benefits are relevant here; subsequent rounds of effects, called secondary benefits or multiplier effects, are not included.

Value of Net Benefits

The focus is marginal (extra) benefits and marginal (extra) costs of changes in the farm system of the adopter. An extra benefit can be extra income or reduced costs, noting that a loss that would occur in the future if an action is not taken, and which is thus avoided if an action is taken, is included as a benefit. Changes in the risk, or volatility of future streams of net benefits too, come into the decision. The net extra benefit in the farm system is the value to use in further analysis. The marginal net extra benefit is the sum of total extra benefits minus total extra costs, including costs of implementation of the change. The highest probability values should be used, with some consideration of the likely range around these values.

A simple change to a farm system can be estimated with all extra costs and extra benefits happening in the same time, as an approximation of the extra benefits and costs for each year of the life of the innovation. More complex changes involve a run of years before the innovation is fully operational (i.e. steady state). The extra net benefits at farm level in the steady state is used when looking at industry-wide adoption.

Secondary Effects

Positive secondary effects need considering. If an innovation reduces a negative technical externality from a system, this is a positive secondary benefit. Secondary effects should be identified. However, secondary economic effects, such as increased economic activity in a region because of the innovation, are not usually genuine social benefits and should not be counted in total benefits. This is because, with fully employed resources in the economy, increased economic activity in one region comes at the expense of existing economic activity somewhere else.

Adoption and Total Benefits

This involves using estimates of the net gain per farm system from the innovation and applying this to an estimate of the potential population of adopters from the relevant population of potential adopters. Extra net benefit per system multiplied by the number of adopting systems over time gives an estimate of potential total net extra benefit from the investment. Note that if estimated over time, the sum of net benefits at system level minus R, D & E costs will give a value for total extra net benefit expressed as a net present value, using some defined discount rate. For research investments, where returns can be high, 10 per cent real discount rate could be used. The NPV indicates the size of the net benefits. These will be shared through the economy between producers and consumers.

Costs

The primary (direct) cost of the investment is the total dollar sum proposed to conduct the R, D & E activities. This should also be set out per year for the life of the investment.

Secondary Costs

These are extra negative externalities, or reduced positive externalities, that could result from adoption of the results of the R, D & E. These externalities are of a technical or non-pecuniary nature, such as increased pollution. Reduced economic activity in an area is not a genuine secondary cost unless the resources affected are to be permanently unused forever.

Risk, Benefits and Costs

The approach to risk involves being honest, complete and rigorous. Identify all the sources and types of risk and how these affect the key variables in the proposal. Consider likelihoods.

If formal quantitative analysis is done, then the implications for the estimates of benefits and costs of variation around the mean of key variables such as yield and price and key costs can be investigated. If qualitative analysis is done, then a view needs to be formed about the likelihood of the identified net benefits occurring over the life of the investment, such as high probability (5/1 on), low probability (5/1 against), even money bet etc.

Set out all the information and have the panel assimilate, consider, form a judgement and rank.

Threshold analysis

A very useful approach to evaluating an investment in agricultural R, D & E, where costs are often well-known, and the benefits and risks are less well-known, is the Threshold (breakeven) approach. Threshold analysis is used to provide a base level of quantitative information about a project by providing specific numbers on the scale and scope of impact (change) needed for the benefits to exceed costs (e.g. White, 1999). Providing information in terms of a threshold, puts focus on the change required (e.g. both the level of change and when it takes place), to generate benefits needed to achieve a target rate of return given the investment cost. Threshold analysis can be tackled as a three-stage process:

1. *Costs*

Estimate the cost of the project and ongoing costs required after the project ends, for example for maintenance of tools developed within the project, extension to increase adoption. Project costs can generally be estimated more easily than the benefits that may flow from the investment.

2. *Size and pattern of cumulative extra benefits*

The size and pattern of adoption and an associated annual R, D&E expenditure that would be consistent with the defined rate of adoption is estimated and included as an annual cost. The annual benefits over the life of the investment, consistent with the adoption pattern, is estimated which will enable the investment to earn the required return. For example, consider a 5-year R&D project. The investment has a required rate of return on capital of 10% p.a., with 10% of annual benefits expected to be adopted by year 6 gradually increasing to 100% of the proportion of total population that will adopt (e.g. 20% of total) by year 15 (10 years after the end of the project). The peak may be maintained for several years and possibly decline towards the end of the life of the innovation, say 25 years. This would be several years after most adoption has occurred and/or a time after which it could be considered this R&D research would have been done.

Having defined the likely pattern of flows of farm net benefits over the life of the innovation and the size of total annual net benefits that is required for the R, D&E investment to earn the required rate of return, the next step is to estimate the number of farmers that will adopting the new technology/practice each year. This number is then divided into the required total annual net benefits of that year to give the required net benefit per farmer per adopter-year.

3. *Assessing the likelihood of achieving the required extra net benefits*

In this stage, form a judgement about the likelihood that the required net benefits at farm level can be achieved. This in turn gives an indication about the likelihood of the investment in this particular R, D & E generating the returns required for it to be a good investment.

This narrative cannot be applied to average data from farm survey information. The 'story' can only be told in terms of marginal changes that will result in whole farm systems, as a consequence of this investment.

Threshold analysis requires researchers to make their assumptions explicit and available for critical review before an investment is made. It provides the opportunity to think about whether these assumptions and the opportunity for benefits to exceed the costs are realistic and achievable. The plausible counterfactual case (that is, the likely outcome if the investment were not made) must also be made apparent when the scale and scope of impacts are described.

To quantify the threshold values, the screening criteria includes questions to identify the potential target of potential adopters to whom the research is relevant. Using this information, and assuming a level of adoption across the potential range a threshold for the annual community benefit per unit of impact could be estimated.

The information from threshold analysis is intended to support a discussion around effectiveness and efficiency: how realistic the expected community benefits are; the likelihood of the research realising such benefits; and whether the estimated threshold values for the community benefits are acceptable to the public. The likelihood of a project achieving the stated community benefits can scaled as high, moderate or low. The scaling would be based on information provided in the screening criteria about the level and type of change expected and the logical links between project activities and the expected change. These rankings need to be based on consensus from experts and relevant research managers about how realistic or strong the assumptions involved.

Included in information in the screening and threshold analyses is judgements about relative risks of alternative investments, with risks encompassing (i) risk of the research being successful in achieving its stated objectives, (ii) risk associated with the identification and the size of the benefits which encompasses variability around the mean yields, prices and assumed rates of adoption and (iii) risk associated with the identification and size of the costs in the analysis.

The appropriate risk analysis approaches are akin to the standard approaches used in private investment analysis, viz: probability analysis, scenarios, sensitivity testing, thresholds. Ultimately, in the face of risk and uncertainty, the investor can only be brutally honest, rigorous, complete and transparent about what is known, what occurrences lend themselves to forming probabilistic judgements about likelihood, and what aspects of the investment are unknowable.

Investing in research, development and extension to ameliorate subsoil constraints

Constraints limiting the profit from cropping are frequently of a physical or mechanical nature, i.e. too much or too little of something, such as lime, gypsum, water, root penetration of subsoil, soil porosity. Physical interventions (or ameliorations) have developed to change biophysical conditions of the soil that are limiting crop performance (assuming that no other constraint is present e.g. water), such as adding lime or gypsum, delving, forming raised beds, subsoil manuring, deep-ripping, adding clay or drainage.

The key criterion when making decisions about adopting innovations at farm level is the extent the innovation might help an operator/owner achieve their goals? Common goals include: (i) making profitable use of resources, (ii) having sufficient cash to meet needs, and (iii) increasing net worth over time, all within a range of acceptable risk. Extra costs, extra returns and net gain from a proposed change are estimated to indicate whether a proposed change contributes sufficiently to meeting farmer goals.

Integral to forming judgements about the merit of investing in R, D & E to reduce soil constraints to marketable yields (and quality) is information about the potential size of benefits at farm level and the likely costs of achieving them. Generally, a reasonable amount is known, or can be estimated, about the costs of implementing these types of interventions. In contrast, the possible benefits of various interventions on crop yields, as measured from experiments or in the field, is often not well known, is always seasonally and spatially variable, and unique to each farmer and their farming system. The extra yield of crop and pasture produced by a soil management intervention needs to cover the opportunity cost of the extra capital invested and the extra annual costs associated with producing the extra yield. The opportunity cost of the capital is the net return that it could earn in another use with similar risk, on-farm or off-farm.

The availability of credible information and data about the net benefits of soil intervention practices determines the analytical approach to use. When benefits are unknown, the Threshold approach is useful. When considering investing in R, D & E in ways of ameliorating subsoil constraints to production, the threshold approach involves the following steps:

i. Estimate the investment per hectare associated with a selection of soil management interventions that potentially could increase yield of crop and pasture, as well as the likely life of the investment.
ii. Calculate the corresponding extra activity gross margin per hectare and per tonne, and per rotation hectare and per rotation tonne, that would be required to earn a required return on capital, for the capital invested to ameliorate constraints to yields of the crop or livestock activities in a 'generic' regional cropping rotation. (Note: this is marginal gross margin, not pre-existing average gross margin).
iii. Calculate the extra yield per hectare that would be required to produce the marginal gross margin per hectare and per tonne required.
iv. Consider research and field evidence about ways the extra yield required to make the change to soil conditions worth investing in, could be achieved in practice.
v. Consider the likelihood of these required extra yields and extra gross margin being able to be achieved.
vi. Use the information generated to form a judgment about the merit of the intervention to ameliorate a subsoil constraint.

For some interventions, in some years over the life of the investment, no extra net benefit above the 'do nothing different' case will be received from the treated area. Some soil management interventions will have logical biophysical explanations for the likelihood of there being extra yields or no extra yields, depending on the type of season. For example, interventions aimed at reducing waterlogging may have no benefits in dry seasons, or less benefit than in a wet season. Understanding when and by how much yields can be expected to vary under different seasonal conditions, enables estimates of the potential distribution of yields and likelihood of achieving the yield required to provide an acceptable ROC, that are more realistic than using average values. To this end, risk analysis is used, such as using a discrete selection of years in which benefits could occur and not occur over the run of years being analysed. Or, using probabilistic analysis such as the @Risk add-in to the Excel spreadsheet. Distributions of extra gross margin/rotation/ha are used to capture the reality that in some years the extra gross margin per rotation hectare and rotation tonne will be low or even zero, and in other years it can have a range of positive values.

Another factor to incorporate in the analysis is if the effect of the intervention declines over time and the extra yield response to the intervention declines over time i.e. 'residual value'. When this is likely an estimated of the annual decay rate of the yield response to the investment is included. If salvage value of the initial capital invested is assumed to be zero at the end of the planning period, and an annual decay rate is not included in the extra yield effects, and the required annual average benefit is estimated, then the average annual benefit that will be achievable in practice will be less in the latter part of the life of the intervention than in the earlier years.

The feasibility of achieving the extra yields required to justify the investment to ameliorate soil constraints to cropping can be judged by considering real world evidence about the crop yields achieved by farmers who have adopted the changed farming methods in question. The evidence about achievable extra yield and views of experts about the likelihood of achieving these required yields is the key to judging the merit of investing to ameliorate subsoil constraints.

Evaluating investment in R,D&E to address multiple soil constraints

Consider a proposed investment in a R,D&E program that aims to investigate multiple subsoil constraints. The proposed projects have been rated as passing the tests of (i) fit with strategy, (ii) market failure, and (iii) good science with good probability of the research succeeding.

Suppose the investment is $1M per year for 5 years, accompanied by $400,000 per year invested in development and extension. The opportunity cost of the capital to be invested in the R, D&E is 10% real.

The life of the outputs of the R, D&E investment is 20 years, starting from year 6. The relevant population of potential adopters of the output is 20,000 farmers. Peak adoption will be 25% of the potential adopters and this reached by year 20. A linear rate of annual approximation of adoption occurs from year 6 to year 20, with dis-adoption at 3% p.a. from year 21-25.

The key question is: 'how much net benefit is required for each adopter for each 'adopter-year', for the investment in R, D&E to earn 10% return on capital?' The answer is: '$500 net benefit per adopter per year of adoption gives 10% return on the investment in the projects in this program'.

The subsequent question is: 'How, specifically, in their farm system, would an adopter gain a net benefit of $500 per year from adopting the innovation(s) that arise from this R, D&E program?' In answering this question, the scientists are required to provide a plausible narrative about how their R, D&E delivers changes and net gains in the farm systems that the R, D&E aims to help. This question is evaluated in the context of the farm systems involved, the nature of the innovation(s), the costs involved at farm level in implementing the innovation, and the risk adjusted extra benefits that are expected to result.

Following consideration of these matters, a view can be formed about the likelihood of the net benefits per adopting farmer being equivalent to an average of $500 per year. If this is considered to have a reasonably good probability of being achievable, then there is a reasonably good chance that the investment in the R, D&E will earn the required 10% return on investment.

Benefit is the Activity Marginal Gross Margin of the Marginal Rotation Tonne of the Changed Situation, not the Activity Extra Average Gross Margin/Ha of the Status Quo situation

There are several key points to make. First, when considering a change to a cropping system, the returns from changes in yields and gross margins of activities in the cropping system are (i) assessed in terms of the rotation in which the crop activities are grown, with all parts of the rotation across the farm in each year and (ii) if crop activity gross margins are the basis of the comparison, the implicit assumption is being made that there are no implications for extra machinery and equipment required after the investment to change soil condition. If capital changes are involved, a partial budget is required.

Second, the additional benefits from a crop activity are the net result of the combined effects of the intervention on yield, gross income and costs.

Third, the way the extra net benefits are measured depends critically on the detail of each situation. That is, the counterfactual of the case. The counterfactual is the circumstances that would exist in the paddock and farm system in question without the proposed investment. In the first instance, the example given below is for the case where the system comprises an all-crop rotation of canola, wheat, barley and faba bean. For situations where the rotation includes livestock, or where the investment makes it possible to crop a paddock that hitherto only ran livestock, or change the mix of livestock and crop in a system, estimating the extra net benefit involves more than the change in marginal gross margin. A partial budget is used because livestock gross margins include capital aspects such as animal depreciation and appreciation while crop activity gross margins include only variable costs.

Marginal activity gross margin (Crop-only rotation, only crop activity gross margins per hectare and per tonne change)

An investment to increase yields of crop activities that increases yield will have associated extra annual crop growing costs. But, not all variable costs will increase. Suppose the activity average gross margin of a wheat crop before the intervention is as shown in Table 32 below.

Table 32: Wheat Gross Margin (Source: Farm Gross Margin and Enterprise Planning Guide 2018 GRDC/Rural Solutions).

										2018 YOUR ESTIMATE
INCOME										
		Rainfall Zone			*LOW*		*MEDIUM*		*HIGH*	
Price (18/19 Forecast)					$245		$245		$245	
Quality	APW (Change Price for other grades)									
Yield (t/ha)					1.5		2.7		4	
GROSS INCOME					**$368**		**$662**		**$980**	
VARIABLE COSTS	Cost			Rate/ha Low	$/ha	Rate/ha Medium	$/ha	Rate/ha High	$/ha	
Seed										
Seed	$0.24	/kg	@	60	$14.40	80	$19.20	100	$24.00	
Seed Treatment(1)	$0.04	/kg	@	60	$2.33	80	$3.10	100	$3.88	
Seed Treatment(2)	$0.07	/kg	@	60	$4.29	80	$5.72	100	$7.15	
Levies										
GRDC Levies	1.0%	Gross Income			$3.68		$6.62		$9.80	
EPR & state levies	$3.50	/tonne sold			$5.25		$9.45		$14.00	
Fertiliser (Bulk)										
18:20:0	$660	/tonne	@	40	$26.40	60	$39.60	80	$52.80	
Flutriafol (on fert)	$26.00	/litre	@	0.2	$5.20	0.2	$5.20	0.2	$5.20	
Urea	$480	/tonne	@		$0.00	80	$38.40	160	$76.80	
Chemicals-*Herbicides*										
Summer Weed Control		Various	Allow		$25.00		$25.00		$25.00	
Pre-emergents										
Trifluralin 480g/L	$5.75	/litre	@	1.5	$8.63		$0.00		$0.00	
Tri-allate 500g/L	$9.58	/litre	@	1.6	$15.33		$0.00		$0.00	
Glyphosate 540	$6.00	/litre	@	1.2	$7.20	1.2	$7.20	1.2	$7.20	
Carfentrazone 400g/L	$190.00	/litre	@	0.02	$3.80	0.02	$3.80	0.02	$3.80	
Sakura	$340.00	/kg	@		$0.00	0.118	$40.12	0.118	$40.12	
Post-emergents										
Topik (3)	$38.80	/litre	@			0.085	$5.62	0.085	$5.62	
M.C.P.A. LVE	$8.85	/litre	@	0.5	$4.43		$0.00		$0.00	
Metsulfuron methyl(4)	$0.06	/gm	@	5	$0.72		$0.00		$0.00	
Clopyralid 600g/L	$39.60	/litre	@	0.04	$1.58	0.04	$1.58	0.04	$1.58	
Affinity®	$122.50	/litre	@		$0.00	0.1	$12.25	0.1	$12.25	
MCPA Amine (750g/L)	8.75	/litre	@		$0.00	0.33	$2.89	0.33	$2.89	
Fungicides										
Epoxiconazole 125g/L	$17.00	/litre	@			0.25	$4.25	0.5	$8.50	
Operations										
Fuel & Oil					$10.78		$12.94		$15.09	
Repairs & Maintenance					$15.76		$18.92		$22.07	
Freight										
Grain (t)	$20.00	/tonne	@	1.5	$30.00	2.7	$54.00	4.0	$80.00	
Fertiliser (t)	$20.00	/tonne	@	0.04	$0.80	0.14	$2.80	0.24	$4.80	
Contract Work										
Aerial spraying	$14.00	/ha	@		$0.00	1	$14.00	2	$28.00	
Urea spreading	$8.50	/ha	@		$0.00	1	$8.50	2	$17.00	
Insurance	$8.50	/$1000	@		$3.12		$5.62		$8.3	
Other	$0.00	/ha								
	$0.00	/ha								
TOTAL VARIABLE COSTS					$189		$347		$476	
GROSS MARGIN/hectare					**$179**		**$315**		**$504**	
Break Even Price (to cover variable costs only)					**$126**		**$128**		**$119**	
Break Even Yield (to cover variable costs only)					**0.77**		**1.42**		**1.94**	
Gross Margin based on last 5 year average price					**$189**		**$334**		**$532**	

COMMENTS	*AGRONOMIC NOTES*
(1) Smuts and Bunts (2) Aphid Treatment (3) Includes Oil @ 0.5% (4) Includes Surfactant at 0.1%	Nitrogen requirements will vary depending on individual paddocks- seek advice. If targeting higher protein, additional N inputs will be required.

From Table 32, for wheat produced in a medium rainfall zone, with an average yield of 2.7 t/ha, the average gross margin/ha is $315 and the average gross margin/t $117.

In Benefit Cost Analysis, only *extra* effects are counted. Which of the variable costs of the average crop activity gross margin will change with the extra tonnes of yield produced? If the intervention is not a direct fertiliser-related intervention, then the extra yield will only result if adequate extra fertiliser is also supplied. The *law of the minimum* is at work here: once the subsoil constraint is lifted, what is the next constraint that will need to be lifted to enable the extra yield. Greater grain yields may involve additional fungicide or pest control costs. The weed control costs may or may not change. Harvest, freight, levies, insurance are per tonne costs and these will increase with the extra yield. The variable costs of cultivation, sowing, spraying are essentially costs that vary with hectares covered, not with per tonnes of output, so will not change directly with yield increases. Seed costs would not change if the same kg/seed/ha is used, but would increase per tonne of extra yield if the kg/seed/ha rate increased in the changed post-investment setting.

The benefit:cost way of thinking about the marginal gross margin per hectare and per tonne when evaluating a change is to allocate the total variable costs per hectare of the average gross margin to the unchanging per hectare variable costs, and to the variable costs that vary directly with yield. Only the variable costs per tonne change with the extra yield resulting from the change to the system that increases yields. When this is the case, the marginal gross margin per tonne will be greater than the average gross margin per hectare or per tonne of the pre-existing production. Recognising this has important implications for the economic evaluation of investments to ameliorate subsoil constraints to grain production.

From the above example, average gross margin per hectare for wheat ($315) and per tonne for wheat ($117), the marginal gross margin of the wheat component of the rotation is:

Wheat

A. Extra Yield 1 t/ha Gross Income	$250/t
B. Extra Yield-related Costs/t	
Fertiliser/t of grain	$15
Urea/t of grain	$15
Fungicides	$3
Harvest	$10
Freight grain	$20
Freight fertiliser	$5
Insurance	$2
Total Extra Yield-related Costs/t	$70
Marginal Gross Margin/t (A-B)	$180
Marginal Gross Margin/ha, extra 1t (A-B)	$180

If the rotation is canola, wheat, barley faba bean, the average gross margin/ha of canola (yield 1.5t/ha, $550/t) is $301/ha and $195/tonne.

The canola marginal gross margin/ha for an extra 0.5t/ha might be:

Canola

A. Extra Yield 0.5t/ha canola Gross Income $275 ($550/t)

B. Extra Yield-related Costs/t

- Fertiliser	$20

- Urea	$40
- Fungicides	$3
- Harvest	$10
- Freight grain	$20
- Freight fertiliser	$5
- Insurance $8/1000	$2
Total Extra Yield-related Costs/t	$130
Marginal Gross Margin/t (A-B)	$145
Marginal Gross Margin/ha extra 0.5t (A-B)	$145

Using the same method, suppose the average gross margin/ha and per tonne for barley and faba beans are:

Barley GM/ha $236, GM/t $81

Faba Bean $GM/ha $324 and $/t $180

If extra yield costs/tonne for extra barley and faba bean are $70/t for barley and $50/t for faba bean, and extra yields are 1t barley worth $220/t, and 0.5t faba bean worth $330/t, the marginal gross margin/tonne of grain for the other components of the rotation, barley and faba bean are:

Barley Marginal GM/ha	$150
Faba Bean Marginal GM/ha	$280

Crop activities can only sensibly be considered in the context of the rotation/sequence in which a crop is grown. The rotation marginal gross margin is explained below.

The average extra income per rotation/ha from the extra 0.5tC, 1tW, 1tB, 0.5tFb = ($275+$250+$220+$$227+$165)/4=$227.50

The extra variable yield cost per rotation/ha is ($130+$70+$70+$50)/4=$80

Marginal Rotation Gross Margin per Hectare (and per Marginal Tonne), on average over the life of the investment:

Marginal Rotation Gross Income/Ha	$227
Marginal Yield-related Rotation Variable Costs/Ha	$80
Marginal Rotation Gross Margin/Ha	$147

If extra yields of the crops in the rotation are 0.5tC, 1tW, 1TB and 0.5t FB, extra yield per rotation/ha is (0.5+1+1+0.5)/4=0.75t/ha. A marginal rotation tonne of a 4-part rotation is the sum of the extra yields of each component of the rotation, divided by 4.

Marginal Gross Margin per Extra Tonne of per Rotation/ha of 0.75t/ha = $147/ha.

Below in Table 33 is a summary of the above calculations, for the ‘before change’ case and the ‘after change’ case.

Table 33: ($) Summary of Average and Activity Marginal Gross Margins

(Before Change)	Av. Gross Margin/ha ($)	Av. Gross Margin/t ($)	(After Change)	Marginal Gross Margin/ha ($)	Marginal Gross Margin/t ($)
Canola	351	195	Extra yield 0.5t	145	145
Wheat	315	116	Extra yield 1.0t	180	180
Barley	236	81	Extra yield 1.0t	150	150
Faba bean	324	180	Extra yield 0.5t	280	280
Rotation	306	139	Extra yield 0.75t	147	147

The annual average marginal gross margin per rotation/tonne is $147 in this example. This is key information when using the threshold approach to judge the worth of an investment that increases the tonnes of grain produced per hectare. This extra gross margin per hectare needs to have a high probability of being achieved, on average over the life of the investment, for the investment to earn the required rate of return and be a ‘good investment’.

In the example above the presumption is that the intervention has not altered the variable costs of growing the crop and achieving the yield/ha that was possible before the intervention. If the intervention has the effect of reducing the variable costs of the pre-intervention crop regime, such as reducing fertiliser requirements/ha for several years as happens with subsoil manuring, then the saving in fertiliser costs are included as an additional benefit. If the intervention makes possible a different cropping regime, then the rotation gross margin of the new crop system per ha and per tonne are compared with the *status quo* case. If the intervention brings about further changes that are attributable to the change condition of the soil, such as requiring extra machinery and equipment, then annual extra depreciation and ownership costs are included as additional cost as well, i.e. a partial budget, not an activity gross margin budget, is the relevant technique.

Investment that makes possible a change from grazing to cropping

In this case the cost of the change includes the activity gross margin from grazing that is given up and the benefit is the activity gross margin minus any additional annual capital costs (depreciation and interest on capital) involved in changing from livestock to cropping. A partial budget, not just gross margin analysis, is done to capture all the effects of this type of change. To be a positive change, the benefit from cropping needs to cover not only the investment cost but also the opportunity cost of the grazing activity that is now foregone by going into cropping, and the additional capital invested earns a return on capital that covers its opportunity cost, considering risk.

Investment that increases production from a grazing activity

If an investment to ameliorate a soil based constraint to pasture production enables an increase in livestock carrying capacity, the benefits can be valued as extra dry matter (DM) expected to be produced, with the extra DM valued at market values, either as replacing supplementary purchases that would otherwise be needed or as agistment values that DM sells for in markets. To use agistment values, a Dry Sheep Equivalent (DSE) required 3000 megajoules of metabolisable energy per year, and the ME of the extra DM produced is used as a guide to the extra DSEs that could be agisted at an agistment rate per DSE.

With livestock activities, the marginal gross margin will differ from the average activity gross margin(s) of the pre-existing livestock activity/activities. Unlike the cropping situation where some activity variable costs will not increase with increased yields, increased stocking rates and animal output per hectare will involve increasing all the same variable costs of the existing activity in direct proportion with stocking rate. With animal activities, feed and labour increase quite directly with stock numbers carried. Additional livestock carried because of extra feed produced by the investment to change soil condition will involve additional amounts of all the variable costs of an animal activity, plus in some cases some extra labour and as always extra risk must be accounted for. That is, because feed shortages are related to stocking rate, supplementary feed costs per head of the additional animals carried will have higher supplementary feed costs than the existing herd or flock. The marginal gross margin of increasing a livestock activity will be less than the average gross margin of the existing livestock activity.

Valuing net benefits of an investment over time

The income capitalization method of valuing an investment assumes that if the net benefit of an investment was a certain $100 per year in perpetuity, and if a 10% return on capital was required, then the investor could invest $1000 to earn the certain annual $100 net benefit and earn the required 10% p.a. return. Investments to ameliorate soil conditions have a range of lives: 5, 10, 15, 20 years or greater for some forms of investment. Analysis of such investments need to be done for defined possible lives, using discounted cash flow analysis. The appropriate discount rate is the opportunity cost of the marginal capital; in other words, the required rate of return.

Risk is accounted for in this type of analysis either by requiring a return on capital that includes a risk premium. Considering the required extra return as an annual average also includes some consideration of the reality that over a run of years the actual annual net benefits will be above and below this average. If these net benefits are normally distributed, over a run of years the extra annual net benefits would be above and below the required average.

CASE STUDY 1: Required extra net benefits on-farm for a range of interventions to ameliorate subsoil constraints, for a range of capital costs per hectare

Presented here is a ‘generic’ look at the yield affects required to justify investing a range of amounts to change the condition of soil. An example of the interventions considered and the per hectare capital costs are shown in Figure 10 below.

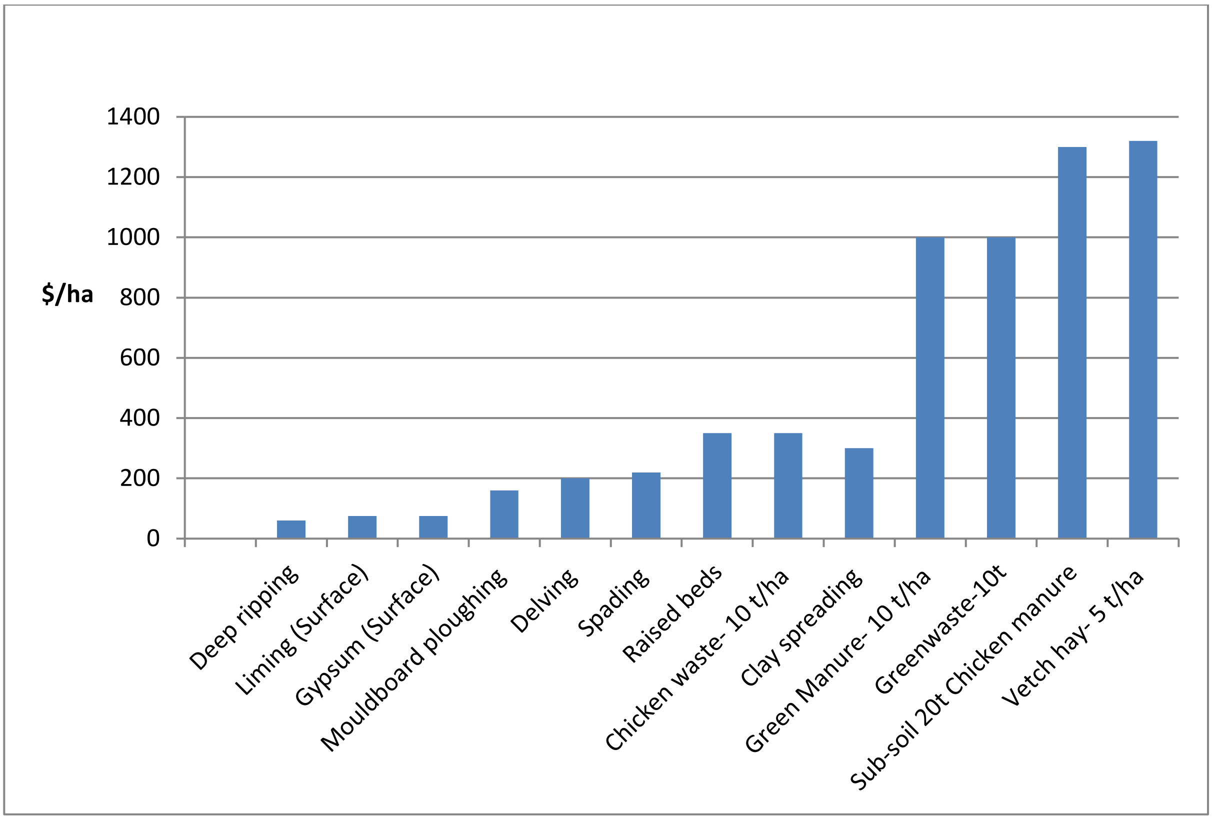


Figure 10. Costs of investment for a range of potential soil management interventions

Table 34 shows the extra yield of dry matter (DM; grain or pasture) required to be achieved as an annual average increase over the life of the investment, if the extra tonne of dry matter has a marginal annual gross margin (or extra net margin if other additional costs are involved above extra variable costs) of $100/tonne of extra DM, and the possible lives of the investment are from one year to 20 years. The investment criterion is that the investor has a required rate of return on the extra capital invested of 10% p.a. real, because of the risk involved. In cropping, $100 marginal GM/rotation/tonne and per hectare on average would be conservative, and $150 GM/rotation/tonne and per hectare would be realistically achievable. Note also that 10% required return on capital is required as a way of 'compensating' for the risk involved, i.e. 'risk-free' rates of return in the economy range from 3-5% real p.a.

Table 34 Extra t/ha Marginal Gross Margin Rotation/Tonne, DM is $100, 10% RoC

$/ha invested	**Years of Life of Investment**			
	5	**10**	**15**	**20**
Ripping, Liming 100	0.24	0.15	0.12	0.11
Delving, Spading 200	0.72	0.44	0.36	0.32
Clay incorporation 300	1.20	0.74	0.60	0.53
400	1.68	1.04	0.84	0.75
500	2.16	1.33	1.08	0.96
600	2.64	1.63	1.31	1.17
700	3.12	1.92	1.55	1.39
Chicken Manure 10t/ha 800	3.60	2.22	1.79	1.60
900	4.08	2.52	2.03	1.82
1000	4.56	2.81	2.27	2.03
1100	5.04	3.11	2.51	2.24
1200	5.52	3.40	2.75	2.46
Chicken manure 20t/ha1300	6.00	3.70	2.99	2.67
1400	6.48	3.99	3.23	2.88
1500	6.95	4.29	3.47	3.10

If the life of investment is 10-20 years, and $100 marginal GM/tonne of DM, the investor could invest $500-600/ha if it produced an annual average extra 1.3t/DM/ha. A shorter life of investment and higher investment cost/ha requires larger average increases in yield.

If the life of investment is 5 to 10 years, and $100 marginal GM/tonne DM, the investor could invest $300-$400/ha if it produced an annual average extra 1.3t/DM/ha.

Note that for an average of 1 tonne extra yield, if benefits are normally distributed with some years achieving below average yield and no extra yield, then this requires some years to deliver above the 1 tonne average yield. If over 10 years, one third of the time there was zero extra yield, e.g. years 3, 6, 9, then the other years would need yields of 1.43t/ha to average 1t/ha over the 10 years.

If 10-20 years life of investment, $150 marginal GM/tonne DM, and if invest $800-900/ha, then the investment earns the 10% real return on capital p.a., if an annual average extra 1-1.3t/DM/ha is produced.

If 5-10 years life of investment, $150 marginal GM/tonne DM, and if invest $300-$400/ha, then the investor earns the 10% real return on capital p.a., if an annual average extra 1-1.3t/DM/ha is produced.

If a marginal gross margin/rotation tonne of $150 is considered ‘reasonably’ achievable with ‘reasonable’ certainty, and the required return on capital does not include as great a risk premium as in the 10% required return case (Table 35) say if 7% return on capital is considered adequate, then the required extra yield required is shown in Table 36.

Using a 7% return on capital (Table 36), there is no yield risk premium in the discount rate, though a small risk premium for other unknowns. In this case the marginal GM/rotation/tonne and per ha is considered reasonably ‘safe’ and risk is represented mostly in the required extra yields. For this attitude to risk, accepting 7% return on capital, extra average yields of 1.5t/ha brings the high cost investments into consideration for the investment portfolio. This is particularly so if significant fertiliser savings are involved for a few years, as is likely to be the case with the subsoil manuring amendments.

To average 1 tonne extra yield over the life of the investment, if yields were normally distributed, would mean that half the time the extra benefit could range from zero extra yield to 1t/ha above the *Status Quo* and half the time above 1t/ha up to 2 t/ha. If in some years there will be no benefit above the *status quo*, in an equal number of years there would need to be a benefit of 2t/ha above the *Status Quo* (ignoring timing and discounting implications).

Table 35 Extra t/ha if Marginal Gross Margin Rotation/tonne DM is $150, 10% RoC.

$/ha invested	**Years of Life of Investment**			
	5	**10**	**15**	**20**
Ripping, Liming 100	0.15	0.09	0.07	0.06
Delving, Spading 200	0.40	0.27	0.21	0.18
Clay incorporation 300	0.65	0.44	0.34	0.29
400	0.90	0.62	0.48	0.41
500	1.15	0.80	0.62	0.53
600	1.40	0.98	0.75	0.65
700	1.65	1.15	0.89	0.76
Chicken Manure 10t/ha 800	1.90	1.33	1.03	0.88
900	2.15	1.51	1.16	1.00
1000	2.40	1.69	1.30	1.12
1100	2.65	1.86	1.44	1.24
1200	2.90	2.04	1.57	1.35
Chicken manure 20t/ha 1300	3.15	2.22	1.71	1.47
1400	3.40	2.40	1.85	1.59
1500	3.65	2.57	1.98	1.71

Table 36 Extra t/ha if Marginal Gross Margin Rotation/tonne DM is $150, 7% RoC.

$/ha invested	**Years of Life of Investment**			
	5	**10**	**15**	**20**
Ripping, Liming 100	0.15	0.09	0.07	0.06
Delving, Spading 200	0.40	0.27	0.21	0.18
Clay incorporation 300	0.65	0.44	0.34	0.29
400	0.90	0.62	0.48	0.41
500	1.15	0.80	0.62	0.53
600	1.40	0.98	0.75	0.65
700	1.65	1.15	0.89	0.76
Chicken Manure 10t/ha 800	1.90	1.33	1.03	0.88
900	2.15	1.51	1.16	1.00
1000	2.40	1.69	1.30	1.12
1100	2.65	1.86	1.44	1.24
1200	2.90	2.04	1.57	1.35
Chicken manure 20t/ha 1300	3.15	2.22	1.71	1.47
1400	3.40	2.40	1.85	1.59
1500	3.65	2.57	1.98	1.71

Saved Fertiliser Costs

If the investment in ameliorating soil condition has the additional effect of reducing the need for applying fertiliser to the crops for the early years after intervention, this is an offset against the initial capital cost, or an addition to the annual marginal gross margin/t and per ha benefit, and with a corresponding reduction in the extra yield that is required to earn the required return on capital. For example, for the case of a required 10% real return, with marginal gross margin/t and per ha of $100, investing $500/ha has a required average extra yield of around 1t/ha. If $100/ha of fertiliser is not required for the first three years, the effective initial capital investment cost is around $200/ha. The required increase in yield/ha per year over the 15-20 years life of the investment is reduced from around 1t/ha to 0.3-0.4t/ha.

CASE STUDY 2: Investing to ameliorate soil acidity

The negative effects of acidic soil layers have been researched extensively and are well-documented (e.g. Coventry et al 1989 and Slattery and Coventry 1993). The concentration of exchangeable Al in the soil decreases the capacity of the soil to neutralize H^+ ions. This is a measure of the pH buffering capacity of the soil, which in turn determines how much lime is required to change the soil pH. Water and nutrient use by acid-susceptible and even moderately acid tolerant plants is restricted, dictated by the 'law of the minimum'. Many wheat varieties, barley, canola and lucerne suffer yield penalties at pH_{Ca} < 4.7 in the top 10-20 cm of soil. Faba beans are constrained in soils with pH_{Ca} below 5.0. Research into applying lime to acid soils in northern Victoria and southern New South Wales on grain yield showed that applying and incorporating several tonnes of 'capital' quantities of lime per hectare (Conyers et al. 2003, Coventry et al. 1987, Scott et al. 1999) can have a residual effect of approximately 10 years. In north-eastern Victoria, research (Conyers and Scott 1989, Conyers et al. 2003) suggested that applying 2.5t/ha of lime and increasing pH_w by 0.5 to 1.5 units can produce extra grain yield (Coventry et al. 1987). An alternative way of deciding how much lime to apply is to consider the amount of lime required to counteract acidification that occurs because of each farm practice (Hazelton and Murphy 2007). The effective and economic quantities of lime required increases as rainfall increases, and as soil acidity increases.

A threshold economic analysis of liming acid soil follows. The lime has 0.15 mm particle size and a neutralizing value of 80% and costs $75/ha incorporated. The lime applied has a life of 10 years and the soil acidifies at a linear rate over the 10-year life of the lime applied. (This is a simplification – the decay rate is likely to not be linear). Benefits from applying the lime are achieved 7 years in 10; in 3 years in 10 the seasonal conditions are such that only reduced yield will be achieved, with or without the lime.

The analysis assumes an application rate of 1 to 4t of lime/ha, extra Dry Matter (DM) produced – grain for crops or pasture – has a Marginal Gross Margin Rotation of $100/t and the added output has no other cost implications for the farm system. The farmer is interested to know whether putting lime on this soil in this way and producing extra tonnes of DM and Marginal GM Rotation/tonne change is a good investment on the farm. The farmer rates an investment on the farm as 'good' if it earns a 10% p.a. on the extra capital invested over the life of the investment.

The economic analysis calculates the extra yield of DM (with a Marginal GM Rotation of $100/t) required for the investment in lime to earn the required 10% p.a. on extra capital. The extra kilograms of DM could be extra yield or avoidance of the loss of the yield that would have occurred if the lime is not applied. The required extra kilograms of grain harvested or pasture consumed is shown in Table 37 and Figure 11.

Table 37 Extra kg DM/tonne (Grain/Pasture at Gross Margin $100/tonne) required to earn 10% RoC, 7 years benefit in 10, 3 years in 10 no benefit

GM $/tonne	t/lime/ha	Kgs extra DM/ha GM/$100/t DM	% of Average yield of 2.5t/ha.
15	1.00	150	6.00
23	1.50	230	9.20
30	2.00	300	12.00
38	2.50	380	15.20
46	3.00	460	18.40
53	3.50	535	21.40
61	4.00	612	24.48

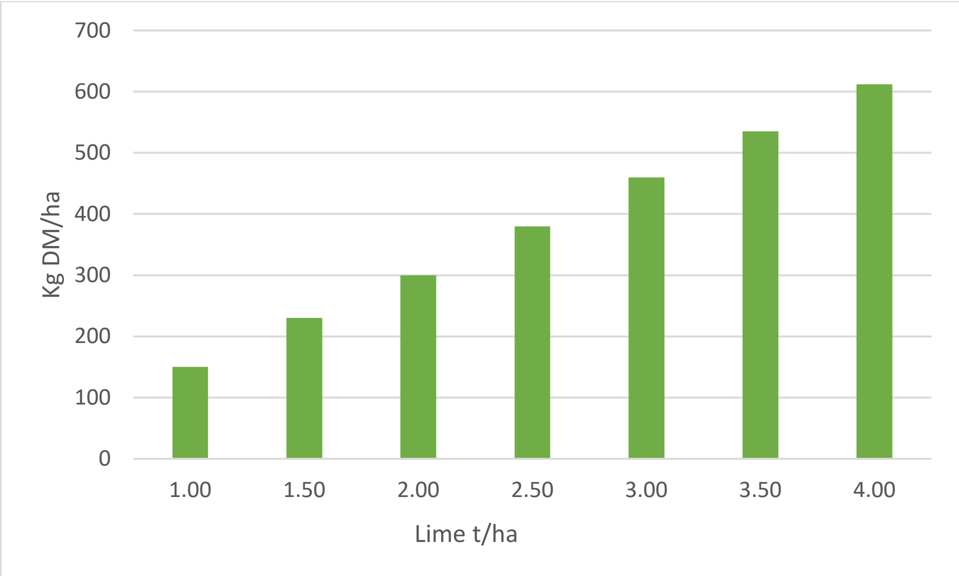


Figure 11. Extra DM/tonne required to earn 10% return on capital, risk weighted with 3 years of no benefit

For this example of applying lime, if the reduction in acidity results in sufficient extra yield of grain or pasture, or if a loss is avoided of grain or pasture that would occur with increasing acidification if lime is not applied, the investment earns the required 10% p.a. on the extra capital invested. In this case for a common range of applications up to 4t/ha, the required increase in Marginal Gross Margin/tonne and per ha is $15-$60/ha, or 150-600kg DM (grain or pasture) extra yield ha a 5% to 25% increase on an average yield of 2.5t/ha.

The next step is to weigh up under what soil, crop and pasture conditions, and how likely, it would be that the addition of these various amounts of lime (with life of 10 years, linear decline in pH) would achieve the required average extra yield 7 years in 10 to financially justify the investment. To this end, research relevant to the region, paddock and crop/pasture in question is investigated to inform a judgement about the economic merit of investing to ameliorate acid soil in a specific case of paddock, crop, pasture, farm system, or conversely, to identify the conditions that would make the amelioration practice feasible, such as at the renovation of a new pasture.

Research by Coventry et al (1989) and Slattery and Coventry (1993) in north-eastern Victoria established information about (i) the quantity of lime required to change the pH of a range of soil types and (ii) the effect on yield of a change in soil pH for a range of crops (Figures 12, 13 and 14, and Table 38).

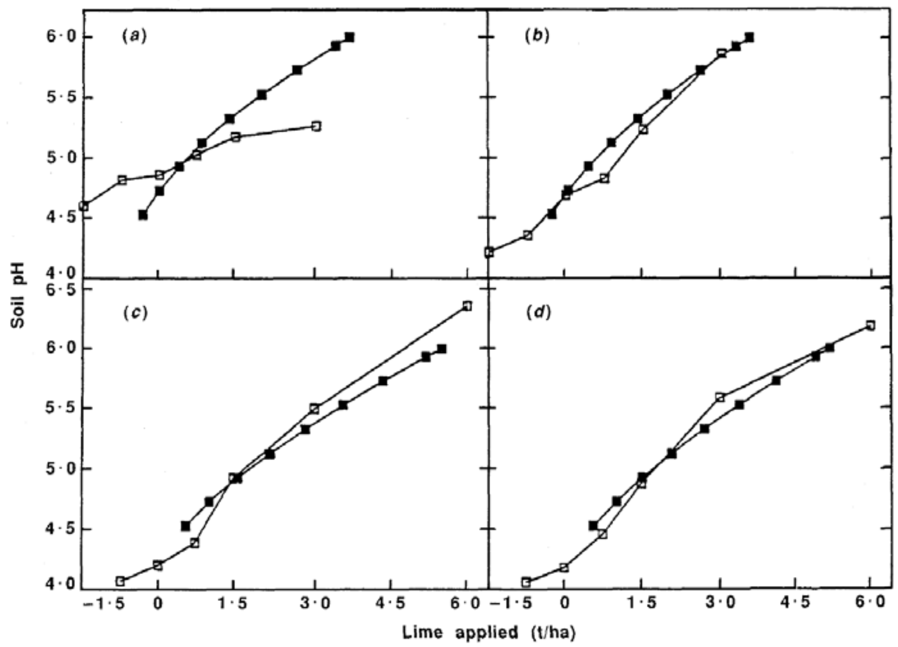


Figure 12. The relationship between lime applied and change in soil pH on 4 soil types. Lime rates were determined from the Hochmann et al. (1989) predictive model (n) and from field lime trials (l7). Soil (a) was a Sodosol (solodic), (b) Chromosol (red brown earth), Sodosol (red podsolic solodic), (d) Kurosol (podsolised red earth). (From Slattery and Coventry 1993).

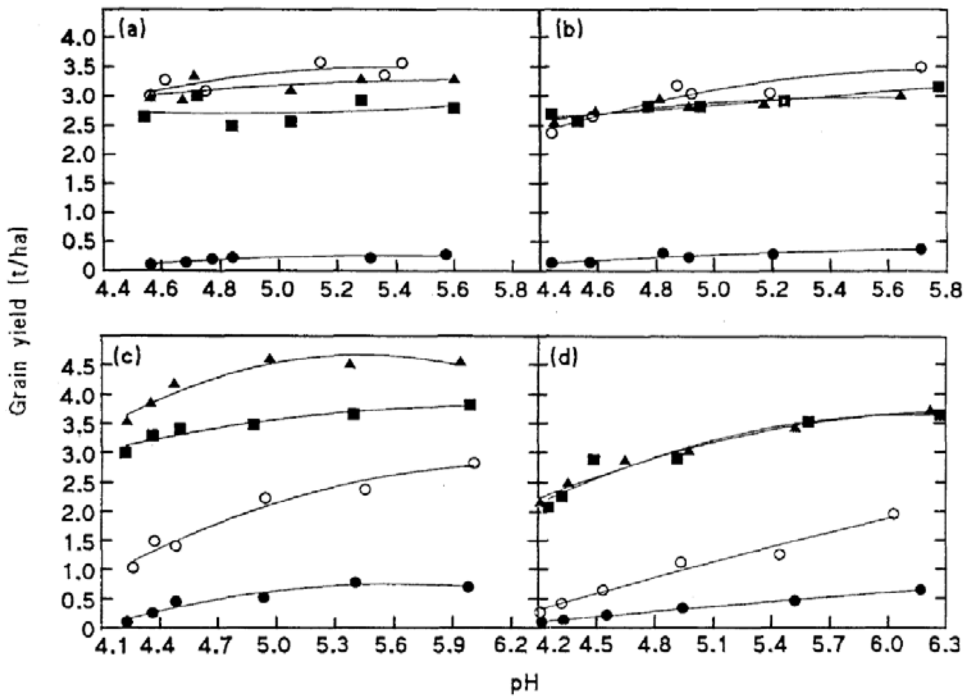


Figure 13. Amount of lime (t/ha) required to raise soil pH from base levels of 4.2, 4.4, and 4.6 to pH 5.5 for three soil groups for acid sensitive crops with subterranean clover (Option 4). (From Slattery and Coventry 1993).

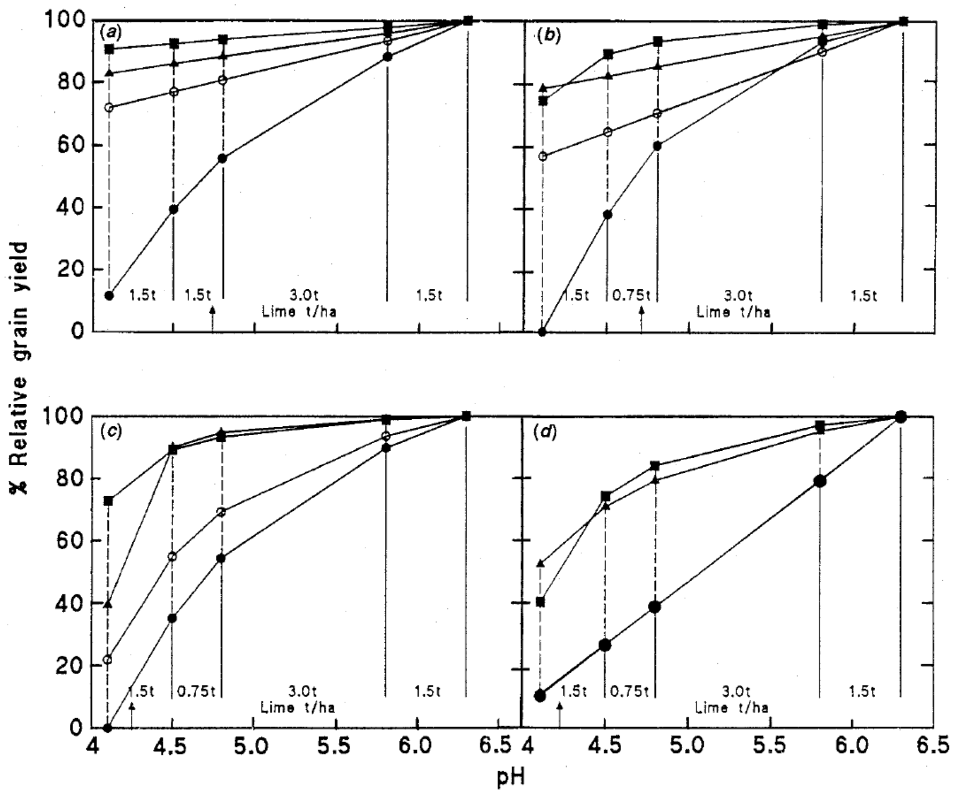


Figure 14. Lime requirement curves for percentage relative grain yield for triticale (A), wheat (m), barley (o), and canola (e) on 4 soil types [(a) solodic, (b) red brown earth, (c) red podsolic solodic, (4 podsolised red earth] at different target pH values.Lime rates indicated between vertical pH lines represent the amount required to increase the pH of the soil. The original soil pH for each site before treatment with lime or sulfur is arrowed. (Source: Slattery and Coventry 1993).

Table 38 Crop responses to lime from 1992 to 2003, (Li and Conyers 2006)

Treatment	Phase	Crop	Limed treatment	Unlimed treatment	Lime responses	
			(t/ha)	(t/ha)	(t/ha)	%
AP/C	Phase 2,4,6	Wheat (1992-2003)	3.01	1.45	1.56	107
PP/C	Phase 4	Oats (1993-1996)	2.48	1.96	0.52	26
		Triticale (1997, 1999-2003)	2.77	1.88	0.89	47
		Canola (1998, 2000, 2001, 2003)	1.66	0.83	0.84	101
	Phase 5	Peas (1992-1995)	1.21	0.36	0.86	241
		Lupins (1996-2003)	1.41	1.39	0.02	1
	Phase 6	Wheat (1992-2003)	3.19	1.45	1.73	119

AP/C: Annual pasture/crop rotation; PP/C: Perennial pasture/crop rotation

Results of research, such as reported above, into changes in soil pH from liming, and extra yields of DM for range of soil types, pH conditions and crops help form judgements about the likelihood that liming in specific conditions of paddocks and farm systems will meet the 'Threshold' requirements for extra DM/ha and Marginal Gross Margin Rotation/tonne and per hectare. While decisions to invest in liming depend on the specific details of a paddock and farm system, if the soil is sufficiently acid or, importantly, if acidity is to continue over the 10-year planning horizon, the research evidence indicates that there are many situations in which investing in liming can be a good investment. In particular, liming may become even more important as soil productivity increases.

CASE STUDY 3: Ameliorating soil constraints by incorporating clay into sandy soils – Analysis including risk

Clay mining involves removing sandy top soils to expose the clay-rich subsoil. This subsoil is extracted, spread on the surface, and incorporated into the surrounding topsoil (Leonard 2011).

There are many methods of introducing clay into sandy soils, all requiring the application of large quantities of clay per hectare, and a wide range of costs per hectare. Transporting heavy clays is a costly activity and to have a chance of being profitable, numerous pits may need to be opened across a single cropping enterprise. The distance clay can be transported economically is limited: 1km or so is suggested by Leonard (2011).

Studies showing a range of increases in yields have been achieved with various methods of ameliorating constraints of sandy soils by adding clay. See below:

- In a claying/deep ripping trial running from 2012 to the present using a cereals, lupin and canola rotation the GRDC project UMU00041 'effect of claying on crop production and soil nutrition: South Coast', reported increases in average crop yields after claying and deep ripping from 30% to 50% p.a.; well above the required 10% increase in yield of the analysis.
- Hall et al 2010 'claying and deep ripping can increase crop yields and profits on water repellent sands with marginal fertility in southern Western Australia', reported crop yields increased by 0.3-0.6 t/ha because of added clay (almost doubling yields in some cases).
- Hall et al 2015, 'Longer term effects of spading, Mouldboard ploughing and claying on the south coast of WA', reported cumulative yield increases of 3.3-4.0 t/ha over a 6-year trial involving Mouldboard plough and spaded clay treatments.
- GRDC Sandy Soils Project CSP00203 (2014 – 2018) - This trial has seen a range of subsoil amelioration methods applied, including the addition of Clay, Organic Matter and Nutrients combined with Spading. The trials encompass five sites across Southern Australia, and have shown consistent high increases in grain yield.

The threshold method of analysis is used when the effects of future change are unknown. A different approach to the economic analysis is possible where credible information about yield responses from an investment in soil amelioration exist – as is the case in the analysis that follows. Further, some risk analysis is conducted.

In the following case study the economics of claying and deep ripping on water repellent sands with marginal fertility in southern Western Australia is assessed. The analysis shows how an innovation in subsoil amelioration is considered using discounted cash flow analysis and incorporating risk. Evidence is used about likely yield responses, from a recent investigation into claying and deep ripping to ameliorate subsoil constraints (Hall et al, 2010).

In this analysis, in which risk budgeting is done, incorporating probabilities about the extra yields that may be achieved, a significant portion of the risk of the investment is allowed to account for the range of possible yields that could be achieved. To include a high premium for risk on the required rate of return, such as a having 10% required return on capital which implies a 5-7% premium above the medium-term 'risk free' rate of return in the economy, as well as including risk in the yields that could be achieved, is to double count some of the risk of the investment. For this reason, in this analysis, a required rate of return (discount rate) of 7% p.a. is used. There is still some risk premium which allows for risks other than yield risk that could still affect the ultimate outcome of the investment in claying. For example, the risk that the new soil 'mix' does not 'work' or has implications for additional costs such as weeds, or crop failures in early years and so on.

The starting point for this analysis is to construct a 15-year cash flow budget based on the processes involved in the investment, with a high salvage value of the investment in year 15. The expected increases in yield, based on research, are used. Claying can make possible changes in crop systems; in this case this is not considered – the investment is assumed to improve the performance of the cropping system currently used.

To account for some of the risk economic analysis of the investment accounts for the likely distribution of extra yields. Using @Risk software Monte-Carlo simulations are run. These simulations generate distributions of possible outcomes as defined by the probability distributions for yields, prices and salvage values and a distribution of possible values for the net present value (NPV) and return on capital of the investment. The probability of exceeding, or not exceeding, the required rates of return on capital is estimated.

The measures that include the time value of future benefits and costs are benefit-cost ratio (BCR), net present value (NPV) and modified internal rate of return MIRR (not the usual internal rate of return (IRR). The usual IRR method has limitations stemming from the assumptions about the reinvestment of cash flow throughout the life of the project (Carland, 1997; Davis, 2000; Satyasai, 2009). To overcome these limits of the IRR criteria, the MIRR is calculated in two steps (Satyasai, 2009). First future cash flows are discounted at the opportunity cost of capital. Then a separate reinvestment rate is applied to calculate returns on surplus cash generated throughout the life of the investment.

<u>Analysis of claying and deep ripping on water repellent sands with marginal fertility in southern Western Australia</u>

In this analysis, the rate of clay incorporation aimed for is between 3-5% (250 t/ha) (Hall *et al*. 2010). The crop rotation is canola, wheat, barley and lupin. The current average gross margin per rotation-hectare is $170/ha., and $135/rotation tonne. The assumption is that one pit can service 1000 ha, and clay is transported 1km from this pit.

The time used in the analysis is the farmer's planning horizon of 15 years, as in contemplating other medium to long term investments. A distribution of the extra yields/ha is used, with a mean of 30% extra yield/ha above the average yield before the change. A triangular distribution is used. The lowest extra yield is zero and the maximum extra yield is 50% above the existing average yield. The distributions for grain prices used are listed in Appendix 5.

The salvage value of the investment to add clay into to sandy soil is high, though there is some possibility that, given the dynamics of soils, and farm systems, some of the benefits and costs of the changed system could dissipate over a medium term run of years. This is unknown. To allow for this chance, in the analysis a probability distribution is used for the salvage value of the initial capital invested to 'clay up' the sand. Salvage used are assumed to have an equal chance of being 75%, 85% and 100% of initial capital. As happens, discounting means that salvage values that occur well down the track do not have a major impact on the returns to capital of an investment.

The results shown in Figures 15, 16, 17 and Table 37 indicate that the expected value of the MIRR is 12%, and in this case the investment is unlikely to return less than the required rate of return of 7% p.a. There is 60% chance (odds of 6/4 on) that this investment in this case would return more than 14% real p.a. Please note that these returns to capital are before tax is considered.

The cumulative net cash flow budget indicates that in nominal dollar terms the initial cash outlay would be recouped by year 6.

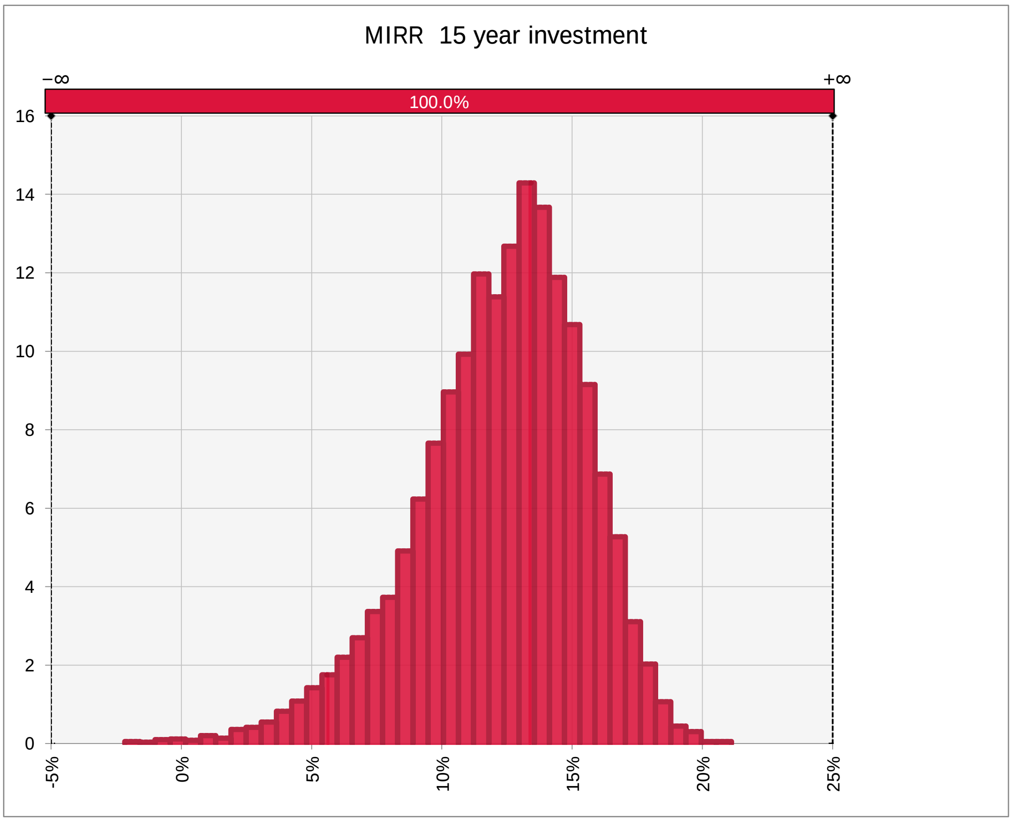


Figure 15. Probability Density Function of Modified Internal Rate of Return on Capital

Table 39 Statistics - Probability Density Function of MIRR

Statistics – MIRR	
Minimum	-$301,661.31
Maximum	$1,071,041.23
Mean	$351,172.53
Mode	$335,352.31
Median	$355,848.82
Std. Dev.	$214,966.68

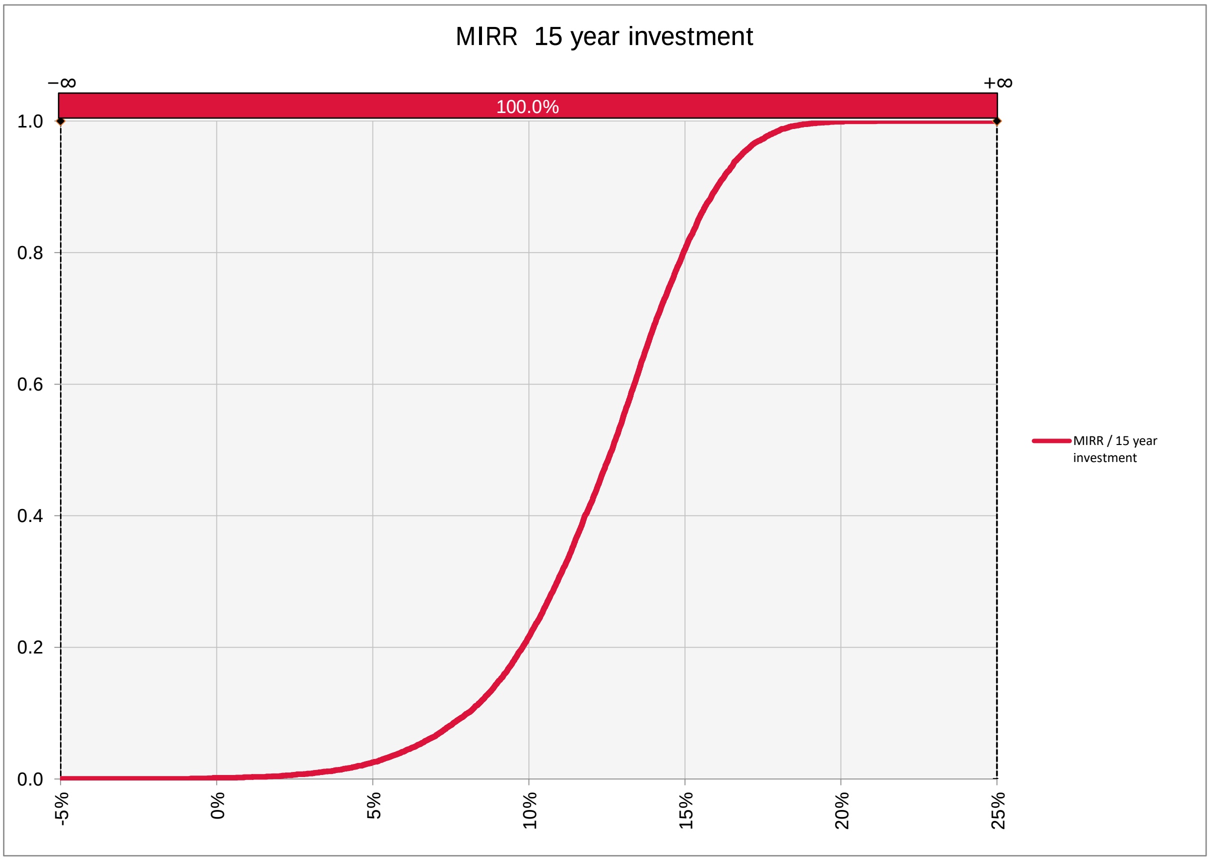


Figure 16. Cumulative distribution of Modified Internal Rate of Return on Capital for 15-year life of investment

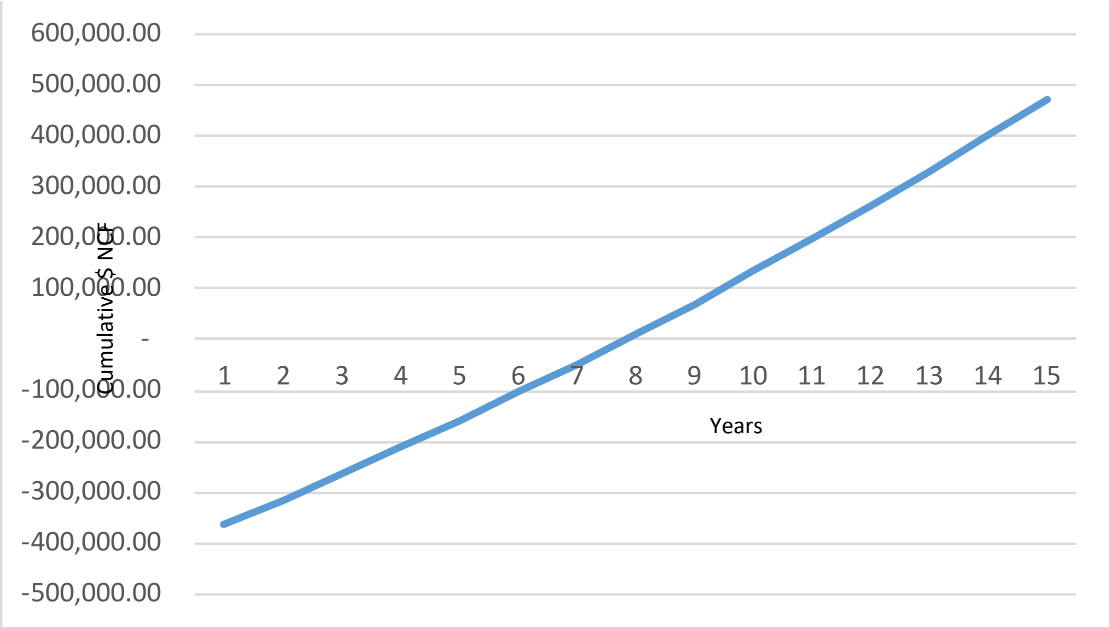


Figure 17. Cumulative Net Cash Flow

5. DISCUSSION AND RECOMMENDATIONS

Priorities for soil constraint research

Below are research areas and key findings identified from this Scoping Study.

General

- Diagnosis of multiple constraints and amelioration strategies. This will also extend to the topic of single *vs* multiple amendments: interactions, physicochemical constraints vs nutritional constraints.
- Investigations into identifying soil specific properties that explain inconsistent response to ameliorants (e.g. Is it related to particular soil types, seasonal conditions or plant type?), thereby helping to reduce risk associated with non-response to amelioration.
- Harmonizing soil constraint mapping across Australia using Digital Soil Mapping (DSM) approaches to synchronise and/or extrapolate, or model soil constraints directly.
- Examine where roots are located in ameliorated profiles and develop novel techniques to investigate roots in real time, non-destructively.

Dispersive and alkaline soils

- Investigate ameliorants that are most effective at alleviating sodicity, alkalinity, salinity and increasing plant available water capacity (PAWC), and determine the residual value of these ameliorants. Particular consideration should be given to soils with multiple constraints (this being representative of the vast majority of constrained soils), as well as ameliorant dynamics in relation to climatic factors and placement (thus, any potential issues such as emergence versus access to subsoil moisture).
- Identify potential to develop plant-based organic matter ameliorants that can be either produced on-farm or sourced locally as alternatives to paying for ‘imported’ products.
- Investigate the interaction between soil management and soil sodicity reclamation under different levels of salinity.
- Understanding root-soil interactions, organic carbon (OC) accumulation and the influence of high pH on the speciation and mobility of OC in alkaline soils.
- Understanding the influence of the ionic composition on soil pH and how this influences nutrient use efficiency and plant biomass production.
- Assess the feasibility of reducing rhizosphere pH in highly alkaline soils.
- Understanding how plants respond to high pH, in particular the multiple stresses such as micronutrient deficiencies and toxicities, salinity in addition to high pH and poor soil structure.
- Examine how alkalinity influences soil functions and nutrient cycling (i.e. the interactions between alkalinity and other soil constraints).

- Develop innovative gypsum-based products which facilitate movement of gypsum into subsurface sodic zones without the need to physically incorporate into subsoils.

Key considerations - Dispersive and alkaline soils

- A rapid data collection methodology is required to provide a useful mapping resolution on-farm that allows for spatial (including soil-depth) and temporal variability of key soil constraints.
- Consider undertaking a strategic assessment (soil type and region), initially using controlled environment screening (using methodology such as that developed in DAV00149) followed by regionally based field trial validation with appropriate R&D agencies and grower groups.
- Utilise specialised subsoil machinery (e.g. NSW DPI Wagga; AgVic Horsham) where possible for field experimentation.
- Consider strategically co-locating sites with existing research sites in order to 'value add' to current investment. For example: DAV00149 has established a number of research sites across NSW, Victoria, South Australia and Tasmania; University of Southern Queensland lead the GRDC-funded Project (B): Soil constraint management and amelioration strategies for the northern region; and other Soil CRC partners have considerable skills and existing research sites to which additional investment could value add.

Soil acidity

- Develop soil sampling and monitoring protocols to capture the vertical and spatial variability of acidity and acidification in modern agricultural production systems.
- Evaluate the precision placement of ameliorants to target zones of acidity that are created by precision placement of acidifying fertilisers.
- Evaluate the use of ameliorants in permanent pasture systems to provide evidence to growers of the impact and potential benefits of soil improvement.
- Develop innovative lime-based products which facilitate the movement of lime into subsurface acidic zones when top-dressed.
- Examine nutrient (in particular P) 'sparing' effects of lime in acidic soils.

Key considerations - Soil acidity

- Acidity often exists in combination with other constraints (for example, an acidic top soil over a sodic B horizon). Therefore effectiveness of management must be evaluated in combination and not isolation with other constraint research.
- Acidity strongly influences soil biology and therefore it is a factor influencing the effectiveness of many biological additives, chemical inhibitors or biological processes in relation to nutrient cycling.
- Very little soil acidity research has been done in the permanent grazing regions of Australia.

- Most agricultural soils have continued to acidify to levels beyond which they were when previous soil acidity was conducted last century, meaning that many issues (such as trace nutrient availability) need to be revisited.

Salinity

Based on the lost economic potential ($130M/yr) and the fact the majority of this could be regained through irrigation improvement ($102M/yr), the knowledge gaps were focused on irrigation. Industry and region are not the most important considerations here; in essence it is where irrigation may occur using waters that increase salinity over time, such as industry wastewater access (Australia wide, but localised to source), saline overland flow (a key issue for SA, but not limited to SA, for example parts of the sugar industry in northern Australia), and where marginal quality aquifers exist that may be either used strategically, or are currently being used where they should not.

Two potential projects/topics were identified for salinity (irrigated agriculture):

- Identify, model and predict the soil-specific threshold electrolyte concentration (C_{TH}) responses linked to tailored management and water treatment options.
- Develop techniques to better determine deep drainage and spatial subsurface water movement.
  a) What is the minimum data-set required to provide adequate spatial information?
  b) How can existing models be integrated to better reflect the complexity (i.e. numerical/computational models capture good complexity in localised landscapes, while catchment models provide mass average movement — can these be linked, and what is the intermediary requirement)?
  c) How do we build in soil-specific interactions (C_{TH})

Both of these projects were considered interlinked, with the first project more likely to be addressed by industry in the short term. The second project was considered to be a key project for investment with regard to ameliorative and management flow on effects to industry from the Soil CRC.

Key considerations – Salinity

It will be important to acknowledge the interaction between salinity and soil structure in any agronomic work, not just from plant soil-water access, but also with regard to how infiltration may change throughout any field trials etc. Within the space of predicting C_{TH} it will be important to link with both GRDC and CRDC projects commencing funding within this soil constraints space.

Compaction

- Quantify the cost of lost potential due to compaction and hard-setting soils. Key components this will include: a) identifying a framework for determining the compaction benchmark on a soil-specific basis (what is a non-compacted soil); b) determining enduring solutions for hardpans resulting in a soil-specific matric of management options, including crop rotation; and c) furthering evidence on controlled traffic farming (CTF) conversion options as applied to crop row spacing, climatic regions and yield performance.

Key considerations – Compaction

In terms of considering the interacting effects of soil compaction, consideration should be given to:

- Efficiencies of water (rainfall and irrigation) and fertiliser use. The latter includes reductions in recoveries of applied nutrients, and responses of yield to N.
- Energy-use efficiency to account for total energy input for the crop. This includes additional energy used on tillage repair treatments, and (reduced) recovery of fertiliser and water in crop yield. Therefore, development of DSS should incorporate models that optimise energy output:input ratio. In grain cropping (clay soil), fuel may be reduced by up to 50% when CTF is used, but research is needed to determine these potential savings for cotton cropping.
- The above research may apply approaches similar to those employed in grain cropping (e.g. Tullberg 2000, Kingwell and Fuchsbichler 2011, Blackwell et al. 2013, Gasso et al. 2014), including life-cycle assessment and environmental audits, and incorporate modelling approaches for simulating the effects of changes in land-use and management practices.
- The effects of compaction on GHG emissions as has been recently described by Bhandral et al (2007), Antille et al (2015) and Tullberg et al. (2018)
- The effect of subsoil compaction on macropore geometry for dispersive subsoils, where deep ripping is liable to be inefficient unless coupled with an ameliorant that is sufficient to deal with the dispersive soil.

Nutrient constraints

- Investigate the extent of crop reliance on subsoil nutrient supply in Australian dryland cropping environments.
- Examine the direct limitations to subsoil root growth from low levels of the nutrients with low phloem-mobility (Mn, B, Cu, Zn, Ca) in field grown crops.
- Determine the role of subsoil N and P placement (as fertiliser or organic amendments) to stimulate subsoil root growth and the uptake of water and nutrients from subsoils in the Western and Southern regions.
- Determine what biophysical tactics mobilise nutrients.

Key considerations – Nutrient constraints

- The subsoil placement of fertilisers or organic amendments may require machinery innovations.
- There is a need for robust methods for measurement of subsoil root distribution (e.g. electrical resistivity tomography), as well as understanding relationships between root-

C inputs and nutrient mobilisation in deep soil layers, in order to demonstrate the link between subsoil roots and improved crop nutrition.

Problematic sandy soils

- Determine soil physical strength particularly in subsoil below the depth of clay and organic matter incorporation.
- Investigate fertilisers for sandy soils; including mineral, slow release and organic-based products and determine when and where deep placement might be beneficial.
- Investigate organic amendments for sandy soils; type, form, amount, depth of placement and determine their impact on sandy soil productivity.
- Assess clay type and synthetic functionalised clays for amelioration and determine their impact on sandy soil productivity.
- Field map, model and group differing sandy soils into management classes, including the preferred configuration of clay and organic matter in re-engineered sands.

Key considerations - Sandy soils

- The physical/ chemical engineering of sands needs to be considered together with the Program 4 (Funding Round 1) Project on "Plant based solutions to improve soil performance through rhizosphere modification" which will explore the biological engineering of sands. Both approaches would benefit from regular testing using new tools developed by the soil metrics projects (Program 2).
- For the physical/chemical engineering, there may be a need for research on machinery innovations.
- The GRDC investment on sands in WA and in southern Australia, has created a number of field sites where the Soil CRC could add value to experiments already established and secure sites for longer term investigation of the benefits of treatments. There would be considerable value in conducting a meta-analysis across Australia of all relevant experiments and demonstrations set up to investigate clay and organic matter inputs on sands. A paper from the meta-analysis would lay the foundation for greater understanding of the benefits of these treatments. It would also help to identify which experiments would be worth continuing for longer to harvest greater insights into the long term benefits of amelioration.

Machinery

Potential topics and key considerations include:

- Define machinery functions – what does the machine need to do? This should capture the type of ameliorant, placement and rate, field operating efficiency, what soil constraint or combination of constraints needs to be addressed.
- Technologies for incorporating soil amendments: identify the relative merits of banding or surface covering followed by soil inversion. This latter option may reduce the complexity of the equipment/delivery mechanism, and may rely on readily available

equipment. The former may require an active placement method at depth as well as the mechanism used for conveying the material through the machine.

- Technologies for handling brought-in products: this requires investigating the opportunities to re-engineer the product to meet the requirements of commercially-available machinery, instead of re-engineering the machine to match the requirements of a variety of products. Material processing could be energy-demanding and therefore expensive, but could significantly resolve problems relating to logistics including storage, handling and field application.
- There is uncertainty as to what amendment is more cost-effective for given constraints, which impacts on machinery selection. The same is true when dealing with multiple constraints and whether multiple amendments can be used simultaneously (e.g., through blending). Two common areas of research across regions and cropping systems are: 'type of amendment' and 'placement'. The soil constraint R&D first needs to be completed in order to guide subsequent research needs in the machinery space.
- Broadly, machine solutions need to be developed to enable handling of 'brought-in amendments', 'in-situ biomass with no additives' or a combination of brought-in amendments and in-situ biomass, which may be dependent on region, cropping system and availability of amendments.
- Relatively higher rates of adoption may be expected if machinery designs allow for flexibility of product choice so that grower can switch to different materials depending on availability and cost. Current machine limitations may be significantly reduced with materials processing such as granulation. However, this may increase material cost.
- A technology that may enable the combined use of in-situ biomass with brought-in amendments appears to be priority for research and development. Improvements in machinery designs must be guided by agronomic evidence supporting best management practice for amelioration, including right product, right rate and timing and right placement.
- Future machinery designs need to be informed by agronomic research, which in turn will also inform farm economics. Re-engineering the product (e.g., pelletising, granulation) may remove some of the existing machinery constraints, but will have a (likely significant) cost associated with processing of a bulk, low concentration material (assuming the agronomic effectiveness of the raw material is similar to that of a processed one).

What do advisers and industry think is needed? Baseline Survey.

- Key soil constraints identified by advisers and industry personnel aligned with themes and topics identified by researchers
- Key drivers of change on farms are increasing yield and improved fertiliser and resource use efficiency
- One of the main barriers to practice change is farmers having the knowledge and skills, and confidence to undertake a practice change. From this survey it is clear that not only does the innovative technology need to be right for the industry, but have clear

channels for communication and extension in a region (e.g. demonstration trials), prior to a new practice being taken up.

- A key issue for producers in adopting new technology is realising they have a problem in the first place and accurately identifying what the problem is, especially if it is multi-faceted, that is which bit to address first?

Soil constraint mapping

This Scoping Study identified that there is a need to provide consistent national, regional and industry-wide products for a number of key soil constraints to help context current, and target future, work (refined constraint mapping or modelling) for priority land uses and regions (and constraints). Current national mapping (Australian Soil Grids) do not adequately map most constraints, instead having focused on soil properties (particularly those useful for modelling, such as clay%, silt%, sand%, pH). Existing national soil grid maps can also be less reliable in certain regions compared to state approaches in Australia.

Harmonizing soil constraint mapping across Australia could be achieved using Digital Soil Mapping (DSM) approaches to synchronise and/or extrapolate, or even model soil constraints directly. National DSM grids could be used, or be further developed, by applying constraint ‘rules’ or condition parameters to these (from expert input or existing traditional products) and comparing existing regional constraint mapping for further refinement and validation (similar to current waterlogging susceptibility work of Dr Darren Kidd with TIA for GRDC). There is also the potential for such an activity through the Soil CRC to link in with the proposed next phase of the TERN project (led by CSIRO).

Determining the economic impact or value of soil constraint amelioration

Some insights from the foregoing analyses of different investments to ameliorate the condition of soil are listed below:

- Investments in agricultural R, D&E must pass the tests of (i) Strategic Fit, (ii) Market Failure, (iii) Good Science, and (iv) Expected Benefits exceed Costs
- To evaluate investments in ameliorating soil constraints, all extra benefits and all extra costs and all changes in risks are considered. The marginal crop gross margin, not average crop gross margin, is the correct measure of extra benefit. Marginal crop gross margin per rotation tonne and per ha can be greater than the pre-existing average crop gross margin. Marginal livestock gross margins can be greater than the pre-existing average livestock activity gross margin if extra stocking rate increases risk and labour requirements.
- Costs of common amelioration investments have often been established and can be incorporated into subsequent economic assessments.
- The extra yields expected, the effect on variability of yields, the proportion of years there are net benefits and zero benefits over a run of years, and how long the investment will be effective, are the major unknowns.

- In the face of these unknowns, threshold analysis indicates that low cost investments to ameliorate soil conditions, about which there is confidence about the likely life of the investment, require relatively small and highly achievable marginal gross margins per tonne and per ha from the activities involved, irrespective of a reasonable range required returns to marginal capital. In the right paddocks, investors could feel reasonably confident some of the array of methods with relatively low-cost investment per hectare and a reasonable life have a good chance of achieving the marginal returns they require over the life of the investment.
- For the larger investments/ha considering risk has the effect of significantly increasing the extra benefits that the investor needs to be confident about achieving. Threshold analysis suggested that for average activity marginal gross margins of $100-$150/t and per ha., and required returns to capital of 5-10% p.a. over the life of the investment, investments greater than around $500/ha with lives of less than 10 years and with no implications for annual fertiliser use, have the challenge of increasing yields by up to 2t/ha in some years, because over a run of years the investment will deliver no benefits above the counterfactual case of business as usual.
- Threshold analysis indicates investing in liming has a reasonable probability of being a good investment, provided soil is sufficiently acid; preventing further acidification that would otherwise occur is also a benefit.
- Threshold analysis suggests investing in claying and deep ripping at $450/ha in the right environment has a good probability of earning required returns on capital of 10% real p.a.
- The R, D&E investment decisions need to be informed well by plausible narratives by the scientists about the detail of the changes that will be made possible on farm, and their effects, that deliver the required annual net gains.

Information investors in soil amelioration require

Some research and practical evidence about each of the common methods of ameliorating soil constraints to the performance of crops and pastures is already known, with more known about some methods than others. Ultimately judgements about the merit of any of the potential investments in ameliorating soil constraints are made on a case by case, paddock by paddock basis.

Potential investors in soil amelioration techniques need a good idea about the likely life of the investment and number of years that there will be marginal net benefits above what would be likely to happen without the investment.

Evidence from research is needed about yield effects and marginal net benefits, longevity of investments and proportion of years in which benefits occur. This information enables investors to form probability-informed judgements, for soils in distinct climates, about the likelihood of earning the opportunity cost on the marginal capital involved.

At a minimum, concept proposals should address the following questions:

1. *Benefits*

- (If you know) For your soil constraint ‘theme’; what is the size of the relevant industry(ies), in total production, gross value of agricultural product, and area (hectares) or proportion of this area affected by the constraint?
- Is the research relevant to all areas of the industry sector e.g. Is it focused on a particular region or crop?
- Who are the next users? Are the benefits intended mainly for on-farm, off-farm, or through the value chain?
- What is the size of the likely primary (direct) benefits to the likely users of the output of this research, e.g. extra yields (range and average), improved product quality, reduced input costs, reduced logistical constraints, extra gross margin? (A sound narrative about how the research output will likely change the current situation is critical here.)
- Are there any secondary (indirect, externalities) benefits and if so, what is their nature and magnitude?
- What is the likely rate of adoption after 5, 10 and 20 years?

2. *For each research priority identified:*
    - Is the research predominantly of an applied or basic nature?
    - Is the concept highly novel?
    - What is the likelihood of the project achieving its scientific aims? (low, medium and high)

By means of an example, each these questions have been addressed for the soil constraint ‘theme’ and the associated suite of concepts proposed at the Technical Specialist Workshop (see Table 40).

Table 40 Addressing key questions to evaluate the likely impact of investment in soil constraints

Industry size, GVP, area (ha)	*Is the research focused on a particular region / industry?*	*Who are the next users? Are benefits mainly for on-farm, off-farm, or through the value chain?*	*Size of the likely primary (direct) benefits to the likely users of the output of this research*	*Are there any secondary (indirect, externalities) benefits (nature and magnitude)?*	*Likely rate of adoption - 5, 10 and 20 years?*	*Is the research predominantly of an applied or basic nature?*	*Is the concept highly novel?*	*Likelihood of project achieving scientific aims? (L,M,H)*
Dispersive and alkaline soils								
13.4M ha in southern NSW, Vic, Tas, SA and WA (Davenport et al 2016) Unsure of total area in northern NSW and Queensland	Wide range of broadacre crops, livestock systems and irrigated horticulture	Benefits mainly on-farm, but also improvements to grain quality and/or changes to higher value crops	13.2M t/yr if whole area is treated (Davenport et al 2016) based on an increase in wheat yield from a current average of 60% water use efficiency (French Shultz) to yields with an average 80% water use efficiency.	Amelioration of poor soil structure can lead to increased and more reliable production with the potential to move to higher value crops. There are NRM benefits including: reduction in waterlogging, reduction in saline water table recharge, increased resilience to climate change through improving access to stored soil moisture.	5 to 10 years – will depend on R&D identifying a cost effective and logistically feasible strategy to ameliorate soils	Basic - to understand the impact of organic amendments on soil: biological activity, physical structure, chemistry, nutrient and water availability and root activity, and enhancing organic amendments with calcium products. Applied - to determine how much, what form and how often to apply amendments x soil types	Portions of the concept (particularly the addition of organic amendments) are novel, including new amendments and chemically fortified products	High - given current research in the area, maturity of the research questions and knowledge of potential sites.
Acidity								
35M ha highly acidic (pH_{Ca} < 4.8); 55M ha moderately/ slightly acidic (pH_{Ca} 4.9–6.0). Approx 50% ag land below pH 5.5_{Ca} (Dolling et al. 2001) $500M/yr in lost production across WA wheatbelt (Grazey)	All areas and industries, all rainfall zones (but worse in high and medium); cropping, grazing and horticulture. Issue in West, South and Eastern Australia.	Farmers (immediately) and advisers and precision agriculture businesses (evidence for BMP relevant to current and new farming systems/technologies. Off-site benefits: better water use = less recharge which lowers salinity risk.	Key factor in the selection of crop or pasture type able to be grown. As such, ameliorating acidity increases grower options allowing growers to be better adapt to economic or environmental situations and make most of opportunities. Current research indicate yield increases of 10-18% for crops, GRDC research reported net benefit of $85/ha due to pH correction in WA.	If acidity is addressed, legume use to provide naturally fixed N becomes more efficient and more suitable for a larger area of farm land. This decreases the need for synthetically produced N fertilisers which have a large C footprint (production, transport and application) and GHG production potential when applied to agricultural land. This also represents a substantial reduction in input costs to growers.	5 yrs	Applied research	Some is novel; products to deliver subsurface and subsoil alkalinity and amelioration of acidity (Programme 3?)	High
Salinity								
2M ha estimated (ABS 2002). 7% (140,000 ha) is irrigated. National Land and Water Resources Audit (2000) estimated over 5.5 million ha	Majority of agricultural salinity extent (2/3 or 1.2M ha) is in WA and the severity in WA tends to be greater.	Farmers – biggest benefit likely on irrigated land. Offsite: NRM groups and stakeholders for environment benefits e.g. aquatic health and water quality, reductions in	Benefits are primarily off-site whereas costs are likely to be incurred on-site. Estimated cost to agriculture is $130M in lost production potential (Hajkowicz and Young 2005), with a further $100M/yr worth of impact on infrastructure, with the 1999 Murray Darling Basin salinity audit suggesting that for	Significant – almost ten times the direct costs to agriculture are sustained in secondary costs to the environment and infrastructure (see figures previous column). MDBA estimated costs of $305M in the Murray Darling Basin of which only 33% was incurred by agriculture and	5-10 yrs with impacts for irrigated salinity tend to show much faster.	Applied – a lot of complex modelling and development of landscape hydrology at a small catchment and farm scale required.	No	Medium on average. Hydrological systems can be complex. Reducing irrigation salinity (primarily through irrigation

Industry size, GVP, area (ha)	*Is the research focused on a particular region / industry?*	*Who are the next users? Are benefits mainly for on-farm, off-farm, or through the value chain?*	*Size of the likely primary (direct) benefits to the likely users of the output of this research*	*Are there any secondary (indirect, externalities) benefits (nature and magnitude)?*	*Likely rate of adoption - 5, 10 and 20 years?*	*Is the research predominantly of an applied or basic nature?*	*Is the concept highly novel?*	*Likelihood of project achieving scientific aims? (L,M,H)*
total land are affected suggesting the majority of affected land is non-agricultural.		infrastructure damage (e.g. roads and buildings).	every 5000 ha of affected land there is a combined cost of $1M to agriculture, infrastructure and environment. Taking the NLWRA audit figures of a total of 5.5M ha affected land, this suggests the total cost of salinity is $1.1B of which $130M is agricultural.	46% was incurred by households, commerce and industry, primarily through saline town water supplies. NB: A range of state Salinity abatement programs in early 2000, the National Action Plan on Salinity and Water Quality commencing in 2004 d subsequent environmental funding saw a significant effort in combatting dryland salinity where the results may be slow to show.				efficiencies) has a much higher chance of success.
Compaction Very limited audit information available to evaluate this reliably (J. Bennett pers comm)								
Nutrient constraints Most agricultural soils to some extent. Insufficient information to define subsoil nutrient deficiencies.	Cropping, grazing and horticulture	Farmers and NRM managers. On-farm through increased profit, but also off-farm as improved nutrient balance can decrease off-site effects of excess nutrients.	Fertiliser comprises ~ 30 % of crop production costs. Widespread negative K and Mg balances, and positive balances for P on farms. Magnitude of subsoil nutrient deficiencies not known.	Eutrophication of surface water bodies is triggered by P and N run-off and seepage from agricultural land (among other sources).	5 yrs for topsoil nutrient management. 10 yrs for subsoil management (engineering and fertiliser product development)	Applied, but novel fertiliser product development and understanding role of subsoil nutrient supply requires basic research	Novel fertiliser product development	High
Sands >7M ha in WA and >3.5M ha in southern Australia have deep sand or sand on clay profiles	Grain cropping (most except lentil and chickpea), mixed farming and grazing (sheep, cattle)	Farmers, advisers, soil researchers, machinery manufacturers and retailers, organic matter producers and suppliers	Ave yield increases from clay addition over 15yrs were ~50% at Esperance. Survey of WA growers found 87% of respondents achieved yield increases 0.25 -3t/ha/yr in cereals after claying. Increase in NPV from clay addition after 6yrs was $61/ha. In SA, field trials on 3 sites conducted in New Horizons program delivered ave yield inc of 1.3 t/ha/yr. Largest inc were delivered where OM was placed into A2 horizons with or without clay addition.	Co-benefits of claying and amelioration through the addition of organic material to bleached A2 horizons include: increased SOM, increased soil extractable P, K, and S; increase in soil buffering capacity, reduced acidification/ wind erosion risk/ frost risk, improved weed management and reduction/suppression of mallee seeps (waterlogged and salt affected mid slopes and swales).	5-10yrs	Basic - role of subsoil OM and clay on subsoil root function, water and nutrient availability, and biological processes. Applied - determine package of clay and OM amelioration practices for different types of sand across different rainfall zones that can improve amelioration practice, increase length of amelioration and an increase crop profit.	Mechanistic and process-based research on subsoil nutrients, biology and root function is novel.	High, based on a background of over 20yrs research in this area. Key questions for further research can now be better defined.

Industry size, GVP, area (ha)	***Is the research focused on a particular region / industry?***	***Who are the next users? Are benefits mainly for on-farm, off-farm, or through the value chain?***	***Size of the likely primary (direct) benefits to the likely users of the output of this research***	***Are there any secondary (indirect, externalities) benefits (nature and magnitude)?***	***Likely rate of adoption - 5, 10 and 20 years?***	***Is the research predominantly of an applied or basic nature?***	***Is the concept highly novel?***	***Likelihood of project achieving scientific aims? (L,M,H)***
			Claying has spread to about 200,000ha in WA and SA already. Area that could benefit from clay addition is over 7.5M ha (4.5M ha in WA, 2M ha in SA and 0.5M ha in Vic, NSW). There is around 10M ha that can benefit from OM inclusion.					
Machinery Not included here as it covers aspects of the other themes								

6. CONCLUSIONS

The findings of the five activities conducted during Scoping Study 3.3.01 (that is, the technical specialist workshop, current research review, baseline adviser and industry survey, inventory of mapping soil constraints and the ‘Needs’ assessment) agreed with the soil constraint ‘themes’ identified in the planning stage of this project. These were: dispersive and alkaline soils, soil acidity, salinity, physical soil constraints, nutrient constraints and sandy soils. This report indicates that there is still some fundamental soil science research to be undertaken to better understand, map and develop metrics for monitoring and evaluating the impacts of soil constraints on agricultural production. While innovative and novel amelioration products are an important part of advancing soil constraint management in agricultural systems, this study highlights that considerable production gains can be achieved through research which adequately defines (maps) the area of soil constraint, targets the complexity of multiple soil constraints and investigates soil specificity in relation to responses to amelioration. The next-user engagement (baseline adviser and industry survey) further emphasised that practical, feasible and accessible amelioration strategies that target the major multi-constraints are more likely to be adopted than expensive novel and niche products. For example, higher rates of adoption are likely if machinery designs allow for flexibility of product choice, or products are designed to be used with existing farm machinery, so that growers can switch to different materials depending on issue, season, availability and cost. The multifaceted nature of many soil constraints means that the effectiveness of soil constraint management should be evaluated in combination with, and not in isolation from, other constraint research. Lastly, research investments should be guided by impact, production and profitability gains and amelioration strategies must be ground-truthed with next and end-users to maximise farm readiness and adoption.

7. ACKNOWLEDGEMENTS

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9. APPENDICES

Appendix 1 Technical Workshop Agenda

Soil CRC

Scoping Study 3.3.01

Technical Specialist Workshop

12-13th March, 2018

Stamford Plaza Sydney Airport

Cnr O'Riordan & Robey Streets, Mascot, NSW

AGENDA

Organiser: Dr Susan Orgill (M: 0428 424 566) **Facilitator**: John Cameron

Time	Topic	Speaker
09:30 am	**Arrival and morning tea**	
10:00 am	Welcome and workshop objectives.	Susan Orgill (NSW DPI)
10:10 am	Housekeeping, overview of workshop process and self-introductions	John Cameron (ICAN)
10:30 am	SOIL CRC Update	Michael Crawford (CEO, SOIL CRC)

11:00 am	Theme presentations. For each soil constraint, theme leaders provide an overview of the impact and research on amelioration strategies (10mins presentation, plus 5mins questions) 1. Sodic/dispersive soils and alkalinity 2. Acidity 3. Salinity and other physical constraints 4. Machinery and engineering solutions 5. Nutritional constraints 6. Sandy and low OM soils	 Ehsan Tavakkoli (NSW DPI) Jason Condon (CSU) John Bennett (USQ) Dio Antille (USQ) Qifu Ma (MU) Richard Bell (MU)
12:40 pm	**Lunch**	
1:10 pm	Description of the breakout group activity	John Cameron and Susan Orgill
1:15 pm	**BREAKOUT GROUPS: Detail, prioritise and consensus on current research and knowledge gaps for managing soil constraints and developing soil amelioration strategies.** 1. Sodic/dispersive soils and alkalinity 2. Acidity 3. Salinity and other physical constraints 4. Machinery and engineering solutions 5. Nutritional constraints 6. Sandy and low OM soils	
1:15 pm	**BREAKOUT GROUPS** organised by theme. Identify knowledge gaps related to managing soil constraints and developing soil amelioration strategies. This may include current research, but should also focus on new research. Key discussion for each 'gap'; - name, and define or describe; - where and why is it a priority issue (region, soil type, ha affected, $/ha crop yield and farming systems impacts) - cost benefit: (est cost $/ha of amelioration process), probability of amelioration success, how long are amelioration benefits likely to last? - probability of research success in addressing knowledge gap (& what factors might affect this) - ease of amelioration and likely adoption barriers or opportunities; difficulty or ease of implementation of research outcomes, logistics etc	ALL
2:45 pm	**Afternoon tea**	

3:05 pm	Breakout group presentations (6): 15 min presentation plus 10 min discussion each group 1. Sodic/dispersive soils and alkalinity 2. Acidity 3. Salinity and other physical constraints 4. Nutritional constraints 5. Sandy and low OM soils 6. Machinery and engineering solutions	ALL
5:35 pm	Day 1 Wrap up	John Cameron
5:45 pm	**Close**	
	Dinner details: 7pm La Boco Restaurant, Stamford Plaza	

Day 2		
Time	**Topic**	**Speaker(s)**
8:00 am	**Arrival and coffee**	
8:30 am	Program 3 Overview (10mins presentation, plus 5mins questions)	Nanthi Bolan (Uni of Newcastle)
8:45 am	Mapping Activity Overview (10mins presentation, plus 5mins questions)	Mark Imhof (AgVic)
9:00 am	Economic Activity Overview (15mins presentation, plus 15mins discussion)	Bill Malcolm (Uni Melb)
9:30 am	Overview of key issues where further feedback and clarity is required (5 min presentation per theme) 1. Sodic/ dispersive soils and alkalinity 2. Acidity 3. Salinity and other physical constraints 4. Machinery and engineering solutions 5. Nutritional constraints 6. Sandy and low OM soils	Theme leaders, or other nominated Ehsan Tavakkoli Jason Condon John Bennett Dio Antille Quifa Ma Richard Bell
10:00 am	**GROUP ACTIVITY: Speed dating, research planning style.** What has not as yet been discussed, or has, but where you feel there was the wrong priority, or for which you can add more clarity on the scale of the issue or cost benefit of amelioration research? The 6 theme leaders will be sitting around the room. This is the time to contribute to other themes and identify cross-overs between themes and amelioration strategies.	ALL
10:45 am	**Morning tea**	
11:10 am	Feedback from theme leaders on additional insights or issues raised (5min presentation and 5min discussion) 1. Sodic/ dispersive soils and alkalinity 2. Acidity 3. Salinity and other physical constraints 4. Machinery and engineering solutions 5. Nutritional constraints 6. Sandy and low OM soils	 Ehsan Tavakkoli Jason Condon John Bennett Dio Antille Quifa Ma Richard Bell

12:10 pm	**Prioritisation exercise** Participants have $10,000 (as 10x $1000) of grower money to allocate/invest on research issues/ideas. Where is research investment most likely to lead to productivity gains for growers?	John Cameron and Bill Malcolm
1:00 pm	**Lunch**	
1:30 pm	**Start drafting:** Theme groups to work on drafting input for Activity 2; take on board feedback from rest of group, determine priorities and what potential future teams might look like.	ALL
2:30 pm	Summary of the workshop - where to from here? - Economics - Mapping - Reporting	Mark Imhof Bill Malcolm Richard Bell Susan Orgill Roger Armstrong John Cameron
3:15 pm	Exit survey	
3:30 pm	**Afternoon tea and close**	

Appendix 2 Baseline adviser and industry survey

Southern Australia soil constraints to production Survey

The Soil CRC is bringing together scientists, industry and farmers to find practical solutions for Australia's underperforming soil.

The Cooperative Research Centre for High Performance Soils (Soil CRC) is bringing together scientists, industry and farmers to find practical solutions for Australia's underperforming soil.

The Soil CRC aims to enable farmers to increase their productivity and profitability by providing them with knowledge and tools to improve the performance of their soils. The Soil CRC is the biggest collaborative soil research effort in Australia's history. There are 39 Participants that contribute to the Soil CRC through both cash and in-kind contributions. For more information see: http://www.soilcrc.com.au/

Through Soil CRC funding, NSW DPI is leading a scoping study (3.3.01 - Mapping projects on ameliorating soil constraints, and review of soil constraints, products and technologies) which aims to better understand the constraints of soil to production that farmers and industry identify with, current amelioration strategies and barriers to practice change.

My name is Melissa Cann, from Agriculture Victoria. My team and I work with dryland farmers to better inform them on soil constraints, and land management issues that impact on production. On behalf of the Soil CRC, I am undertaking this survey, utilizing the perspective of farm advisers such as yourself.

The information gathered from this short survey will aid in the development of relevant and farm ready research over the next 8 years to bridge the gap between soil science and decisions on farm and ultimately increase profitability.

Collated information from your industry responses will be returned to you for your records if you are interested and all individual responses will be kept confidential, with no information be used to identify specific individual responses.

Thank you for participating in our survey. Your feedback is really important to us and should only take around 10 minutes to complete.

This survey should only take a 7 -10 minutes to complete

Q1.Are you a farm Adviser?

Q2. What is your closest locality? (postcode and town)

Q3. How many clients do you work with?

Q4. Can you estimate what percentage of your clients use farming as their primary source of income?

Q5. Which industries do your clients farm? (Select all that apply)

Beef
Sheep
Cropping
Dairy
Cotton
Sugar Cane
Rice
Fruits/vegetables
Irrigated cropping
Other

Q6. Please tell us the total farmed area (ha) for each of the industries selected above. Please include industry with the ha number given

Q7. Please list the soil types in your region that you are working with?

Most productive soil type and why

Least productive soil type and why

The ones in-between

Q8. What soil constraints are of greatest concern to your clients? (Topic 1 is their greatest concern)

Do you actively work with your clients on this constraint?

Pick 6

Topics to include are:

Alkalinity
Acidity
Sodicity
Salinity
Wind erosion
Water erosion
Nutrient decline and deficiencies
Nutrient toxicities
Poor retention of groundcover
Low levels of soil biology
Compaction

- Low organic carbon
- Loss or lack of soil structure (non-friable)
- Diseases and Pests
- Drainage
- Infiltration rates, porosity
- Water Use Efficiency
- Waterlogging
- High soil strength eg hard setting, dense
- Contamination Surface crusting
- Water repellency
- Low soil water holding capacity

Q9. For the soil constraints listed below, please describe the current amelioration technique(s) being used in your region (eg. could be agronomic, mechanical solutions) (if there are none, leave blank).

Constraint/issue	Technique 1	Technique 2	Technique 3
Soil structural (Including; compaction, sodicity infiltration/drainage/waterlogging,			

structure decline, high soil strength, surface crusting)			
Erosion (water and wind)			
Soil acidity			
Soil alkalinity			
Soil salinity			
Nutrient decline			
Poor groundcover			
Low biological activity			
Low organic carbon			
Water use efficiency			
Water repellency			
Soil contamination			
Other soil constraints of importance			

Q10. What is preventing your clients from implementing practices to address their soil constraints? (Select all that apply)

Knowledge/skills
equipment
time
capacity
confidence in the practice
no other farmer in region has tested it
confidence in the practice
risk
cost
capital
relative advantage (perceived net benefit of incorporating a new practice)
Other

(Have room for people to put a description if want to)

Q11. Where do you usually source your soil information? (Select all that apply)

State Government Departments

Catchment Management Authority/Natural Resource Management groups

Professional memberships

Agricultural industry group

Other private agricultural/industry consultant/agronomist

University resources

Social media

Other_______________________________________

Q12. What innovative/new practices would you like to see validated/demonstrated in your region? And why?

Q13. What will drive your clients to address their most limiting soil constraints? And why? (eg. economic returns, length of time an intervention lasts, productivity gains)

Q14. What do you think are the biggest gains to be made in your industry and/or region?

Thank you for participating in this survey. Your response has been successfully recorded.

If you would like to participate in follow up, in depth discussions, regarding soil constraints, or would like to receive a summary of the relevant collated results from this survey, then please fill out the follow up survey where you will be redirected after you press 'Done' below or copy this link into your web browser https://www.surveymonkey.com/r/SoilConstraintsFollowUp

If you have any questions, further feedback about this project or would like to participate in future project activities, please contact one of the following:

Melissa Cann - Agriculture Victoria

melissa.cann@ecodev.vic.gov.au

03 5036 4815 or 0408 052 845

or

Dr Susan Orgill - NSW Department of Primary Industries

susan.orgill@dpi.nsw.gov.au

0428 424 566

Appendix 3 Potential gross benefit of acidity amelioration based on 1996-97 dollars.

Industry	AUD$ Million
Beef	95.0
Sheep	50.5
Dairy	255.0
Cereals	156.7
Coarse Grain	5.4
Cotton	1.8
Oilseeds	22.5
Legumes	12.7
Hay	2.1
Horticulture	955.0
Sugar	27.8
Total	**1584.5**

Source: (Hajkowicz and Young 2005)

Appendix 4 Key soil constraints by industry – from adviser survey

	Beef Industry Soil Constraint Priority (50)	Sheep Industry Soil Constraint Priority (56)	Cropping Industry Soil Constraint Priority (62)
Extremely high	Acidity	Acidity	Acidity
	Nutrient decline and deficiencies	Nutrient decline and deficiencies	Nutrient decline and deficiencies
Very High	Compaction	Low organic carbon	Sodicity
	Low organic carbon		Compaction
			Low organic carbon
High	Water Use Efficiency	Water Use Efficiency	Water Use Efficiency
	Loss or lack of soil structure (non-friable)	Alkalinity	Waterlogging
	Waterlogging	Sodicity	Loss or lack of soil structure (non-friable)
	Sodicity	Waterlogging	
		Loss or lack of soil structure (non-friable)	
Medium	Poor retention of groundcover	High soil strength eg hard setting, dense	Salinity
	Low levels of soil biology	Low levels of soil biology	Infiltration rates, porosity
	Drainage	Water repellency	Surface crusting
	Infiltration rates, porosity	Compaction	Drainage
	Low soil water holding capacity	Poor retention of groundcover	High soil strength eg hard setting, dense
	Surface crusting	Low soil water holding capacity	Low soil water holding capacity
	Water repellency	Salinity	Low levels of soil biology
	Drainage	Water repellency	
		Infiltration rates, porosity	Poor retention of groundcover
		Surface crusting	
Low	Diseases and Pests	Diseases and Pests	Wind erosion
	Salinity	Wind erosion	Alkalinity
	High soil strength eg hard setting, dense		Diseases and Pests
	Wind erosion		Nutrient toxicities
	Water erosion		
Very Low	Alkalinity	Water erosion	Water erosion
	Contamination	Nutrient toxicities	Contamination
	Nutrient toxicities	Contamination	

	Dairy Industry Soil Constraint Priority (23)	Fruit and Vegetable Industry Soil Constraint Priority(22)	Irrigated Cropping Industry Soil Constraint Priority (30)
Extremely high	Waterlogging	Waterlogging	Nutrient decline and deficiencies
	Acidity	Acidity	Compaction

	Compaction		
Very High	Nutrient decline and deficiencies	Nutrient decline and deficiencies	Acidity
	Loss or lack of soil structure (non-friable)	Compaction	Low organic carbon
	Low organic carbon		Water Use Efficiency
			Sodicity
			Waterlogging
High	Drainage	Low organic carbon	Loss or lack of soil structure (non-friable)
	Water Use Efficiency	Loss or lack of soil structure (non-friable)	High soil strength eg hard setting, dense
		Sodicity	Salinity
		Water Use Efficiency	Surface crusting
Medium	Sodicity	High soil strength eg hard setting, dense	Infiltration rates, porosity
	High soil strength eg hard setting, dense	Drainage	Drainage
	Infiltration rates, porosity	Infiltration rates, porosity	Low levels of soil biology
	Poor retention of groundcover	Salinity	Alkalinity
	Low soil water holding capacity	Low soil water holding capacity	Low soil water holding capacity
	Surface crusting	Poor retention of groundcover	
		Surface crusting	
Low	Salinity	Alkalinity	Diseases and Pests
	Low levels of soil biology	Low levels of soil biology	Poor retention of groundcover
	Diseases and Pests	Water repellency	Wind erosion
	Water erosion	Diseases and Pests	Nutrient toxicities
	Water repellency	Nutrient toxicities	
	Alkalinity		
Very Low	Nutrient toxicities	Water erosion	Water erosion
	Wind erosion	Wind erosion	Water repellency
	Contamination	Contamination	Contamination

	Cotton Industry (12) Soil Constraint Priority	**Sugar Cane Industry (2) Soil Constraint Priority**	**Rice Industry (5) Soil Constraint Priority**
Extremely high	Water Use Efficiency	Alkalinity	Nutrient decline and deficiencies
	Compaction	High soil strength eg hard setting, dense	Water Use Efficiency
	Low organic carbon		
Very High	Nutrient decline and deficiencies	Nutrient decline and deficiencies	Low organic carbon
	Acidity	Sodicity	Compaction
	Sodicity		

High	Surface crusting	Acidity	Acidity
	High soil strength eg hard setting, dense	Low organic carbon	Loss or lack of soil structure (non-friable)
	Salinity	Nutrient toxicities	Salinity
	Loss or lack of soil structure (non-friable)		
Medium	Alkalinity	Drainage	Alkalinity
	Infiltration rates, porosity	Water Use Efficiency	Waterlogging
	Waterlogging		Low levels of soil biology
	Low soil water holding capacity		Infiltration rates, porosity
	Poor retention of groundcover		Nutrient toxicities
			Surface crusting
Low	Drainage	Compaction	Low soil water holding capacity
	Low levels of soil biology		Sodicity
	Diseases and Pests		Contamination
Very Low	Contamination	Contamination	Diseases and Pests
	Nutrient toxicities	Diseases and Pests	Drainage
	Water erosion	Infiltration rates, porosity	High soil strength eg hard setting, dense
	Wind erosion	Loss or lack of soil structure (non-friable)	Poor retention of groundcover
		Low levels of soil biology	Water erosion
		Low soil water holding capacity	Water repellency
		Poor retention of groundcover	Wind erosion
		Salinity	
		Surface crusting	
		Water erosion	
		Water repellency	
		Waterlogging	
		Wind erosion	

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