SOIL CRC

Performance through collaboration

FINAL PROJECT REPORT

A review of indicators of soil health and function: Farmers' needs and data management

Project 2.1.01

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Title	Final Project Report. A review of indicators of soil health and function: farmers' needs and data management - Project 2.1.01.
ISBN	N/A
Date	June 14th 2018
Keywords	Soil indicators, Soil performance, Soil data
Publisher	Cooperative Research Centre for High Performance Soils
Preferred citation	Dahlhaus P.G., Bennett J.McL., Corbett J., Crawford D., Grelet G., Imhof M., MacLeod A., Mele P.M., Stevenson B., Wells N. and Wong M. (2018) A review of indicators of soil health and function: farmers' needs and data management. Final Project Report, Soil CRC Project 2.1.01. Cooperative Research Centre for High Performance Soils, May 2018.

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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

There are many soil health/quality/fertility/function indicators that could be used to measure and monitor soil performance. The aim of this review is to investigate the range of soil indicators and their potential practical use to land managers, both private and public. This includes examining the global literature on soil performance indicators; surveying current use of indicators by farmers, agricultural practitioners, public land managers and researchers; and investigating the availability of suitable data to measure and monitor trends, and the tools to store, share and make these data available.

The review finds that no individual soil property or group of properties can universally indicate soil performance across all farming systems, ecosystems, geographies, seasons and markets. Indicators must be matched to their purpose, in the context of when and where they are measured and how the indicator value relates to a baseline and the acceptable range of the measure for that purpose. The usefulness of any indicator, or suite of indicators, can only be truly evaluated within the context of the business operation, its management subsystems, and the impacts of management decisions.

Soil performance may be evaluated as the sum of soil capability and soil condition, where capability indicates potential and the condition indicates actual state at the time of measurement. Since the indicator values vary in their spatiotemporal landscapes, and in relation to each other, a collection of indicators may be a more realistic measure of soil performance. It is likely that some of these may be more widely measured (in the spatiotemporal sense) using new sensor technologies.

OBJECTIVES	RESULTS
1) a review of the global literature to ascertain key soil properties that could form the basis for soil performance indicators, and the need for developing new, robust and affordable indicators.	A comprehensive review of physical, chemical and biological indicators was completed, gaps identified and recommendations made.
2) a participant workshop to ensure that the outputs of the scoping study are a true consensus of the industry and research perspectives, as well as ensure that the research findings and recommendations are pragmatic for industry and relevant to the future projects within the Soil CRC.	Thirty-eight people representing seventeen organisations attended a workshop held over three days. Consensus was reached on seven key projects for future research.
3) an online survey to collect data from agricultural industry practitioners to compliment the information gathered by the collaborating researchers from the published research literature.	An online questionnaire was completed by 122 respondents (38% farmers, 30% agronomist/consultant, 10% researchers, 7% industry representatives).

4) a review of the available data on indicators and the potential for real-time delivery of the data to end-users (i.e. Soil CRC participants)	A comprehensive review of global soil data availability was completed, with recommendations for a soil data federation.
NEXT STEPS	**TIMING**
Seven projects have been recommended to fill the research gaps, extend the research into new areas, and meet the Soil CRC milestones. These are:	
1) Building resilient and productive farming systems through linking sensitive indicators, soil functionality and plant performance.	Project submitted to first funding round in 2018
2) Visualising Australasia's Soils: A Soil CRC interoperable spatial knowledge system.	Project submitted to first funding round in 2018
3) Healthy soils, healthy country: exploring a framework for indigenous indicators of soil health.	Potential submission in future funding round
4) Developing a framework for soil security and natural capital using a suite of indicators, and guidelines for assessment.	Potential submission in future funding round
5) Quantitative links between 'tactical' and 'strategic' indicators: building a better suite of soil function indicators for decisions on the farm.	Potential submission in future funding round
6) 'Horses for courses': matching indicators to their purpose and standardising their measurement and interpretation.	Potential submission in future funding round
7) Benchmarking soil compaction: severity, extent, variability.	Potential submission in future funding round

1 INTRODUCTION

There are many soil properties and health/quality/fertility/function indicators that could be used to measure and monitor soil performance. The aim of this review is to investigate the range of soil indicators and their potential practical use to land managers, both private and public. This includes examining the global literature on soil performance indicators; surveying current use of indicators by farmers, agricultural practitioners, public land managers and researchers; and investigating the availability of suitable data to measure and monitor trends, and the tools to store, share and make these data available.

Measuring and monitoring soil performance is challenging due to the inherent temporal and spatial variability of soil and the variety of functions it delivers. The variability and variety of soil properties means that there are numerous potential measures that can be used to indicate soil health and function, but selection of indicators is specific to the need of individual programs. A significant focus for Program 2 of the Soil CRC is accurate and low-cost automated assessment of soil indicators at the farm scale that will link soil measurements with yield, productivity and profitability (both short-term and long-term). This review aims to identify the scope of appropriate measures and provide future research directions to develop soil indicators that are fit-for-purpose, along with the required measuring and instrumentation, data collection and management, data processing and analytics, and data modelling and visualisation approaches. The outcomes will guide the development of industry appropriate, robust, credible and practical management tools for farmers to improve their farm productivity and profitability.

Outside of the agricultural sector, appropriate soil performance/health/quality/function indicators are also required by people who regularly assess land and landscapes. They may include public land managers, indigenous land managers, catchment managers, ecologists, planners, environment protection agents, produce marketers, realtors, bankers and financiers.

1.1 Relationship to Soil CRC Outputs

This project draws on expertise from six university partners, three government agencies and six industry groups to contribute to four milestone outputs in Program 2 of the CRC, *viz:*

- Milestone Output 1 - Key indicators of high performance soils

  Identification of data and thresholds defining a high performance soil and determine key indicators of high performance soils, including microbial functionality across key soil types.

- Milestone Output 2 - Sensor networks for on-demand assessment of key soil indicators

  Development of 'use appropriate' sensors to provide actionable information on soil water, nutrients and microbial function. This may include the novel re-configuration of existing sensors or the creation of new sensors to fill any identified technology gaps.

- Milestone Output 3 - Intelligent analytics of big data

  Development of back-end capability to analyse raw soil data and assess the interactions within it and provide the results to farmers and agronomists. The analytics will be driven by intelligent and machine learning algorithms to process a continuous multi-source data stream.

- Milestone Output 4 - Mobile apps to deliver sensor data for day-to-day soil management.

  Development of user-friendly and informative app-based user interfaces in consultation with farmers.

As a scoping study, the outcomes are intended to guide future CRC projects.

1.2 Project aims

The overarching aim of this project is to review which soil properties (physical, chemical and biological) might be used as indicators of soil health and function, for farmers, agronomists and advisors to translate into practical management of the agricultural resource, meeting profitability and sustainability expectations of land managers and government.

As a scoping study, the intention is to guide the Soil CRC in future projects by providing a comprehensive and considered review of:

- what data farmers are collecting, why they collect it, whether they use it and what data they would ideally like,
- what tools and methods (indicators) are farmers already using to assess their soil performance,
- the current availability of soils data and the usefulness and limitations of this data,
- a review of the current initiatives (international, national, state and regional) that are doing the same thing,
- models of current soils and sensor data collection, storage, management, etc.,
- the ability to scale up the indicators from point to landscape, and
- conceptual models for interoperable (on-the-fly) data federation, manipulation, modelling and visualisation.

The project draws conclusions and makes recommendations for future research projects that will fulfil the Soil CRC Research Program Milestones.

1.3 Research methods

The scoping study was undertaken in four distinct, but linked, components:

1. a review of the global literature to ascertain key soil properties that could form the basis for soil health/function/performance indicators, and the need for developing new, robust and affordable indicators.

   This component was delegated to three expert panels:

   A. Physical Indicators led by Mark Imhof (Agriculture Victoria Research) and Bryan Stevenson (Manaaki Whenua Landcare Research);

   B. Chemical Indicators led by Naomi Wells (Southern Cross University) and Doug Crawford (Agriculture Victoria Research), and

   C. Biological Indicators led by Pauline Mele (Agriculture Victoria Research) and Gwen Grelet (Manaaki Whenua Landcare Research).

2. a workshop, held over three days in late March 2018, brought together key participants in the project to ensure that the outputs of the scoping study are a true consensus of the industry and research perspectives, as well as ensure that the research findings and recommendations are pragmatic for industry and relevant to the future projects within the Soil CRC. The workshop was co-convened with a separate Scoping Review, led by Marcus Hardie (University of Tasmania) and John McLean Bennett (University of Southern Queensland), that examined the analytical approaches and/or sensor technologies that

could contribute indicators.

3. an online survey was devised and used to collect data from agricultural industry practitioners to compliment the information gathered by the collaborating researchers from the published research literature. The survey allowed a comparison of perceptions of soil indicators across agricultural systems, as well as exploring the perceived value of indicators across the roles of agricultural practitioners (farmers, advisors, researchers) and the geographies in which they operate. The survey and analysis of results was led by Megan Wong, Jennifer Corbett and Peter Dahlhaus (Federation University Australia). Ethics approval for the questionnaire was granted by FedUni Human Research Ethics Committee (#A18-007, 27/2/2018).
4. a review of the available data on indicators and the potential for real-time delivery of the data to end-users (i.e. Soil CRC participants) was undertaken by Peter Dahlhaus and Andrew MacLeod (Federation University Australia). The review includes international, national, state and regional initiatives to make soil data open and available, as well as the potential for accessing soil data from the private sector and community contributed data.

1.4 Project outputs

The Scoping Study is presented through three main outputs, viz: a written report (this document) that compiles all the information, analysis, conclusions and recommendations; four short video presentations that present the key messages from the study; and a separate report documenting all the results of the online questionnaire, for access by future researchers.

1.4.1 Structure of this report

The main components of the Scoping Study are outlined in the chapters of this report, i.e.: review of physical soil indicators (Chapter 2); review of chemical soil indicators (Chapter 3); review of biological soil indicators (Chapter 4); summary of the workshop outcomes (Chapter 5), summary of the online questionnaire (Chapter 6) and review of soil data and access systems (Chapter 7). The components of the Scoping Study are brought together in a discussion (Chapter 8) and the key findings are stated in the conclusion (Chapter 9). Recommendations for future research projects are presented in Chapter 10.

1.4.2 Video reporting

Four short videos have been prepared to present the key findings of the Scoping Study, in a way that makes the information more accessible to a broader audience. The videos feature interviews with the project team leaders who have contributed to this report, delivering key messages on the following topics:

- What are soil indicators?
- Are your soil indicators fit for purpose?
- Is a suite of soil indicators a better measure of soil performance?
- The Soil CRC journey to find soil health, soil function and soil performance indicators.

1.4.3 Survey structure and data

The online questionnaire, the results of the survey and the data collected has been archived for future use by researchers if required. It may provide a useful 'benchmark survey' for future comparisons and evaluation of the impact of the research undertaken by the Soil CRC.

2 PHYSICAL INDICATORS OF SOIL PERFORMANCE

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2.1 Overview and summary

The Soil CRC defines soil health as the ability to support highly productive farming systems that are also highly profitable both in the short and long term. Physical indicators are related to the arrangement of solid particles and pores. The size, abundance and arrangement of soil pores for instance largely determine the ability of water to infiltrate into the soil, the transmission of water through the soil and the soils ability to store water. Deterioration in soil physical condition is related to erosion, soil sealing, compaction and desertification (Bünemann *et al*. 2018), which directly impact the productivity of soils.

The general criteria used for selecting the physical and biological indicators, previously described by Moebius (2006), were listed by Idowu *et al*. (2008) and included:

- Sensitivity to management, i.e., frequency of significant treatment effects in the controlled experiments and directional consistency of these effects.
- Precision of measurement method, i.e., residual errors from analyses of variance.
- Relevance to important functional soil processes such as aeration, water infiltration/transmission, water retention, root proliferation, nitrogen mineralization, development of root diseases, etc.
- Practicality - ease and cost of sampling.
- Cost of analysis.

According to Idowu *et al*. (2009), most studies agree that a minimum data set for the assessment of soil health should include key indicators that: (1) are sensitive to changes due to management and climate variations, (2) integrate soil physical, chemical and biological properties, (3) are relatable to important soil functions, (4) applicable to field conditions and (5) accessible to many users.

There is a relatively small number of soil physical indicators that are widely used (e.g. bulk density, texture, available water holding capacity, infiltration rate, water stable aggregates, penetration resistance, erosion rating), but a variety of measures could be used depending on the specific purpose. The purpose of soil monitoring should dictate indicators selected and the appropriate sampling, measurement and assessment of those indicators. Indicators can be used for many purposes, including:

- Guiding tactical management decisions on-farm, or whole-farm-planning (e.g. how susceptible is the soil to structural degradation?; when is an appropriate time for tillage?; how is the soil meeting needs of the crop?). This could involve use of visual soil assessment and semi-quantitative techniques (e.g. dispersion, slaking, field test for determining plastic limit, cloddiness, visual assessment of roots in soil profile).

- Measuring change in soil condition on-farm, or paddock, performance (e.g. water and nutrient use efficiency).
- Monitoring soil condition change (on trial site, in paddock, regional, national or industry-wide) - usually requiring more quantitative techniques that are sensitive enough to show real change (e.g. discriminate between treatments). For monitoring, the analytical and sampling methods selected need to reflect soil temporal and spatial variability.
- Providing industry or regional benchmarking, credence values or sustainability metrics for a variety of purposes such as product branding or state of the environment reporting.

It is therefore difficult to advocate a generic approach to measuring soil condition and function. Instead we advocate the development of an appropriate suite of indicators appropriate to the purpose of the assessment and tailored to specific soil types and regions where the assessment will take place. Assessments could be a mix of field observations of soil characteristics (e.g. from soil pits, cores or digging), to laboratory analyses that complement the field observations with more quantitative data, to more advanced assessment that may be relevant to a key issue (e.g. assessments that relate to OC fractions).

Rabot *et al*. (2018) highlight the greater relevance of pore network characterisation compared to an aggregate perspective and identified porosity, macroporosity, pore distances, and pore connectivity, derived from imaging techniques, as being the most relevant indicators for several soil functions. Since imaging techniques are not widely accessible, they suggest using this technique to build an open-access "soil structure library" for a large range of soil types, that could form the basis to relate more easily available measures to pore structural attributes in a site-specific way (i.e. accounting for texture, organic matter content etc).

McKenzie (2013) noted that despite major advances in remote sensing and soil landscape modelling, the use of Visual Soil Examination and Evaluation (VSEE) techniques in the field should be a key component of soil assessment and management packages in Australia. These field-based techniques complement well established procedures such as laboratory analysis of soil samples. He proposed a new scheme for 'whole-farm assessment and management planning' based on a mix of VSEE methods, modern soil databases, and additional laboratory testing where appropriate.

2.1.1 Opportunities for the Soil CRC

- Soil health management requires an integrative approach that recognises the physical, biological and chemical processes in soils. The development of an integrated soil health test, or kit, would be a valuable research priority for the Soil CRC to allow farmers to make better management decisions, especially those other than basic fertiliser management. Also, Soil CRC researchers investigating new products and management strategies need appropriate integrated soil assessment tests that are tailored to the specific soil types that they are investigating.
- While there are interrelationships between chemical and physical indicators that are commonly assessed, there are few documented interrelationships between soil biotic indicators and soil physical indicators. This also presents an opportunity for the Soil CRC.
- There are very few studies that have financial metrics associated with changes in soil health and economic performance of farms.
- Farmers, consultants, advisers have usually played an insignificant role in development of soil quality assessment schemes – despite being important end users (Bunemann et al. 2018). This is an area that offers opportunities for the Soil CRC.

- Spatial and temporal variability needs to be considered in developing indicators and associated sampling strategies.
- Grading of soils by indicators across soil types, climates and cropping systems is difficult (Schjønning et al., 2004). However, context is critical and future Soil CRC work should maintain focus on contexting measurement of soil properties according to soil type, landscape, agricultural industry, agro-ecological zone etc. The SOILPak for Cotton work provides an excellent example of tailoring soil assessment to a specific soil (Vertosols) associated with a specific industry (cotton cropping).
- Integration of pore space architecture with soil function is likely to be a valuable research area that will bring together soil biological, chemical and physical measures.
- Indicators that can be surrogates for other soil functions provide more versatility in assessments.

Soil compaction and erosion are two of the most detrimental effects of decreased soil physical condition and assessment of these two areas should be a priority. Compaction and soil variability are issues that directly affect productivity and were identified by grower groups as a priority at the recent Soil CRC Program 2 workshop in Melbourne. There is a need for a project that addresses soil compaction as a key soil constraint and provides a framework for the identification, assessment, benchmarking and monitoring of soil compaction for key cropping soils for different agricultural industries. Such a project could develop the concept of identifying and measuring where a soil is on the 'compaction continuum' for a range of key soil types. Techniques could be developed for farmers and advisers to understand where they are on the compaction continuum and better understand and manage variability. This work would then provide Programs 3 and 4 with more robust methods for measuring changes in compaction due to amelioration interventions. Existing sensing techniques, such as constant velocity penetrometers, along with proximal sensing (e.g. Ground Penetrating Radar (GPR), EM38 and Electrical Resistivity Tomography (ERT) could be utilised to determine the best indicators to map and measure compaction at the paddock scale (linking to Theme 3 on mapping soil constraints). Novel imaging techniques could also utilised to visualise compaction and effects on plant roots and soil pore architecture (which affects water and air movement through the soil). Assessments for CTF and non-CTF systems and for key industries such as Grains, Sugar and Horticulture. Confounding variables such as soil moisture, clay content and soil structure need to be factored in to assessments. Interactions between other relevant constraints (e.g. sodicity) could be assessed and consideration given to determining how some biological and chemical properties 'shift' along the 'compaction continuum' (relating to amelioration and degradation).

2.2 Soil Physical indicators and attributes - what they represent

Soil physical analyses (along with soil chemistry) form the basis of the most widely accepted and standardised indicators (Table 1). Although some of these analyses can be performed in the field, they are most often performed in the laboratory using standard techniques for greater accuracy of measurement. Infiltration rate, for example, is typically performed in the field, but is also considered to be highly variable spatially and would require many samples to adequately determine the range of values on a paddock scale. Choice of indicators, and associated sampling strategies, therefore depend on the objectives for measurement (e.g. guide on-farm management, state of the environment (SOE) reporting, monitoring change in condition), required precision and soil spatial variability.

We have reviewed many manuscripts and reports (see reference list), but for brevity of synthesis of literature we rely heavily on several very recent and comprehensive reviews (particularly Rabot *et al*. 2018 and Bünemann *et al.* 2018) and key studies. Additional material is contained in the appendix. While this chapter specifically covers soil physical indicators, it is important to emphasise that physical, chemical and biological indicators all influence each other and should not be considered in isolation.

Table 1. Soil Health Institute (SHI) 'Tier 1' Indicators* represent the most widely accepted and standardised methodologies. Soil physical indicators included in the list are **bolded**.

organic carbon	Potassium
pH	carbon mineralization
water-stable aggregation	nitrogen mineralization
crop yield	**erosion rating**
texture	base saturation
penetration resistance	**bulk density**
cation exchange capacity	**available water holding capacity**
electrical conductivity	**infiltration rate**
nitrogen	Micronutrients
phosphorus	

*http://soilhealthinstitute.org/tier-1-indicators-soil-health/

Whilst the indicators presented in Table 1 are the most widely accepted, there is a great variety of methods used to characterise soil physical properties. These have been grouped into several broad categories and the attributes they represent in Table 2.

Table 2. Soil physical indicators grouped into broad categories

Category or Issue	Indicator/Attribute/Measurement
Morphological characteristics	Mineralogy Texture / consistence Soil colour Soil horizons Presences of pedogenic features (e.g. pans, impermeable layers, nodules, fracturing) Stoniness (size / abundance)
Soil/Solum depth	Topsoil (A1) depth Rooting depth Soil profile depth Depth to impermeable layer
Soil Structure and Stability	Aggregate size and class Aggregate stability Slaking/dispersion Water-stable aggregation (wet-sieving)

Soil Strength/Deformation/Compaction	Modulus of rupture / soil strength Load bearing capacity Penetration resistance Liquid and Plastic limits (Atterberg limits) Bulk density Soil shrinkage
Soil porosity and Pore Distribution	Bulk density/particle density Total porosity Pore size distribution (e.g. macropores) Pore architecture/pore connectivity Mercury porosimetry
Water Infiltration, Transmission, Storage	Infiltration rate Hydrophobicity/water repellence Hydraulic conductivity/preferential flow Water holding capacity Water content Water balance/leaching potential

Pedological characteristics are the inherent soil characteristics that pedologists use to map soils. These characteristics (e.g. soil texture), can be used to create pedo-transfer functions that correlate to other properties. Topsoil depth, solum depth and rooting depth are also measures closely linked to pedological characteristics. There is a strong link with some of these soil attributes to Program 3 (mapping soil constraints component) of the Soil CRC program.

Soil structure represents one of the main soil physical indicators and is closely linked with both inherent pedological characteristics (particularly particle size distribution) and pore size distribution/pore architecture. Rabot *et al.* (2018) argue that there are currently two distinct ways of looking at soil physical structure: 1) aggregate size and structure, versus 2) pore imaging and pore architecture. There is a variety of methodologies for both (see methodologies); however, pore architecture tends to be dominated by more sophisticated (and expensive) imaging techniques such as X-ray computed tomography (Rab *et al*. 2014). Pore size imaging and architecture presents unique perspectives on integrating aspects of biology into soil physical indicators as pore size determines the habitability of microsites for micro- and meso- biota (based on size of the organism). Rabot *et al* (2018), suggest that “bottle necking” of pores can occur so that even though a majority of a pore may be of habitable size, the entry to the pore may be narrower so that organisms cannot inhabit the pore space even though some measures of overall pore size/distribution may indicate habitable space.

Climate overall determines the soil water regime; however, soil physical properties such as infiltration rate, hydraulic conductivity, and soil water holding capacity also affect the amount of plant available water (PAW). The amount of water stored in the soil that plants can utilise is largely a function of the particle size distribution of the soil and is typically measured by water release curves. Water entering the soil, however, is a function of the Infiltration rate and can also be affected by hydrophobicity (water repellence). Preferential flow pathways (i.e. large macropores), can result in less water stored in the soil and minimise the “filtering” effect of the soil matrix (soil minerals and organic compounds) on pollutants in the soil water (McLeod *et al*. 2008).

Compaction and erosion are some of the major consequences of poor soil physical condition. Erosion can result in loss of the topsoil altogether, while compaction can affect air diffusion into the soil, and infiltration and transmission of water into and through the soil. Decreases in infiltration rate and hydraulic conductivity can in turn lead to increased surface runoff and decrease rooting depth). More details are provided in Appendix 1.

2.3 Relationships of Physical attributes to Soil Function

Rabot *et al*. (2018) reviewed soil structure (physical attributes) as an indicator of soil functions. Table 3 below (direct from Rabot *et al*., 2018) provides an overall summary. A selection of frequently used soil structural properties was analysed and discussed from a methodological point of view and with respect to their relevance to soil function (biomass production, storage and filtering of water, storage and recycling of nutrients, carbon storage, habitat for biological activity and physical stability and support. Properties assessed include visual soil assessment (VSA), aggregate size distribution and stability (dry-sieving, wet-sieving, water-dispersible clay), bulk density, and pore space characterisation. Pore space characterisation can be undertaken by indirect methods (such as mercury porosimetry, water retention curve); derived indicators such as gas adsorption, direct methods such as imaging techniques. They highlight the greater relevance of pore network -characterisation compared to an aggregate perspective and identified porosity, macroporosity, pore distances, and pore connectivity, derived from imaging techniques, as being the most relevant indicators for several soil functions. Since imaging techniques are not widely accessible, they suggest using this technique to build an open-access 'soil structure library' for a large range of soil types, that could form the basis to relate more easily available measures to pore structural attributes in a site-specific way (i.e. accounting for texture, organic matter content etc).

Table 3. Soil physical attribute relationship to soil functions (from Rabot *et al*.,2018).

Measurement method	Indicator	Soil function					
		Biomass production	Storage and filtering of water	Storage and recycling of nutrients	Carbon storage	Habitat for biological activity	Physical stability and support
Whole profile evaluation	Ped grade		×				
	Ped size						
	Ped shape						
Topsoil evaluation	Visual evaluation score	×	×				×
Bulk density	Bulk density	(×)					×
	Degree of compactness	×	×				
	Packing density	×					
Aggregate size distribution and stability	Stability index		×	×			×
	Aggregate size distribution	×	×		×		×
	Water-dispersible clay		×	×			×
	Microaggregates-within-macroaggregates				×		
Mercury porosimetry	Porosity						
	Macroporosity					×	(×)
	Microporosity					×	
Water retention curve	Porosity		×				
	Macroporosity	×				×	
	Microporosity					×	
	Air capacity	×					
	Relative field capacity	×		×		×	
	Available water capacity	×	×				
	LLWR	(×)					
	S index	(×)	×				×
Gas adsorption	Specific surface area				(×)		
	Mesoporosity (2–50 nm)						
	Microporosity (< 2 nm)						
Imaging techniques	Porosity	×	×	(×)			×
	Macroporosity	×	×	(×)	×	×	
	Microporosity	×	×	(×)	×	×	
	Connectivity		×	(×)	×		×
	Pore orientation		×	(×)			
	Pore shape		×	(×)			

Arshad et al. (2002) provided a list of key soil indicators and relevance to soil function (Table 4 below). The five key physical indicators listed are topsoil depth, aggregation, texture, bulk density, infiltration.

Table 4. Key indicators for soil quality assessment and rationale for selection (Arshad *et al*., 2002).

Table 2
Key soil indicators for soil quality assessment (after Arshad and Coen, 1992; Doran and Parkin, 1994; Gregorich et al., 1994; Larson and Pierce, 1994; Carter et al., 1997; Karlen et al., 1997; Martin et al., 1998)

Selected indicator	Rationale for selection
Organic matter	Defines soil fertility and soil structure, pesticide and water retention, and use in process models
Topsoil-depth	Estimate rooting volume for crop production and erosion
Aggregation	Soil structure, erosion resistance, crop emergence and early indicator of soil management effect
Texture	Retention and transport of water and chemicals, modeling use
Bulk density	Plant root penetration, porosity, adjust analyses to volumetric basis
Infiltration	Runoff, leaching and erosion potential
pH	Nutrient availability, pesticide absorption and mobility, process models
Electrical conductivity	Defines crop growth, soil structure, water infiltration; presently lacking in most process models
Suspected pollutants	Plant quality, and human and animal health
Soil respiration	Biological activity, process modeling; estimate of biomass activity, early warning of management effect on organic matter
Forms of N	Availability to crops, leaching potential, mineralization/immobilization rates, process modeling
Extractable N, P and K	Capacity to support plant growth, environmental quality indicator

The interrelationships of the five soil physical indicators with other soil quality indicators is also shown in Table 5 below.

Table 5. Interrelationship of soil indicators (Arshad *et al*., 2002).

Table 1
Interrelationship of soil indicators

Selected indicator	Other soil quality indicators in the MDS affecting the selected indicator
Aggregation	Organic matter, microbial (especially fungal) activity, texture
Infiltration	Organic matter, aggregation, electrical conductivity, exchangeable sodium percentage (ESP)
Bulk density	Organic matter, aggregation, topsoil-depth, ESP, biological activity
Microbial biomass and/or respiration	Organic matter, aggregation, bulk density, pH, texture, ESP
Available nutrients	Organic matter, pH, topsoil-depth, texture, microbial parameters (mineralization and immobilization rates)

2.4 Quantitative Methods

The Australian standard handbook on 'Soil Physical Measurement and Interpretation for Land Evaluation' (McKenzie *et al*., 2002) provides guidance on estimation for soil physical properties but does not provide a broad group of procedures used for rapid diagnosis, or screening, either in the field or laboratory. These diagnostic methods have greatest utility when related to physical parameters such as those generated by the handbook. The handbook discusses some soil engineering methods, but most, such as the United Soil Classification System, are well described in other publications (such as Hicks (2000), Crouch *et al*. (2000) and Das (2002), as well as Australian Standards.

Soil porosity and Pore Distribution	Bulk density/particle density
	Total porosity
	Pore size distribution (e.g. macropores)
	Pore architecture/pore connectivity
	Mercury porosimetry

Pore space relations characterise the proportions of air, water and solids in soils, expressed either as volume or mass fractions. They provide useful indicators of the physical condition of the soils and allow inferences to be made about biological processes and soil responses to management (Cresswell and Hamilton 2002). Laboratory and field methods for the measurement of bulk density and pore space relations are described by Cresswell and Hamilton (2002). These properties are critically important in the soil-plant-atmosphere system as they affect movement of water and air through the soil.

2.4.1 Bulk Density

Particle density (density of solids) is defined as the mass of solid divided by its volume. Bulk density (BD), usually expressed in units of Mg/m^3, is a measure of the degree of compaction of the soil. One of the most important factors agriculturally in terms of bulk density is plant growth, if the soil has a high bulk density (compaction) emergence and root growth will be restricted which will affect plant growth and yield. Root crop growth decreases with increase in BD. There is a threshold value depending on soil type and plant species.

Creswell and Hamilton (2002) describe various laboratory and field methods for the measurement of bulk density and pore space relations. Methods used for measuring bulk density use intact cores, intact soil clods, or field excavation (water replacement). The intact core method (Method 503.01) requires collection of intact core (preferably at least 75 mm diameter and 50-75 mm length). A method variation (503.02) for soils with vertic properties involves placement of the specimen on contact material on top of ceramic plate, which is then saturated and drained to 11.0 m matric potential. For soils containing coarse fragments another variation is recommended (Method 503.05-503.08). The Intact clod measurement (Method 503.03) involves coating clods with paraffin wax to allow measurement of volume by displacement of water. The Field excavation (water replacement) method (Method 503.04) based on the NRCS (USDA) method.

Rabot *et al*. (2018) consider that bulk density, by itself, is not considered a good indicator of soil functions in general as it does not account for important soil structural attributes.

2.4.2 Porosity

Soil porosity is expressed either as a percentage or in units of m^3/m^3 or cm^3/cm^3. Porosity can also be calculated from bulk density and particle density. Large values of bulk density, and correspondingly small values of porosity, could be due to compaction and may result in impeded root penetration and water movement (Cresswell and Hamilton 2002). Air-filled porosity of a soil is the volume of air divided by the total volume of soil. It is a measure of the relative air content and varies according to water content. Air-filled porosity at water contents near field capacity is sometimes used as an index of soil aeration and an important factor determining biological activity. Poor aeration often results from compaction or impeded drainage and waterlogging. (Cresswell and Hamilton 2002).

There is a range of methods used to measure porosity – ranging from indirect techniques such as mercury porosimetry, gas adsorption and calculated water retention curves, to more direct methods such as the visualisation and quantification of pore size, pore connectivity and pore size distribution using techniques such as X-ray computed tomography scanning.

X-ray Computed Tomography (CT) is a non-destructive and non-invasive technique that has been successfully used for three-dimensional (3D) examination of soil. A review of the application of x-ray CT to soil science was published by Taina *et al*. (2008). Valuable information has been obtained by the application of CT for the description and quantitative measurements of soil structure elements, especially of soil pores and pore network features. In many studies, X-ray CT has been used to investigate the hydro-physical characteristics of the soil, in a functional and temporal manner. A dynamic approach has also been utilized in the evaluation of biotic factor influences on soil. The analysis of soil solid phases, by X-ray CT, has been challenging due to the similar X-ray attenuation of different solid constituents. However, the use of multiple X-ray energy levels has facilitated the discrimination of minerals in soil. Many of these problems associated with interpreting X-ray CT imaging of soil are being overcome by the improvement of X-ray image acquisition techniques and by the development of new approaches and algorithms for image processing. Advanced methods and algorithms that consider relationships between members of selected populations allow the use of all dimensions, spatial and spectral, of the X-ray CT data. X-ray CT brings an important contribution to the characterization of spatial variability of root systems, as well as rhizosphere processes.

Rab *et al*. (2014) discussed the use of X-ray CT scanning to characterise (and visualise) pore space. Results suggested that while absolute measures of macroporosity might not change with core size or the volume of soil analysed, the pore-space characteristics that are captured differ significantly. Macroporosity values for various pore size classes (0.2 to 298 μm pore diameters) assessed using soil–water retention curves compared with those determined using the X-ray CT were found to be comparable. Consequently, X-ray CT is viewed as a valuable tool for characterising pore-space from the macro- to the micro-scale; however, sampling and analysis strategies must be appropriate for the specific research aims.

A more recent paper by Pires *et al*. (2017) presents a detailed analysis of changes in soil structure induced by conventional (CT) and no-tillage (NT) systems. Three different soil depths were studied (0–10, 10–20 and 20–30 cm). Data of the soil water retention curve (SWRC), micromorphologic (impregnated blocks) (2D) and microtomographic (mCT) (3D) analyses were utilized to characterise the Soil Porous System (SPS).

Rabot *et al*. (2018) noted that indirect methods to characterise pore space, such as water retention curve, MIP and gas adsorption, all require assumptions on an idealised pore shape to interpret results. These assumptions may be suitable for studying soil functions related to water retention and transport but need to implicitly cater for 'ink-bottle' effect. Laboratory based imaging techniques appear to be efficient in characterising soil structure because they allow quantification of pore volume, pore size distribution, pore connectivity etc. A major conclusion from Rabot *et al*. review is that pore network characterisation based on undisturbed samples is much more powerful to assess soil functions compared to analysis of disturbed aggregates. There are new tools to quantify soil structure using non-destructive tomographic techniques (mainly x-ray computed tomography) but these are not widely applicable to characterise field soils.

Effort should be made to produce knowledge about structural characteristics for a large range of soil types in connection to their functional characteristics. Rabot *et al.* suggest developing standardised protocols for quantifying soil structure based on undisturbed imaging in terms of pore morphology and topology. As a next step, developing an open access "soil structure library", gathering information on selected indicators together with metadata (e.g. imaging technique, sampled volume, image resolution), a site and soil characterisation (i.e. soil type, texture, SOM, sampling depth etc) and complementary soil properties (e.g. other soil structure indicators, saturated hydraulic conductivity, air permeability etc). Through this database it will become possible to establish relationships between selected indicators of undisturbed soil structure with simpler indicators of soil structure in a site-specific way. They identified porosity, macroporosity, pore distance and pore connectivity as relevant for several key soil functions.

According to Beare *et al*. (2007), macroporosity is greatly influenced and distorted by tillage and target ranges are poorly defined for arable and horticulture land uses.

Soil Strength/Deformation/Compaction	Modulus of Rupture/soil strength
	Load bearing capacity
	Penetration resistance
	Liquid and Plastic limits (Atterberg limits)
	Bulk density
	Soil shrinkage

2.4.3 Modulus of Rupture

Modulus of Rupture (MOR) is a laboratory technique used to measure the structural stability of hard-setting surface soils and susceptibility to crusting. A summary of the techniques is discussed by Cochrane and Aylmore (2002), based on Aylmore and Sills (1982). For many apedal soils, MOR is correlated with permeability and workability and provides a convenient means of assessing overall physical behaviour. The method uses a single wetting and drying cycle to form a soil briquette. Soil cohesion is then measured in a flexure test and is an index of soil structural stability. It is well-suited to measuring the effects of soil treatments or amendments ion structural stability. Method 521.01 Cochrane and Aylmore, in McKenzie *et al.* (2002).

Modulus of Rupture has been used as a predictor of seedling emergence in crusted soils. Agrawal and Sharma (1984), for example, studied the effect of triple superphosphate (TSP) and polyvinyl alcohol (PVA) application on crust strength, soil physical properties and seedling emergence of pearl millet was studied on a sandy loam soil. Crust strength measured by cone and pocket penetrometers in-situ and by MOR in the laboratory correlated significantly. Final seedling emergence percentage and rate of emergence increased significantly under TSP at 800 kg ha-1 P and PVA at 0.1% (wt/wt) treatments. Soil physical properties viz., water-stable aggregates > 0.25 mm, dispersion percentage and modulus of rupture of soil governed the final seedling emergence of pearl-millet, in addition to the crust strength. These soil properties can be used for evaluation of crust strength and final seedling emergence of pearl millet. Aylmore and Sills (1982) concluded that although more detailed studies are required, the value of this approach was illustrated by its apparent ability to differentiate clearly between the effects of different management techniques (e.g. continuous cultivation as against continuous cropping), and even between short term effects arising within 1/1 rotations

2.4.4 Penetrometer resistance

Field penetrometers (Hignett, 2002) have a tip diameter of >5 mm and length of up to 1 metre. Larger penetrometers (with diameters >10 mm) can help overcome soil variability issues. Use of cone penetrometer involves pressing it into the soil at a steady rate and measuring required force. A useful summary of soil strength is ‘penetration energy’ – the integral of penetrometer resistance for depth range measured (estimating total energy needed for plant roots to ramify into the soil). Soil moisture content or matric potential needs to be determined as soil strength depends largely on water content. Drained Upper Limit (DUL), after soil has been thoroughly wet and allowed to drain, usually results in most useful data. Utility of field penetrometer data diminishes when determinations are made at potentials drier than DUL – measurement variability increases with decreasing water content. Penetrometers do not follow pathways available to roots such as pores and cracks. Laboratory measurements using micro penetrometers on soil cores can also be carried out (Method 520.01 in McKenzie *et al*., 2002).

2.4.5 Liquid and Plastic Limits

Liquid Limit (LL) and Plastic Limit (PL) are somewhat arbitrary empirical measures of soil consistency and are well described in Kirby (2002). Liquid limit is soil water content at divide between plastic, ductile behaviour and liquid, flowing behaviour. Plastic Limit is soil water content at divide between plastic, ductile behaviour and brittle, cracking behaviour. For both tests, soil is brought to a fully remoulded and saturated condition. Since introduction by Atterberg (1911a), the Liquid and Plastic limits (collectively referred to as Atterberg limits) have become widely used indicators of soil behaviour for engineering (predicting soil performance as a construction material) and agriculture. The limits are correlated to many other soil properties useful for agriculture as they:

- Correlate with many fundamental soil properties (e.g. bulk density) and properties such as soil strength, friability and compressibility.
- Provide indicators for management operations (plastic limit particularly).

Plastic Limit suggested for some soils as useful indicator when soil is sufficiently dry to withstand traffic without excessive compaction (Kirby 1988); optimum workability (optimum condition suitable for ploughing is at, or near, PL). Difference between PL and FC gives useful indication of soil workability (Dexter 1988). Plastic Limit is fully described in Australian Standard AS 1289.3.2.1 (1995) and involves using dried, ground sample (passed through 425 µm sieve) and rolling by hand on a glass plat to form a thread 75 mm long and 3 mm diameter. When it becomes impossible to roll the thread without it cracking into separate pieces then the soil water content is determined by oven-drying at 105°C.

Lab measurements are fully described in various standards, including Australian Standard AS1289 (1991, 1995). Two tests have been used for measuring Liquid Limit – 'Casagrande method' (Method 519.01) and 'Drop Cone method' (method 519.02).

A basic version of the traditional PL test can be performed in the field to indicate workability of a soil for tillage (Daniells and Larsen, 1991). A sample of soil from relevant depth (corresponding to tillage depth) is rolled into a thread. If the thread is rolled easily, soil is too wet to work; if it crumbles then it is at plastic limit and may be tilled. This is an example of a more simplified method that can be used by a farmer, or adviser, to support tactical soil management. A more quantitative measurement can be used if greater precision is required.

2.4.6 Soil Shrinkage

Recommended methods, as detailed by McGarry (2002), are:

- Linear Shrinkage (based on Standards Association of Australia, 1977) where determination is made of % decrease of a subsample of remoulded soil from liquid-limit to oven-dry (Method 518.01).
- Coefficient of Linear Extensibility (COLE) (Grossman *et al*. 1968) where determinations of volume change of intact soil clods are made between moist and oven-dry (Method 518.02).
- Modified linear shrinkage (McKenzie *et al.* 1994) where linear shrinkage is determined on sieved rather than remoulded soil (Method 518.03).

In land resource assessment studies, soils are often classed in terms of their potential for volume change. This would provide quantitative assessment beyond visual assessments of cracking intensity and soil structure (e.g. lenticular peds). Potential, and growing demand, though for express resiliency or potential, through wetting and drying cycles, to self-repair compaction.

2.4.7 Soil Consistence

Consistence refers to the strength of cohesion and adhesion in soil (NCST 2009). Strength varies according to soil water status (that must be recorded with strength). Strength of soil is its resistance to breaking or deformation. It is determined by the force just sufficient to break or deform a 20 mm piece of soil (ped, part of a ped, compound ped or fragment) when a compressive shearing force is applied between thumb and forefinger (i.e. loose - no force required (separate particles such as loose sands); Very weak - very small (almost nil) force; weak - small but significant force; firm - moderate or firm force; very firm - strong force (but within power of thumb and forefinger); strong - beyond power of thumb and forefinger (crushes underfoot on hard flat surface with small force; very strong – crushes underfoot on hard flat surface with full body weight applied slowly; rigid – cannot be crushed underfoot by full body weight applied slowly).

Water Infiltration, Transmission, Storage	Infiltration rate
	Hydrophobicity/water repellence
	Hydraulic conductivity/preferential flow
	Water holding capacity
	Water content
	Water balance/leaching potential

2.4.8 Soil Water Characteristic

Plant available water is a key factor for plant growth, influencing plant C input, nutrient cycling, microbial activity, with implications for resource use efficiency, etc. A range of techniques are described by Cresswell in McKenzie *et al*. (2002). The total soil water potential can be considered as: mutual attraction between water and soil particles (matric potential), a component due to gravity (gravitational potential) and a component due to soluble salts (osmotic potential). These affect the movement of water in soil, and the way in which soil retains and releases water in the soil-plant-atmosphere continuum.

The soil water characteristic can be measured in various ways, that include:

- Ceramic suction plates (Method 504.01)
- Pressure plate equipment (Method 504.02)
- Filter paper method (Method 504.03) – simple routine technique for directly measuring soil water potential in range from -0.1 to -1000 m. Requires laboratory balance and drying oven only. Hamblin (1981) considers this method to be under-utilised but practical and convenient with adequate accuracy for many agronomic applications.

The Dexter "S-value" (Sgi) was viewed by Reynolds *et al*. (2009) as a promising new indicator of Soil Physical Quality (SPQ), but had not been well tested against established indicators, such as relative field capacity (RFC), plant-available water capacity (PAWC), air capacity (AC), macroporosity (PMAC), bulk density (BD), organic carbon content (OC), and structural stability index (SI). Furthermore, all SPQ indicators are direct or indirect expressions of pore volume and/or pore function, but optimal pore volume-function characteristics have not been identified. The objectives of this study were to: i) compare Sgi to the other seven indicators for a range of rigid to moderately expansive soils and artificial porous media; ii) use the indicators to propose an optimal pore volume distribution and soil water release curve; and iii) assess the SPQ of a compost-amended soil using indicators, pore volume distributions and water release curves. Indicators measured in the laboratory on intact soil cores and grab samples were collected from 13 soil management combinations. Soil texture included clay loam, sandy clay loam, loam, sandy loam and sand; management included virgin soil, no-till cropping and mouldboard plough cropping. Also included were two artificial media consisting of glass beads and builders sand. Pore volume distributions and water release curves were determined by fitting the van Genuchten function to desorption data obtained from the soil cores and grab samples. The Sgi indicator gave correct SPQ designations for the structured loamy soils, but erroneous designations for the structureless sands, glass beads and builders sand. The indicators, pore volume distributions and release curves showed that adding 75 t ha^{-1} compost improved the SPQ and maize yield of a clay loam soil, but addition of 300 t ha^{-1} compost was required to achieve optimal SPQ and maximum measured yield. It was concluded that the Sgi indicator should be used judiciously and in concert with other indicators for assessing SPQ; and that the suite of eight indicators used in conjunction with an optimal pore volume distribution and water release curve are effective for quantifying the physical quality of rigid to moderately expansive agricultural soils.

2.4.9 Soil Physical Quality (SPQ) index *S*

The S index of Soil Physical Quality (SPQ), as discussed by Pulido Moncado (2015), is defined as slope of soil water release curve (SWRC) on a mass base at its inflection point on a logarithmic matric potential scale. Use of the *S* index, originally proposed by Dexter (2004), suggested that it correlates with several important soil physical properties, supported by the ability of the van Genuchten (1980) equation to integrate over the whole SWRC and the corresponding pore size distribution (Dexter et al 2008). The utility of *S* indicator is based on soil physical degradation being related to alteration of structural pore distribution, leading to change in shape of the SWRC, and therefore a change in *S* value.

2.4.10 Water Repellence

Water repellence is discussed by DJ Carter in McKenzie *et al.* (2002). A range of tests can be used to measure water repellence of soils. Molarity of Ethanol Droplet (MED) test (Method 505.01) is preferred due to its simplicity and pre-treatment that makes it more reproducible than other tests. MED test can also be related to underlying physical properties (Letey *et al*. 2000). It is advisable to sample when soils are dry.

NCST (2009) recommends assessment of degree of repellence by determining concentration of ethanol required to wet sand in 10 seconds (King 1981). An abbreviated form of this method is recommended for field situations – non-water repellent (water is absorbed into soil in 10 seconds or less); water repellent (water takes greater than 10 seconds and 2-molar ethanol takes 10 seconds or less to be absorbed), and strongly water repellent (2-molar ethanol takes greater than 10 seconds to be absorbed).

2.4.11 Saturated Hydraulic Conductivity

McKenzie and Cresswell (2002) discuss selection of method for hydraulic conductivity measurement. Soil factors influencing measurement include vertic features, water repellence, low aggregate stability soils, macroporosity (e.g. root channels, burrows), coarse fragments, thin layers, biological activity, and water content profiles. They recommend that the effort devoted to a hydraulic property measurement program should be determined by a functional sensitivity analysis based on the process or scenarios of interest.

Field methods have become more prevalent in recent years because efficient measurement devices have become commercially available. In situ measurement is considered superior because sampling volumes are not large and soil disturbance is minimised. Various field methods have been utilised that include: disc permeameter, constant auger hole method, Guelph permeameter method, constant infiltration method. A constant-head lab method using small cores has also been used.

The appropriateness of any particular method depends on a range of factors including cost of equipment, level of expertise, and adequacy of underlying theory. Many methods are restricted to a limited range of soil conditions and can return misleading results if not applied appropriately. A summary of various methods is provided by McKenzie and Cresswell (2002) that considers factors such as range, accuracy, time, cost, domain, advantages, and disadvantages.

Soil Structure and Stability	Aggregate size and class
	Aggregate stability
	Slaking/dispersion
	Water-stable aggregation (wet-sieving)

2.4.12 Emerson Dispersion Test

The Emerson (1967) method has been adopted as Australian Standard (1980) with one change: dispersion in water judged using 3 mm ball of soil at plastic limit condition dropped into water (rather than a portion of soil remoulded at notional field capacity).

The Loveday and Pyle (1973) test is a modification of Emerson test to provide a relatively rapid assessment of susceptibility to dispersion. Dispersion assessed semi-quantitatively (index rated 0-16). Results have been related to key soil properties affecting crop production (e.g. hydraulic conductivity). A variation of this test can be usefully applied in the field.

The aggregate stability in water (ASWAT) (Field et al. 1997) is a further modification of the Emerson test, whereby it modifies the time period for assessment used in the Loveday and Pyle test. The assessment is again semi-quantitative and based on the same index as for the Loveday and Pyle test. The test was specifically developed for use with Vertosols, and it was suggested that due to the swelling nature of these soils that complete dispersion would occur within 2 hours, significantly shortening the test period. Bennett (2006) used this method with non-Vertosol soils and compared this to the Loveday and Pyle test, finding that significant information was not lost, but concluding that a large set of soils was required to be conclusive.

2.4.13 Clay Dispersion and the threshold electrolyte concentration

As discussed by Rengasamy (2002), when soil particles disintegrate during rain or irrigation, unsatisfactory soil structure can develop. As soil in the field becomes wet, clay may disperse (i.e. disintegrate into particles <2 um), affecting the pore system and influencing a range of physical properties that ultimately control plant growth. A method for measuring clay dispersion (Method 514.01 in McKenzie *et al.* 2002) and dispersive potential (Method 514.03 in McKenzie *et al.* 2002) is detailed. The measurement of clay dispersion is based on Rengasamy et al. (1984) for classifying the dispersive behaviour of Red Chromosols and Sodosols – based on the threshold electrolyte concept of Quirk and Schofield (1955).

In terms of determining the quantity of clay dispersed, Zhu et al. (2016) further the method for measuring clay dispersion (Method 514.01) by introducing a rapid approximation. This approximation is related to the turbidity, measured in standard Nephelometric Turbidity Units (NTU) of the dispersion and uses the returned NTU value to approximate dispersed clay in g/L with very high accuracy. This significantly improves the use of dispersed clay as a quantifiable indicator.

2.4.14 Wet-sieving

During dry-sieving, air or oven-dried soil samples are sieved for a given duration until completely separated. During wet-sieving, aggregates are subjected to slaking due to rapid wetting, micro-cracking through differential swelling, or mechanical breakdown. Breakdown force is applied during the wet-sieving process (caused by initial wetting treatment and by mechanical abrasion – i.e. impact of aggregates against each other and with sieve). The percentage of water-stable aggregates is the mass of aggregated soil remaining on sieve after wet-sieving vs the total mass pre-sieving. The proportion of fragments > 250 μm constitutes water-stable aggregates, whereas 50-250 μm fractions represent water-stable microaggregates. Wet-sieving is essentially a measure of the slaking characteristic of a soil.

The review of wet-sieving methodologies by Imhof (1988) covers: the principles of wet sieving of soils; factors involved in the analysis of aggregates by wet-sieving, including sampling and sample preparation, pre-wetting of aggregates and sieving procedure; expression of results; reproducibility; variations to the basic method; and applications and limitations. There are many variations in wet-sieving techniques:

- Soil preparation (e.g. air-drying, dry sieving).
- ‘working range’ of aggregates used on sieve (e.g. 1-2 mm, 2-4 mm, 2-6 mm).
- Sample weight (e.g. 5 g, 50 g).

- Method of wetting (e.g. capillary, spray, immersion, rainfall simulation).
- Sieving mechanism (e.g. mechanical, manual).
- Oscillation duration (e.g. 3 minutes, 30 minutes).
- Stroke length (e.g. 13 mm, 30 mm, 48 mm).
- Frequency of oscillation (e.g. 35, 60 cycles/minute).
- Sieve aperture sizes (e.g. 0.26 mm, 0.5 mm. 1.2 mm, 2 mm).
- Expression of results (e.g. Mean Weight-Diameter (MWD), %Water Stable Aggregation (%WSA), Geometric Mean Diameter (GMD).

Many studies using various wet-sieving techniques were summarised in the Imhof (1988) review. Many of these techniques could detect significant differences in aggregate stability between various agricultural management treatments, for example:

- Stubble mulching and tillage on US wheatland soils
- Effect of subsoiling
- Application of gypsum to Red Sodosols
- Data and sugarbeet waste products for improving soil structure
- Effect of burning crop residues
- Stability of surface soil aggregates under different cultivation methods.
- Effect of frequency of cropping.
- Index of erodibility (soil loss, splash erosion, runoff (R^2 = 0.26-0.96).

The protocol developed by Le Bissonnais (1996) for assessing stability of soil aggregates subjected to the action of water is listed as an international standard (ISO 10930, 2012) and provides a unified framework for measurement of aggregate stability to assess susceptibility of soil to crusting and erosion. It combines three wetting treatments (fast wetting, slow wetting and stirring after pre-wetting) and measures resulting fragment size distribution after each treatment. Five classes of stability and crustability, according to Mean Weight-Diameter (MWD) values, are proposed.

The method proposed by Kemper and Rosenau (1986) is also used widely, particularly in USA. It is used to assess macro-aggregation (i.e. aggregates >250 μm diameter) using a 1-2 mm aggregate size range sample ('working range') on the basis that macroaggregates of 1-2 mm are sensitive to short-term management. It uses a single sieve, as opposed to a 'nest' of sieves.

The review of wet-sieving technologies by Imhof (1986) provides a detailed listing of the use of wet-sieving methods in agricultural studies. Some additional studies are listed in Appendix 2 as well as details on field-based wet-sieving kits (such as USDA and Herrick *et al*. 2001).

2.5 Semi-quantitative and Visual Assessments

Morphological characteristics	Mineralogy Texture/consistence Soil colour Soil horizons Presences of pedogenic features (e.g. pans, impermeable layers, nodules, fracturing) Stoniness (size / abundance)

2.5.1 Morphological characteristics

The Australian Soil and Land Survey Field Handbook (NCST, 2009) provides standard terminology for the characterisation of soil and landform attributes. For a soil profile, key attributes include: horizons (notation, depth, boundaries), colour, field texture, coarse fragments, structure (grade, size, type), fabric, cutans, voids, soil water status, consistence, surface condition, water repellence, pans, segregations, effervescence of carbonate in fine earth, field pH, roots, vertic features, and soil water drainage.

Soil structure forms a key component of soil quality, and its assessment by semi-quantitative visual soil evaluation (VSE) techniques can help scientists, advisors and farmers make decisions regarding sampling and soil management. Emmet-Booth *et al*. (2016) reviewed published Visual Soil Evaluation (VSE) techniques and found that soils of certain textures present problems and there is a lack of research into influence of soil moisture content on VSE criteria. Generally, profile methods evaluate process interactions at specific locations within a field, exploring both intrinsic aspects and anthropomorphic impacts. Spade methods focus on anthropogenic characteristics, providing rapid synopses of soil structure over wider areas. Despite a focus on structural form, some methods include criteria related to stability and resiliency. They recommended further work to improve existing methods regarding texture influences, on-farm sampling procedures and more holistic assessments of soil structure.

One of oldest and most accepted is that of Peerlkamp (1967). Later methods development by Ball et al (2007) provide excellent illustrations to support assessment. The New Zealand Visual Soil Assessment (Shepherd 2009) is an illustrated multi-criteria method.

Methods of visual soil evaluation remain poorly used in research as they are operator dependent and only provide semi-quantitative results (Rabot *et al.* 2018). There is also subjectivity involved and often a lack of standardisation (e.g. range of water content at which evaluation performed). Methods of visual soil structure examination can usefully enable semi-quantitative information for use in monitoring and extension (Shepherd 2000, McKenzie 2001), and even modelling (Roger-Estrade *et al.* 2004, 2009). They can often be correlated with measured data of physical soil quality (e.g. Lin *et al.*, 2005) and crop yield (e.g. Mueller *et al*., 2009).

Visual Soil Assessment (VSA) approaches were reviewed by Rabot *et al*. (2018), ranging from surface soil evaluation, or ‘spade tests’ - Peerlkamp (1959); Visual Evaluation of Soil Structure (VESS) – Ball *et al.* 2007, Guimaraes et al 2011; Visual Soil Assessment (VSA) Shepherd (2009, 2000)’ and the “SOILpak score” (McKenzie 2001). Generally, an undisturbed soil block is extracted from soil surface with a spade and manually broken or dropped from height of 1 metre, to produce aggregates. Aggregates are then described in terms of size, porosity, shape, colour, ease of break-up, together with identification of presence of any tillage pan, depth of root penetration, or number of earthworms. Samples compared to photographs of a reference key and assigned a soil structure score. Visual soil evaluation methods have usually demonstrated a good sensitivity to different management practices (Ball et al 2007; Giarola *et al*. 2013; Guimaraes *et al.* 2011) and have been particularly useful to detect soil compaction. Scores correlated to agricultural productivity function (Mueller *et al*., 2009); water infiltration through to saturated HC (Mueller *et al*., 2009, Pulido Moncado *et al*. 2014b) and to gas transport through air permeability and air capacity (Guimaraes *et al*., 2013). When compared, the different visual soil evaluation methods sometimes led to different results in terms of soil physical quality (Mueller *et al*., 2009; Giarola *et al*., 2013).

Mueller *et al*. (2009) conducted a study on sites in Canada, China, and Germany on soils that included loamy and silty textured Haplic Luvisols and Haplic Cambisols. Seven methods, including Shepherd (2009) and Ball *et al*. (2007), with an emphasis on aggregate and pore characteristics, were selected. Structure scores of most methods gave similar results after standardizing data. Measured soil physical qualities and crop yields correlated significantly with visual soil structure. Soil measurements most closely associated with visual soil structure and grain yield were soil density and macroporosity. The correlation between dry soil Bulk Density and Peerlkamp scores indicates that the latter seems to have a scale level not far from metric level and could be dealt with in some statistical tests as quasi-metric variables. Unfavorable visual structure was associated with increased dry bulk density, higher soil strength and lower infiltration rate but correlations were site-specific. Biological features like earthworm or root numbers were less reliable indicators of soil structure than aggregate characteristics. Visual soil structure assessment is a useful diagnostic tool and may indicate soil structure states clearly. Methods should be selected, and adapted, according to site conditions and should include a fast method of the Peerlkamp type.

The French method "*Le profil cultural*" (Roger-Estrade *et al*., 2004) is a more sophisticated method (based on Roger-Estrade et al 2000) that provides detailed information on whole soil profile. It is based on stratification of the observation face of a soil pit dug perpendicular to the direction of tillage and traffic. Spatial compartments are distinguished based on the nature of the mechanical stresses that they have been submitted to during tillage and crop management. Soil structure is characterised on a morphological basis: clod size distribution and classification of clods (into three types, on basis of the importance and origin of their internal structural porosity. Physical measurements (bulk density, compaction, water retention) demonstrate that physical behaver is different between clod types. Results justify use of the method to model changes in soil structure with time under the effects of the main factors influencing soil structural dynamics in tilled fields (compaction, fragmentation, climate and biological activity).

Roger-Estrade *et al*. (2008) proposed an indicator of soil structure dynamics based on proportion of compacted clods in the tilled layer, as measured from the observation face of soil pits. The method was studied in a long-term field experiment involving various risks of compaction, and results showed that the indicator gave a more precise description of time course changes in soil structure than mean soil bulk density measured on same plots. A model is proposed that can be used to evaluate the effects for different crop management systems on soil structure and soil water transfer. The morphological description of soil structure allows a precise analysis of spatial variability in soil structure within tilled horizons as well as 2-D modelling of the dynamics of soil structure in the field.

Subjectivity is often involved and approaches often lack of standardisation (e.g. range of water content at which evaluation performed (Rabot *et al*. 2018). Visual examinations are, however, reliable semi-quantitative methods to assess Soil Structural Quality and can be considered promising visual indicators of soil physical properties (Pulido Moncada *et al*. 2014).

Table 6. Comparison of different visual assessment methods and indicators of soil structure

Table 1
Comparison of different measurement methods and indicators of soil structure.

Measurement method	Indicator	Sample size	Pore size observed	Level of expertise[a]	Reproducibility[b]	Duration[c]	Cost	Measure	Methodological limitations
Whole profile evaluation	Grade, size, shape of peds	Horizon	> 200 μm	High	Medium	Half an hour + pit	Low	Qualitative	- Subjective - Depends on soil texture and moisture
Topsoil evaluation	Visual evaluation score	Full size of a spade and ≈ 20 cm-thick	> 200 μm	Medium	Medium	Half an hour	Low	Semi-quantitative	- Subjective - Depends on soil texture, moisture, and biological activity - Difficulty in breaking soil manually along planes of weakness - Compaction may occur during the drop-shatter test or by breaking soil manually
Bulk density	Bulk density	Hundreds cm^3 to hundreds dm^3	–	Low	High	Half an hour + drying	Low	Quantitative	- Difficulties with soils with abundant rock fragments, plant roots, or residues - Depends on soil moisture - Compaction may occur with the core method - Inadequate representation of large pores with the clod method
	Degree of compactness			Medium	Medium	A few hours + drying	Medium		- No standard method to evaluate the reference BD - Not satisfying for organic soils, doubt for sandy soils
	Packing density			Low	High	A few hours + drying	Low		- (Poorly explored so far)
Aggregate size distribution and stability	Stability index Aggregate size distribution Water-dispersible clay Microaggregates-within-macroaggregates	Tens to hundred g	–	Medium	Low	A few hours	Low	Quantitative	- Wide number of measurement methods - Unknown applied energy - Non-negligible effect of the type of sieving, duration, oscillation frequency, loading rate, number and size of sieves, storage duration, and pretreatment (moisture history)
Mercury porosimetry	Porosity Macroporosity Microporosity	A few cm^3	0.003 to 500 μm	Low	High	A few hours	Medium	Quantitative	- Assumes non-connected cylindrical pores - Ink-bottle effect - Contact angle of mercury with soil surface often unknown - Sample dried
Water retention curve	Porosity Macroporosity Microporosity Air capacity Relative field capacity Available water capacity LLWR S index	Hundreds cm^3 to dm^3	0.2 to 3000 μm	Medium	High	Days to weeks	Medium	Quantitative	- Assumes non-connected cylindrical pores - Ink-bottle effect - Adjustment of a model can introduce small errors
Gas adsorption	Specific surface area Mesoporosity (2–50 nm) Microporosity (< 2 nm)	1 to tens mm^3	0.001 to 0.2 μm	High	Medium	A few hours to days	Medium	Quantitative	- Assumes an idealized pore shape - Sample dried - N_2 inadequate to characterize soils with high amounts of SOM
Imaging techniques (lab)	Porosity Macroporosity Microporosity Connectivity Pore orientation Pore shape	1 cm^3 to dm^3	A few μm to hundreds μm	High	Medium	A few hours	High	Quantitative	- Sensitive to the segmentation step and image resolution

[a] High: several protocols exist to perform the measurement and/or to analyze the data, which need to be adapted for the case study, a dedicated training and experience is required; Medium: several protocols exist to perform the measurement and/or to analyze the data, which need to be adapted for the case study, but skills can be learned easily; Low: a protocol exist to perform the measurement and/or to analyze the data, skills can be learned easily.
[b] Different operators characterize the same soil sample and choose between the different protocols available to perform the measurement and/or to analyze the data. The step of soil sampling is not taken into account. High: same results; Medium: same results to same trends; Low: same results to different trends.
[c] We aimed at showing how labor-intensive the methods are for a single sample. The step of soil sampling is not taken into account.

As reported by Guimaraes *et al*. (2011), some European and Brazilian users of Visual Evaluation of Soil Structure (VESS), development of Peerlkamp test, had been concerned about its subjectivity (particularly method of soil break-up and operator influence). Guimaraes *et al*. aimed to make soil scoring more objective and revised the scoring guide. Method of reducing larger aggregates to 1.5 – 2.0 cm core fragments and describing their shape and porosity was developed to score soil structural quality (Sq). Positive correlations have been recorded between tensile strength (as per Dexter and Kroesbergen 1985) and VESS.

2.5.2 SOILpak for Cotton

The SOILpak scheme (Daniells and Larsen, 1991) uses soil structural features such as size and shape of peds, grade, colours and mottling and root behaviour to rate soils. Originally developed as a scheme to assist cotton farmers and their advisors, its use has since expanded. Methodological aspects are discussed by McKenzie (2013).

For three key depth intervals assessments are made of:

- Severity of compaction (SOILpak score) – can be separated into as many as 20 categories on scale of 0.0 (severely compacted) to 2.0 (excellent structure for root growth).
- Stability of soil moisture for tillage
- Natural regeneration potential (CEC as measure of soil shrink-swell capacity).
- Soil stability in water (ASWAT test – as modification of Loveday and Pyle (1973). 0-10, 15-25, 40-50, 70-80, 100-110.

- Salinity hazard and pH
- Subsoil infiltration

Table 7 and 8. Alternative methods to SOILpak compaction score & likely biological significance of soil morphology

Table C4-6. Alternatives to the SOILpak 'severity of compaction/smearing' scoring procedure

Method	Situations where the method could be used when assessing structure in a cotton field	Drawbacks
1. Penetrometer	Useful if used immediately before and after a tillage operation, where the soil water content throughout the profile is around the plastic limit; penetrometers have good depth resolution.	Insensitive to differences in bulk density in sticky soil. Results need to be corrected for water content—the calibration equations vary from site to site.
2. Shear vane	Provides useful reference data at key sites—allows cross-checking of the SOILpak scores.	Results need to be corrected for water content – the calibration equations vary from site to site.
3. Bulk density cores	Provides useful reference data at key sites—allows cross-checking of the SOILpak scores, and gives information about air-filled porosity.	Time consuming. Soil water content needs to be close to the plastic limit. No information given about how well the pores are interconnected.
4. Clod shrinkage analysis	In compacted soil, can be compared easily with the large amounts of published data.	Time consuming. May be a risk of sampling bias in moderately- and well-structured soil.
5. Image analysis after resin impregnation	Provides very useful reference data at key sites—allows cross-checking of the SOILpak scores.	Time consuming and expensive. Requires specialised equipment. Soil water content needs to be close to the plastic limit.
6. Infiltration rate	Well permeameter data from the deep subsoil are useful for assessing how the structure will influence deep percolation.	Time consuming; data are often highly variable and influenced strongly by initial soil water content; potential for operator bias.
7. Calculation of non- and partly-limiting water ranges	Provides excellent information that can be related directly to crop management.	Time consuming and expensive (requires detailed strength, aeration and water content data).

Table 3. Likely biological significance of the factors listed in Tables 1 and 2

Soil morphology factor	Biological significance
Clod width	As clods become wider, taproot obliquity is likely to increase
Ease of breakage of soil sample	As clod strength increases, cotton taproots and their laterals will find it increasingly difficult to grow between, and through, the component clods because of poor aeration and/or mechanical impedance
Clod shape	As clod platiness increases, taproots are more likely to develop a zig-zag pattern as they grow downwards. Platy and conchoidal clods usually are hard and compact, without much scope for entry and exploration by root hairs
Features of fracture faces	The incidence of clods with shiny faces appears to be associated with a decrease in the strength of inter-aggregate bonding, and of a decrease in aggregate size. This shininess becomes more obvious as the number of shrink–swell cycles increases
Proportion of primary clods within the compound clods, produced by rolling the compound clods between thumb and forefinger	The very narrow, but stable, fissures between small, primary shiny-faced clods should allow root hairs to enter compound clods and extract water and nutrients, unlike large, apedal aggregates which do not sub-divide easily into smaller components
Internal porosity of primary clods	The presence of biopores, e.g. old root and fauna channels, within primary clods is likely to encourage soil exploration by root hairs
Colour of the interior of primary clods	Poor soil aeration caused by compaction often is associated with a bluish tinge. Red and brown colours generally indicate an adequate supply of oxygen for root growth. However, well-structured soil can develop a bluish tinge (sometimes accompanied by the presence of manganese oxide nodules) in the presence of a perched water table. Mottling indicates temporary waterlogging

2.5.3 Review of visual soil evaluation techniques for soil structure (Emmet-Booth et al 2016)

Reviewed published Visual Soil Evaluation (VSE) techniques and found that soils of certain textures present problems and that there was a lack of research into influence of soil moisture content on VSE criteria. Generally, profile methods evaluate process interactions at specific locations within a field, exploring both intrinsic aspects and anthropomorphic impacts. Spade methods focus on anthropogenic characteristics, providing rapid synopses of soil structure over wider areas. Despite a focus on structural form, some methods include criteria related to stability and resiliency. Further work is needed to improve existing methods regarding texture influences, on-farm sampling procedures and more holistic assessments of soil structure.

Visual soil evaluation profile methods – includes SOILpak (McKenzie 1998), SubVESS (Ball *et al.* 2015). Allow more detailed structural assessment than spade methods but at cost of reduced coverage of within-field variation due to time constraints.

Visual soil evaluation spade methods (Drop test procedures) – includes Peerlkamp Method (Peerlkamp 1959), Spade Analysis (Munkholm 2000).

Reported on the wide, and growing, evidence of utility of VSE techniques. Both spade and profile approaches offer information not attainable using quantitative measurements.

<u>Further research could include</u>:

- assessing interaction between moisture content and VSE criteria

- variation in soil texture. Modified procedures or classification systems related to soil texture may be
- exploration of sampling strategies and analysis of spatial variation (minimum sample replication per method should be determined).
- New procedures and on less utilised existing methods – useful approaches to improve existing methods and explore wider aspects of soil structure such as stability and resilience.

2.5.4 Comparison of wet-sieving, Visual Evaluation of Soil Structure (VESS) and Visual Soil Assessment (VSA) – Pulido Moncada *et al*. (2014)

Pulido Moncada *et al*. (2014) evaluated the use of visual examinations for assessing Soil Structural Quality (SSQ) in soils with contrasting textures and under different land uses in Flanders region of Belgium. Looked for similarities in SSQ class between visual examinations and soil physical and hydraulic properties (SOC, aggregate stability, BD, porosity, PAWC and Hydraulic Conductivity (saturated and unsaturated) and statistical relationships between them. Samples taken on a sandy loam and silt loam soil, both under cereal monoculture (CM) and permanent pasture (PP) with conventional tillage (CT) and no-tillage (NT) respectively.

- Wet-sieving based on Kemper and Rosenau (1986)
- Visual assessment by modified Emerson test (Field et al 1997).
- Visual Soil Assessment (VSA) - Shepherd (2009)
- Visual Evaluation of Soil Structure (VESS) – Ball *et al*. (2007).

Visual examination methods indicated significant differences between CM and PP in silt loam soil (0.01 <P>0.05) which were confirmed by significant differences in soil porosity and PAWC values. Wet-sieving and visual aggregate assessment index were similar in identifying differences between land uses in both soils. Wet-sieving showed that there was an effect of land use on aggregate stability for both soils. Aggregates from PP were more resistant to breakdown after wet-sieving when rapid wetting was applied. Like wet-sieving, the visual evaluation of aggregate stability could distinguish differences in soil structural quality between land uses in both soils. Moderate to good relationships were found between visual examinations and values of soil physical and hydraulic properties. Visual examinations are reliable, semi-quantitative methods to assess Soil Structural Quality (SSQ) and could be considered as promising visual predictors of soil physical properties (0.33 <R2<0.95).

Wet-sieving and the visual type of aggregates index were similar in identifying differences between land uses in both soils. Measurements of the visual type of aggregates index and of the hydraulic conductivity at different pressure heads were similar in indicating the soil structure condition of the soils. In the silt loam soil, the visual examinations were most related to properties such as SOC, PAWC, aggregate stability and porosity, whereas in the sandy loam soil they were most associated with water flow properties. The present study demonstrated that visual examinations are reliable semi-quantitative methods to assess SSQ and could be considered as promising visual predictors of soil physical properties ($0.33 < R^2 < 0.95$). Finally, from the dissimilarities in terms of soil quality found with the VSA, VESS and porosity compare to the amount of SOC, SOC should be used cautiously as a sole indicator for soil structural quality as has been proposed in the literature, because SOC *per se* is not always well related to soil structural quality. Dissimilarities in terms of soil quality found with VSA, VESS and porosity compare to amount of Soil Organic Carbon (SOC). They suggest that SOC should be used cautiously as sole indicator of soil structural quality as proposed in literature, because SOC per se is not always well related to soil structural quality.

2.5.5 The visual examination of soil structure under arable management (Askari et al 203)

Independent evaluation of VESS methods on arable farms in Ireland indicated that it could differentiate the effects of tillage management practices on soil structural quality, and is suitable for use as reliable, rapid method for assessing soil quality on arable farms.

VESS method (Ball *et al*. 2007; Guimaraes *et al*. 2011) considered to be far quicker and simpler than other visual methods such as Shepherd (2000, 2009). VESS detected the effects of tillage on soil quality, and results were generally supported by measured soil properties. VESS can therefore be used as fast method for early detection of detrimental impacts of management on soil quality. Provides farmers with easy and low-cost method that does not need specific knowledge to evaluate the influence of current management practices and for ongoing soil quality monitoring. Subjectivity is still a concern despite efforts of Guimaraes *et al*. to make VESS more objective – therefore parameters such as soil texture, sampling location and soil moisture status should be considered. Suggested as complementary method to laboratory analysis for evaluation of soil structural quality – allowing high sampling frequency with limited resourcing requirements. It is suggested that VESS (Visual Evaluation of Soil Structure) methods be considered as complementary to laboratory analysis for evaluation of soil structural quality – allowing high sampling frequency with limited resourcing requirements. VESS can provide rapid, practical approach for soil structural assessment in the field and detect at least some impacts of management practices.

2.5.6 Review of published Visual Soil Evaluation (VSE) techniques – Emmett-Booth *et al*. (2016)

Emmett-Booth *et al*. (2016) reviewed published Visual Soil Evaluation (VSE) techniques and found that soils of certain textures present problems and that there was a lack of research into the influence of soil moisture content on VSE criteria. Generally, profile methods evaluate process interactions at specific locations within a field, exploring both intrinsic aspects and anthropomorphic impacts. Spade methods focus on anthropogenic characteristics, providing rapid synopses of soil structure over wider areas. Despite a focus on structural form, some methods include criteria related to stability and resiliency. Further work is needed to improve existing methods regarding texture influences, on-farm sampling procedures and more holistic assessments of soil structure. The three tables below (Table 9, 10, 11) are from the Emmett-Booth *et al*. (2016) review and provide an outline of VSE Spade drop test methods and manual aggregate exposure procedures, and profile methods.

Emmett-Booth *et al*. (2016) reported wide, and growing, evidence of the utility of VSE techniques. An appropriate method can be selected for any situation, whether research, monitoring or management. Assessment objectives, survey area, and operator expertise will dictate method selection. Profile methods allow a more detailed structural assessment than spade methods but at the cost of reduced coverage of within-field variation due to time constraints. However, both approaches offer information not attainable using quantitative measurements. Improvements requiring further research include the following:

The interaction between moisture content and VSE criteria appears to have received limited attention, while variation in soil texture presents problems for some procedures. Modified procedures or classification systems related to texture might be beneficial. Nevertheless, research shows methods are robust and valuable.

As the utility of VSE techniques has been established, recommended that exploration of sampling strategies and analysis of spatial variation be undertaken. Minimum sample replication per method should be determined. Further research is encouraged on new procedures and on less utilized existing methods. The latter may offer useful approaches to improve more widely adopted methods and to explore wider aspects of structure such as stability and resiliency, important for an integrated and holistic assessment, notably of agricultural soils.

Tables 9, 10 and 11. Outline of VSE spade drop test methods, manual aggregate exposure procedures and profile methods (Emmett-Booth *et al*. 2016).

Table 1 Outline of VSE Spade Methods (Drop Test Procedures)

Method*	Origin	Objective	Land assessed	Characteristics assessed	Criteria employed	Depth assessed	Scoring system used	Intended users	Time requirement
The Diez Method (Diez *et al.*, 2012)	Germany	To assess structure in relation to soil functioning, notably plant growth and water infiltration	Emphasis on arable	Anthropic impacts on structure	Aggregate type, size, shape, inter-aggregate porosity, rooting, redox morphology, transition layer	40[b] cm	Score between 1 and 5 used *(1 = best, 5 = worst)*	Advisors and farmers[b]	- -
Visual Soil Assessment (VSA) (Shepherd, 2000, 2009, 2010)	New Zealand	To assess soil state, plant performance and the impact of farm management	Arable and grassland	Intrinsic soil quality and anthropic impacts on structure	Texture, aggregate size distribution, macro-porosity, redox morphology surface ponding and deformation, earthworms, smell, colour, potential rooting depth	Varying depths	*VS* score of between 0 and 50 *(<20 = poor, 20-35 = moderate, >35 = good)*	Advisors and farmers	40 minutes
FAL Method (Hasinger *et al.*, 2004)	Switzerland	To provide an accurate evaluation of structural state at a specific point[a]	Arable and grassland	Anthropic impacts on structure	Aggregate type, size, distribution and mean weight diameter[a]	45 cm	Score between 1 and 14 used for aggregate mean score *(1= worst, 14 = best).* Aggregate mean weight diameter is described in mm	Researchers and advisors[a]	90 minutes[a]

*Sources provided are not necessarily the original description of methods, [a] Sourced from: Boizard *et al.* (2005), [b] Points are of the authors' opinions

Table 1 (continued)

Method*	Origin	Objective	Land assessed	Characteristics assessed	Criteria employed	Depth assessed	Scoring system used	Intended users	Time requirement
Soil Quality Scoring Procedure (SQSP) (Ball & Douglas, 2003)	United Kingdom	To assess physical fertility in terms of structure, rooting and soil surface conditions	Arable and grassland	Anthropogenic impacts on structure	Soil surface, aggregate type, size, shape, rupture resistance and rooting	30 cm	Three separate scores are assigned, each between 1 and 5 (*1 = worst, 5 = best*)	Researchers and advisors[a]	1 h[a]
Visual Soil Structure Quality Assessment (VSSQA) – Visual Evaluation of Soil Structure (VESS) (Guimarães *et al.*, 2011)	United Kingdom	To semi-quantitatively assess soil structural quality in a manner accessible to non-experts	Arable and grassland	Anthropogenic impacts on structure	Aggregate size, shape, intra-porosity, rupture resistance, rooting and redox-morphology	25 cm	*Sq* Score between 1 and 5 (*1 = best, 5 = worst*)	Advisors and farmers	15 min
Thinksoils Manual (Environment Agency, 2007, 2010)	United Kingdom	To assess soil structure with regard to erosion and run-off potential	Arable and grassland	Anthropogenic impacts on structure	Fissures and porosity, aggregate size, shape, rupture resistance, redox morphology, rooting and crop growth	40 cm	No numeric scores used	Advisors and farmers	–

*Sources provided are not necessarily the original description of methods, [a]Sourced from Boizard *et al.* (2005) [b]L. J. Munkholm, personal communication.

Table 1 Outline of visual soil evaluation spade methods (Manual aggregate exposure procedures)

Method*	Origin	Objective	Land assessed	Characteristics assessed	Criteria employed	Depth assessed	Scoring system used	Intended users	Time requirement
Spade Diagnosis (Görbing, 1947)	Germany	To assess structure in relation to plant growth	Emphasis on arable	Anthropogenic impacts on structure	Aggregate size, shape, porosity and rooting	30 cm	No numeric scores used	Advisors and farmers	90 min[b]
Peerlkamp Method (Peerlkamp, 1959)	The Netherlands	To assess structure in relation to fertility, summarised by a single score	Emphasis on arable	Anthropic impacts on structure	Aggregate size shape, rupture resistance, inter- and intra-porosity, rooting and surface soil dispersion	15 cm	*St* Score between 1 and 10 (*1 = worst, 10 = best*)	Researchers, advisors and farmers[a]	30 min for 10 assessments[a]
The Werner Method (Werner & Thamert, 1989)	Germany	To assess soil physical condition in relation to plant growth	–	Anthropogenic impacts on structure	Layers, aggregate size, width, shape, inter-aggregate porosity and bio-pores	50 cm	Scores between 1 and 4 or 1 and 5 used to describe individual properties, resulting in a five digit nominal value score for each layer	Researchers	–
Extended Spade Diagnosis (Beste, 1999)	Germany	To assess structure with regard to rooting conditions and habitats for soil biota	Emphasis on arable	Anthropogenic impacts on structure	Aggregate type, size, shape, along with aggregate stability	40 cm	Scores between 1 and 5 used for structure and between 0 and 2 for silting type. Three sample layers are assessed separately	Advisors and farmers	–
Spade Analysis (Munkholm, 2000)	Denmark	To describe and relate soil tilth to management while aiding and evaluating soil management decisions	Emphasis on arable	Intrinsic soil quality and anthropic impacts on structure	Texture, colour, layer boundaries, aggregate size, shape, grade, soil consistence, macro-porosity, pore distribution, connectivity, orientation and rooting, OM decomposition and soil fauna	30 cm	Different scoring systems used for different properties, though no summarising numeric scores used	Researchers and advisors[a]	1–3 h[a]

Table 3 Outline of visual soil evaluation profile methods

Method*	Origin	Objective	Land assessed	Characteristics assessed	Criteria employed	Depth assessed	Scoring system used	Intended users	Time requirement
Le Profil Cultural (Gautronneau & Manichon, 1987)	France	To examine the impact of tillage on soil structure features	Arable	Emphasis on anthropogenic impacts on structure	Soil layers, structural zones, macro-pores, aggregate/clod size, intra-porosity, redox morphology and rooting	1.5 m	No numeric score used	Researchers	1–3 h[a]
Whole Profile Assessment (Batey, 2000)	United Kingdom	To assess the anthropogenic impact on intrinsic soil properties in relation to crop growth[a]	Arable and grassland	Intrinsic soil quality and anthropogenic impacts on structure	Soil layers, texture, aggregate size, shape, aggregate stability, compacted zones, soil bearing capacity, soil colour and redox morphology	1.2–1.5 m	No numeric score used	Researchers and consultants[a]	20–40 min[a]
SOILpak (McKenzie, 1998)	Australia	To identify and assess compaction in relation to crop growth	Emphasis on arable	Intrinsic soil quality and anthropogenic impacts on structure	Texture, soil surface, rooting, aggregate size, shape, rupture resistance, macro-pores and aggregate stability	1.5 m	Score between 0 and 2 used for structural (*0 = worst, 2 = best*) and ASWAT score between 0 and 16 used for aggregate stability (*0 = negligible dispersion, 16 = serious dispersion*)	Land surveyors, advisors and farmers	25–90 min[a]
SubVESS Flowchart (Ball *et al.*, 2015)	United Kingdom	To assesses any anthropogenic transition layer in terms of crop growth	Emphasis on arable	Anthropogenic impacts on structure	Redox morphology, porosity, rooting, aggregate size and shape	1.4 m	*Ssq* scores of between 1 and 5 (*1 = best, 5 = worst*)	Advisors	20 min

*Sources provided are not necessarily the original description of methods, [a]Sourced from Boizard *et al.* (2005).

2.6 Relationships and Indices

McKenzie (2013) presented a checklist (Table 12 below) of soil, physical, chemical and biological factors that should be considered for soil assessments on Australian farms, with associated soil amelioration strategies that may be appropriate (also relevant to Program 3 of the Soil CRC). This highlights the potential mix of testing that can be used to assess these factors, ranging from 'first approximation' Visual Soil Examination and Evaluation (VSEE) techniques to more detailed testing using more quantitative approaches and relatively complicated equipment.

Table 12. Checklist of soil physical, chemical and biological factors that should be considered for soil assessments on Australian farm land, and associated amelioration strategies (McKenzie 2013).

A checklist of soil physical, chemical and biological factors that should be considered for soil assessments on Australian farm land, and associated soil amelioration strategies that may be appropriate.

Soil factor to be tested	Associated processes that have practical importance for farmers (Kay, 1990; White, 2006)	'First-approximation' VSEE testing (rapid and inexpensive tests for use in the field or at home)	Detailed testing, if required, at selected sites (uses relatively complicated testing equipment) (McKenzie et al., 2002; Rayment and Lyons, 2011)	Amelioration strategies to consider, if economically feasible for the land use under consideration (McKenzie et al., 2008)
Structural form (compaction severity)	Water intake Water storage Rate of drainage of excess water and pollutants Erosion losses Root growth and function Emissions of nitrous oxide and methane (see waterlogging section below)	SOILpak score (McKenzie, 2001a) VESS (Ball et al., 2007) VSA (Shepherd, 2009)	Bulk density measurement Penetrometer/shear vane Image analysis/clod shrinkage parameters Moisture status; content, potential and rate of flow	Mechanical loosening "Biological tillage" (loosening via shrink–swell processes; bioturbation)
Structural stability in water	Ability of soil to maintain vital functions associated with its soil structural form after water has been applied	Emerson slaking/dispersion assessment (Emerson, 1983), ASWAT dispersion test (Field et al., 1997)	Exchangeable sodium percentage (ESP) Electrochemical stability index (ESI) (Blackwell et al., 1991) Ca/Mg ratio Organic carbon Loveday and Pyle (1973) dispersion test	Gypsum Gypsum-lime blends Organic matter
Structural resilience	Ability of a soil to regain a desirable soil structural form via natural processes, for example shrinkage/swelling associated with wetting and drying cycles	Slurry dried in a Petri dish in the oven (linear shrinkage)	Cation exchange capacity, COLE testing	Clay addition to sandy soil Deep mouldboard ploughing of duplex soil
Texture	Water storage capacity Nutrient retention	Hand texturing (NCST, 2009)	Particle size analysis	Clay addition to sandy soil Deep mouldboard ploughing of duplex soil
Stoniness	Water storage capacity Reduction in erodibility	Visual estimation of coarse fragment content (NCST, 2009)	Particle size analysis	
Depth to hard rock	Water storage	Direct measurement in soil pit	–	Soil importation
Water repellence	Water intake	Time taken for a drop of water to be absorbed by the soil (Hall et al., 2009)	'Molarity of ethanol drop' (MED) test	Clay addition to sandy soil
Waterlogging severity associated with impermeable bedrock and shallow watertables	Root growth and function Emissions of nitrous oxide and methane	Redoximorphic features in the deep subsoil (Batey, 1988) Depth to slowly permeable layer	Eh assessment (James and Bartlett, 2000) Soil gas movement (Scanlon et al., 2000)	Install drains
pH	Nutrient availability and the possibility of aluminium toxicity	Indicator solution sprayed onto the soil profile (Hall et al., 2009) Carbonate patterning in alkaline soil (NCST, 2009)	Laboratory testing of pH ($CaCl_2$), aluminium availability, 'acid sulphate soil' status	Lime application
Salinity	Water uptake restriction, toxicities	Hand-held electrical conductivity meter with approximate 1:5 soil:water suspension (Lanyon, 2011)	Laboratory testing of ECe, boron concentrations EM surveys	Profile leaching
Nutrients	Deficiency avoidance	Visual plant deficiency symptoms (Grundon, 1987)	Soil and plant tissue analysis by laboratories	Fertilisers
Soil biological status	Soil structure improvement, improved nutrient availability	Soil fauna observations, soil aroma, soil darkness, stubble cover	Organic carbon status Micro-organism assessments	Biological additives

There are many examples of integrated soil assessment rating frameworks that factor in physical, chemical and biological factors. These include:

2.6.1 Soil Management Assessment Framework (SMAF)

The Soil Management Assessment Framework (SMAF) was developed in USA (Andrews et al 2004). The assessment protocol based on three steps: i) indicator selection (chemical, physical, biological); ii) indicator interpretation (non-linear scoring curves); and iii) integration into overall Soil Quality Index (SQI). Overall SMAFF SQI is expressed as a fraction or percentage of full performance of soil functions such as crop productivity, nutrient cycling, or environmental protection.

Cherubin *et al*. (2017) assessed the potential of SMAF for evaluating Brazilian Oxisols of contrasting texture and variety of land uses including i) horizontal and vertical distribution of soil properties in long-term orchard; ii) Impacts of long-term land use change from native vegetation to agricultural crops on soil properties; iii) effects of short-term tillage on soil properties in cassava production area; iv) changes in soil structure due to mineral fertiliser and pig slurry application coupled with soil tillage practices, and v) row and inter-row sowing effects on soil properties in long-term no-tillage area. Six Soil Quality indicators – pH (water), P, K, BD, SOC and microbial biomass – were individually scored using SMAF curves and integrated into an overall Soil Quality Index (SQI) focusing on chemical, physical and biological sectors. SMAF was sensitive for detecting SQ changes. SMAF can be used as tool for assessing SQ in Brazilian soils.

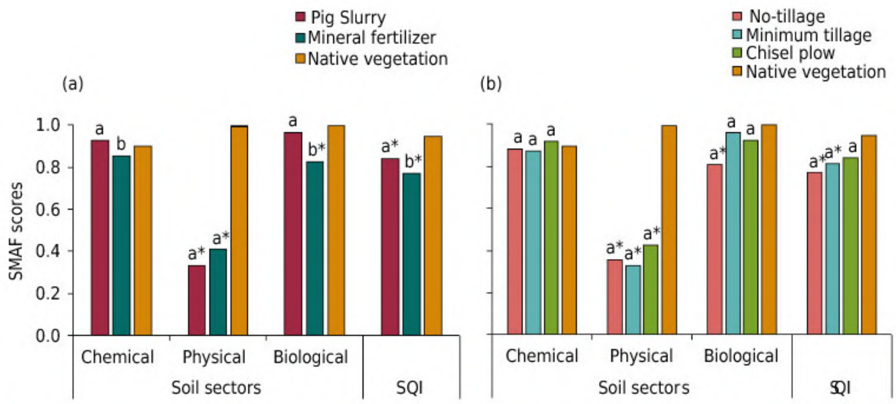

Figure 4. Soil sectors (chemical, physical, and biological) and overall Soil Quality Index (SQI) for the 0.00-0.10 m layer under pig slurry and mineral fertilizer treatments (a) and no-tillage, minimum tillage, and chisel plow treatments (b). All treatments were compared with native vegetation. Mean scores within each sector and SQI followed by the same letter do not differ among themselves according to Tukey's test ($p<0.1$). Mean scores followed by * statistically differ from native vegetation according to Dunnett's test ($p<0.1$).

They concluded that SMAF was sensitive for detecting Soil Quality (SQ) changes induced by land uses and management practices in Brazilian Oxisols with contrasting texture. The overall SMAF SQI scores summarise individual soil indicator scores (chemical, physical, biological) into a comprehensible number that assists evaluation of overall soil functioning. Individual sector scores (chemical, physical, biological) enable identification of principal soil limitations and where to prioritise soil management actions. Useful tool for assessing Soil Quality and assisting land managers make the best decisions regarding sustainable use and management practices for their land. Field studies are encouraged that improve sensitivity of SMAF algorithms for detecting management-induced Soil Quality changes under different soils, crops and climates.

2.6.2 Assessing the productivity function of soils. A review. Agronomy for Sustainable Development (Mueller *et al*. 2010)

Mueller *et al*. (2010) found that soil structure is a crucial criterion of agricultural soil quality, and methods of visual soil assessment, such as Peerlkamp (Ball *et al*. 2007) and Visual Soil Assessment (Shepherd 2009), are powerful tools for recognising dynamic agricultural soil quality and controlling soil management processes at field scale. They concluded that these types of approaches have the potential to be integrated into an internationally applicable assessment framework of soil productivity potential on a global scale and as an operational tool for controlling further soil degradation. Methods such as the multi-indicator based Muencheberg Soil Quality Rating meet most criteria of such a framework, but needs further testing and amendment of indicator thresholds. Table 13 below shows the evaluation criteria used to assess agricultural soil quality rating systems.

Table 13. Evaluation criteria used to assess agricultural soil quality rating systems (Mueller et al., 2010).

Table I. Evaluation criteria and scheme of some existing methods for assessing overall agricultural soil quality (evaluation numbers 0 = none/false/worse; 1 = low/few/slow; 2 = medium; 3 = high/many/much/fast/good; 3 is always the best rating).

Criterion ↓	Storie index [1]	German BS [2]	AEZ [3]	VSA [4]	M-SQR [5]
Purpose of method					
Overall soil rating	3	3	0–1	0	3
Capability rating potential	3	0	1–2	0–1	3
Crop suitability rating	0	0	3	0–1	0–1
Tool for soil monitoring	0	0	1	3	2–3
Tool for soil management/extension	0	0	0	3	2–3
Tool for land use planning	2–3	2	3	1	3
Performance in spatial scales					
Field to regional level	3	3	0	3	3
Large regional to nation level	3	3	3	2–3	3
Trans-National	2	1	3	1–2	3
Indicator criteria					
Number of inherent SQ[6] indicators [a]	2	1	2	0	3
Number of dynamic SQ indicators	0	0	0	2	1
Climate inclusion	0	0	3	0	2
Interactions between indicators considered	0	0–1	2–3	0	0–1
Potential for assessing soil functions other than productivity	1–2	1	1	1	2–3
Further key criteria					
Simplicity in the field	3	3	0	2	2
Applicable without soil test kits	2–3	3	3	3	2–3
Speed of field rating [b]	2–3	3	0	3	2–3
Changes with soil depth included?	2	2	1	1	3
Correlation of scores with crop yields					
Field to regional level	2	2	0–1	1–2	2
Large regional to nation level	1–2	1	3	1–2	2
Trans-National	1	0–1	3	0	2

Abbreviations and references: (1) Storie index (Storie, 1933), (2) German BS (German Soil Rating, Rothkegel, 1950), (3) AEZ (Agro-ecological zoning, Fischer et al., 2002), (4) VSA (Visual Soil Assessment, Shepherd, 2000), (5) M-SQR (Muencheberg Soil Quality Rating, Fig. 2, Mueller et al., 2007) (6) SQ (Soil Quality).
[a] Number of indicators/criteria 1, few <5, 2 medium (5–15), 3 high >15.
[b] Time required for field rating (minutes per pedon/unit): 3 fast < 20, 2 medium 20–40, 1 slow >40, 0 no field method.

2.7 Monitoring

Principles and practices for monitoring soil change for Australian conditions are discussed in detail in McKenzie *et al*. (2002).

Murphy *et al*. (2013) assessed the use of visual soil assessment (VSA) schemes to evaluate surface soil structure in a soil monitoring program in NSW. Three VSA procedures were assessed to determine their value for monitoring the condition of soil structure of surface soils at regional or statewide scale. These included methods of Shepherd (2009) and the SOILpak scheme (McKenzie 1998, 2001a, 2001b). The rapid visual soil assessment schemes in this field study showed strong relationships to conventional measures of structural condition of soils including modulus of rupture, exchangeable sodium percentage (ESP), electrochemical stability index (ESI), and the degree of self-mulching. The rapid visual soil assessment methods quantified a broad range of inherent structural differences in the field and clearly identified severely compacted soils under wheel tracks. The VSA system and the SOILpak score are both strongly related to soil structural condition for the range of soils tested. They are cost-effective way of quickly monitoring progress with regional management initiatives, but further improvements with the methods are possible. The proposed use of the aggregate display from a drop test as used in the VSA test, to develop a quantitative estimate of friability has the potential to be a useful procedure to distinguish the self-mulching behaviour and sodicity of surface soils, especially clay surface soils. Relationships between three VSA methods (SOILpak, Shepherd VSA and Drop Test Friability) and quantitative methods (ESP, ESI, MOR) are summarised below.

- SOILpak (McKenzie 1998) score vs: ESP ($r^2 = 0.37$); ESI ($r^2 = 0.36$); MOR ($r^2 = 0.68$); SOC ($r^2 = 0.22$); DT Friability ($r^2 = 0.65$).
- VSA (Shepherd 2009) score vs: ESP ($r^2 = 0.53$); ESI ($r^2 = 0.29$); MOR ($r^2 = 0.48$); SOC ($r^2 = 0.005$); DT Friability ($r^2 = 0.57$).
- Drop Test Friability (DT Friability): ESP ($r^2 = 0.64$); ESI ($r^2 = 0.54$); MOR ($r^2 = 0.77$); SOC ($r^2 = 0.11$).

The NSW soil structure monitoring (now discontinued) involved the following soil physical assessments: Visual Soil Assessment (drop shatter test, porosity), Aggregate stability in water (ASWAT), Bulk density (core), Water repellence, Particle size assessment and Dispersion

Taylor *et al*. (2010) reviewed the performance of soil indicators used in the Waikato region of New Zealand since 1995. Macroporosity (-10 kPa), aggregate stability and bulk density were key indicators of erosion risk. The target range for aggregate stability is well-defined only for production under arable land use (aggregates < 1.5 m.w.d mm). Lower target range for bulk density for mineral soils is between 0.5 and 0.7 t/m^3, depending on soil type.

Table 2: Variability of soil properties that occur in landscape units of a few hectares or less (Wilding and Drees 1983).

Variability of property	Number of profiles needed*	Property
Least (Coefficient of Variation <15%)	>10	Soil colour (hue & value)
		Soil pH
		Thickness of A horizon
		Total silt content
		Plasticity limit
Moderate (Coefficient of Variation 15-35%)	>10-25	Total sand content
		Total clay content
		Cation exchange capacity
		Base saturation
		Soil structure (grade & class)
		Liquid limit
		Depth to minimum pH
		Calcium carbonate equivalent
Most (Coefficient of Variation >35%)	>25	B2 horizon and solum thickness
		Soil colour (chroma)
		Depth to mottling
		Depth of leaching (carbonates)
		Exchangeable hydrogen, calcium, magnesium, & potassium
		Fine-clay content
		Organic matter content
		Plasticity index
		Soluble salt content
		Hydraulic conductivity

2.8 Summary

The general criteria used for selecting the physical and biological indicators, previously described by Moebius (2006), were listed by Idowu *et al*. (2008) and included:

- Sensitivity to management, i.e., frequency of significant treatment effects in the controlled experiments and directional consistency of these effects.
- Precision of measurement method, i.e., residual errors from analyses of variance.
- Relevance to important functional soil processes such as aeration, water infiltration/transmission, water retention, root proliferation, nitrogen mineralization, development of root diseases, etc.
- Practicality - ease and cost of sampling.
- Cost of analysis.

According to Idowu *et al*. (2009), most studies agree that a minimum data set for the assessment of soil health should include key indicators that: (1) are sensitive to changes due to management and climate variations, (2) integrate soil physical, chemical and biological properties, (3) are relatable to important soil functions, (4) applicable to field conditions and (5) accessible to many users.

There is a relatively small number of soil physical indicators that are widely used (e.g. bulk density, texture, available water holding capacity, infiltration rate, water-stable aggregates, penetration resistance, erosion rating), but a variety of measures could be used depending on the specific purpose. The purpose of soil monitoring should dictate indicators selected and the appropriate sampling, measurement and assessment of those indicators. Indicators can be used for many purposes, including:

- Guiding tactical management decisions on-farm, or whole-farm-planning (e.g. how susceptible is the soil to structural degradation?; when is an appropriate time for tillage?; how is the soil meeting needs of the crop?). This could involve use of visual soil assessment and semi-quantitative techniques (e.g. dispersion, slaking, field test for determining plastic limit, cloddiness, visual assessment of roots in soil profile).
- Measuring change in soil condition on-farm, or paddock, performance (e.g. water and nutrient use efficiency).
- Monitoring soil condition change (on trial site, in paddock, regional, national or industry-wide) - usually requiring more quantitative techniques that are sensitive enough to show real change (e.g. discriminate between treatments). For monitoring, the analytical and sampling methods selected need to reflect soil temporal and spatial variability.
- Providing industry or regional benchmarking, credence values or sustainability metrics for a variety of purposes such as product branding or state of the environment (SOE) reporting.

It is therefore difficult to advocate a generic approach to measuring soil condition and function. Instead we advocate the development of an appropriate suite of indicators appropriate to the purpose of the assessment and tailored to specific soil types and regions where the assessment will take place. Assessments could be a mix of field observations of soil characteristics (e.g. from soil pits, cores or digging), to laboratory analyses that complement the field observations with more quantitative data, to more advanced assessment that may be relevant to a key issue (e.g. assessments that relate to OC fractions).

Rabot *et al*. (2018) highlight the greater relevance of pore network characterisation compared to an aggregate perspective and identified porosity, macroporosity, pore distances, and pore connectivity, derived from imaging techniques, as being the most relevant indicators for several soil functions. Since imaging techniques are not widely accessible, they suggest using this technique to build an open-access “soil structure library” for a large range of soil types, that could form the basis to relate more easily available measures to pore structural attributes in a site-specific way (i.e. accounting for texture, organic matter content etc).

McKenzie (2013) noted that despite major advances in remote sensing and soil landscape modelling, the use of Visual Soil Examination and Evaluation (VSEE) techniques in the field should be a key component of soil assessment and management packages in Australia. These field-based techniques complement well established procedures such as laboratory analysis of soil samples. He proposed a new scheme for ‘whole-farm assessment and management planning’ based on a mix of VSEE methods, modern soil databases, and additional laboratory testing where appropriate.

2.9 Opportunities for Soil CRC

1. Soil health management requires an integrative approach that recognises the physical, biological and chemical processes in soils. The development of an integrated soil health test, or kit, would be a valuable research priority for the Soil CRC to allow farmers to make better management decisions, especially those other than basic fertiliser management. Also, Soil CRC researchers investigating new products and management strategies need appropriate

integrated soil assessment tests that are tailored to the specific soil types that they are investigating.

2. While there are interrelationships between chemical and physical indicators that are commonly assessed, there are few documented interrelationships between soil biotic indicators and soil physical indicators. This also presents an opportunity for the Soil CRC.
3. There are very few studies that have financial metrics associated with changes in soil health and economic performance of farms.
4. Farmers, consultants, advisers have usually played an insignificant role in development of soil quality assessment schemes – despite being important end users (Bunemann *et al*. 2018). This is an area that offers opportunities for the Soil CRC.
5. Spatial and temporal variability needs to be considered in developing indicators and associated sampling strategies.
6. Grading of soils by indicators across soil types, climates and cropping systems is difficult (Schjønning *et al*., 2004). However, context is critical and future Soil CRC work should maintain focus on contexting measurement of soil properties according to soil type, landscape, agricultural industry, agro-ecological zone etc. The SOILPak for Cotton work provides an excellent example of tailoring soil assessment to a specific soil (Vertosols) associated with a specific industry (cotton cropping).
7. Integration of pore space architecture with soil function is likely to be a valuable research area that will bring together soil biological, chemical and physical measures.
8. Indicators that can be surrogates for other soil functions provide more versatility in assessments.
9. Soil compaction and erosion are two of the most detrimental effects of decreased soil physical condition and assessment of these two areas should be a priority. Compaction and soil variability are issues that directly affect productivity and were identified by grower groups as a priority at the recent Soil CRC Program 2 workshop in Melbourne. There is a need for a project that addresses soil compaction as a key soil constraint and provides a framework for the identification, assessment, benchmarking and monitoring of soil compaction for key cropping soils for different agricultural industries. Such a project could develop the concept of identifying and measuring where a soil is on the 'compaction continuum' for a range of key soil types. Techniques could be developed for farmers and advisers to understand where they are on the compaction continuum and better understand and manage variability. This work would then provide Programs 3 and 4 with more robust methods for measuring changes in compaction due to amelioration interventions. Existing sensing techniques, such as constant velocity penetrometers, along with proximal sensing (e.g. Ground Penetrating Radar (GPR), EM38 and Electrical Resistivity Tomography (ERT) could be utilised to determine the best indicators to map and measure compaction at the paddock scale (linking to Theme 3 on mapping soil constraints). Novel imaging techniques could also utilised to visualise compaction and effects on plant roots and soil pore architecture (which affects water and air movement through the soil). Assessments for CTF and non-CTF systems and for key industries such as Grains, Sugar and Horticulture. Confounding variables such as soil moisture, clay content and soil structure need to be factored in to assessments. Interactions between other relevant constraints (e.g. sodicity) could be assessed and consideration given to determining how some biological and chemical properties 'shift' along the 'compaction continuum' (relating to amelioration and degradation).

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3 CHEMICAL INDICATORS OF SOIL HEALTH: WHAT'S USED AND WHAT NEEDS TO IMPROVE

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3.1 Overview of current state

Soil health indicators mean many things to different people; e.g. ask a farmer - what is the difference between soil health, soil quality, soil condition, and soil fertility? Here we are concerned with indicators based on chemical analysis of soil that can inform on the soil as a root growth medium and ignores academic arguments over definition. Note that some soil tests used to indicate soil 'chemical health', and thus included in this review, are also used to evaluate physical (e.g. sodicity tests are used to inform on soil water stability and aeration) and biological (e.g. soil organic matter has been used to infer biological potential) properties.

Laboratory tests of soil chemistry, especially those used to manage ameliorants and fertilizers, have a long history of research, development, extension and adoption compared to physical and particularly biological indicators. Many are commercially available as can be seen on price schedules from routine soil test laboratories (e.g.

Table **1**). Today they are used by farmers and their consultants to answer profitability/productivity/sustainability questions at a paddock scale. Natural resource managers use a more limited suite to answer productivity/sustainability questions at a regional scale, whereas policy makers use them for answering productivity/sustainability questions at a state-/national- scale within a public-good benefit rather than private gain. Both of the latter use collated data from farmers as substitutes of purpose-built studies of soil condition at large scales, e.g. National Land and Water Resources Audit (Natural Heritage Trust (Australia) 2001). At each scale the nature of support information used to spatialize the product used for decision making changes accordingly, e.g. site features used to provide a context to interpret the soil chemical indicator in a paddock (a map unit reduced to a uniform polygon) are replaced by areas of interest consisting of multiple map units of increasing soil complexity, as the scale increases beyond the paddock to the national scale. That is, the model of complementarity of modelling, monitoring and mapping applies proposed by McKenzie et al. (2002) at all scales (Figure 1). The ways in which this model is applied at different scales is changing with developments in sensors, sensor platforms, geostatistics and the demand from farmers, e.g. precision agriculture, digital soil mapping.

In contrast to physical and biological indicators, chemical indicators have calibration models supported by substantial field research. This research has been reviewed (Peverill et al. 1999) and collated into databases (Gourley et al. 2007, Speirs et al. 2013) to supply computer aided interpretations of soil tests to commercial service providers. These interpretative services are offered by some commercial routine testing laboratories, or built into packages provided by fertilizer suppliers. For some indicators, calibrations can be adapted for economic soil test interpretation by suggesting optimal application rates to achieve a cost-based outcome.

Table 1. Examples of soil chemical indicators and their application

	Paddock scale commercial indicators Price schedule from IPL (package E13 for crops in SE Australia)	Regional scale indicators Typical soil survey	National scale indicators National soil condition monitoring
Ammonium and nitrate N	✓		
Phosphorus (Colwell)	✓		
Phosphorus Buffer Index (PBI)	✓		
Exchangeable Cations (Ca, K, Mg, Na, CEC)	✓	✓	
Exchangeable Aluminium (KCl)	✓	✓	
Sulfur (KCl 40°C)	✓		
pH (1:5 water) & pH (1:5 $CaCl_2$)	✓	✓	✓
Electrical Conductivity (1:5 water)	✓	✓	
Chloride (1:5 water)	✓	✓	
Organic Carbon (Walkley and Black)	✓	✓	✓ (Dumas SOC)
Texture (Hand Bolus) and soil Colour	✓	✓	
ECSE (calculation)	✓		
Boron (hot $CaCl_2$)	✓		
Copper, Iron, Manganese, Zinc (DTPA)			
Moisture (at 105°C)			

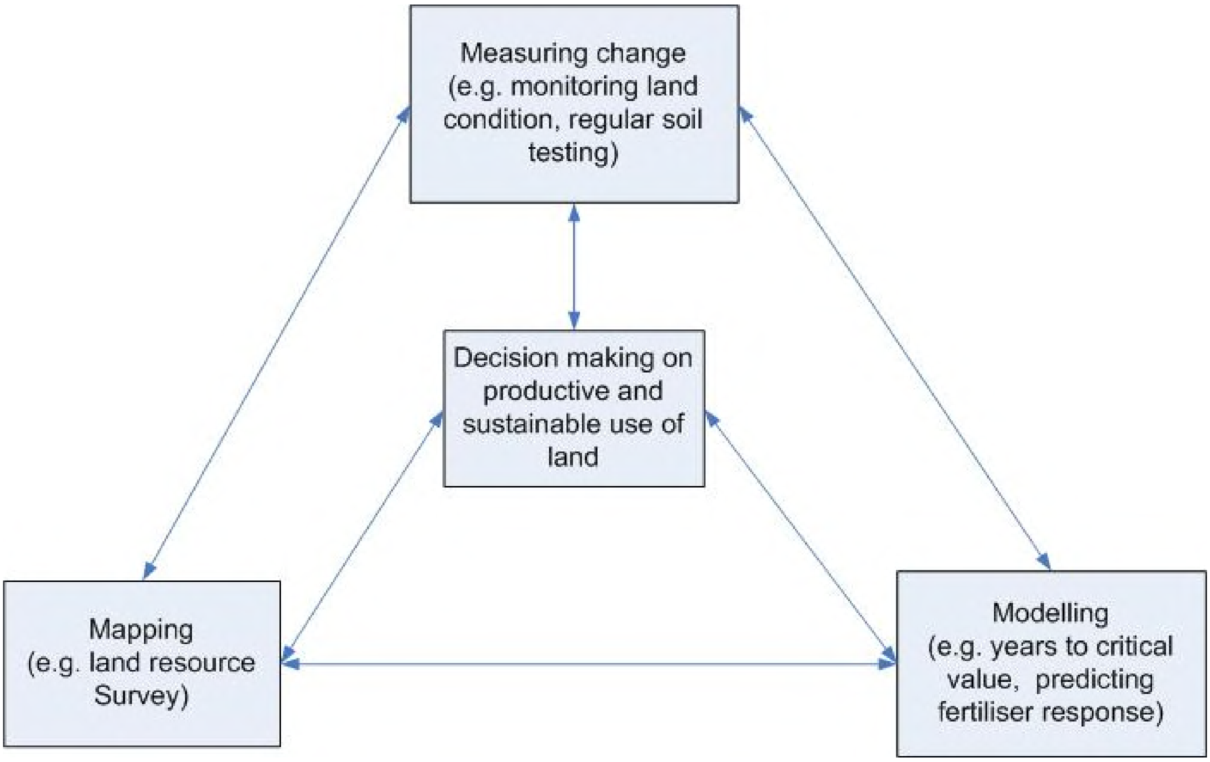

Figure 1. Complementary nature of mapping monitoring and modelling, from McKenzie et al. (2002)

Routine soil testing for chemical indicators is considered to have been “widely adopted”. However, the most recent survey of farm management conducted by the Australian Bureau of Statistics (2013) shows that “widely adopted” actually only constitutes 20% of farm enterprises (based on surveys of the 135,692 farm enterprises carried out in 2011-12) (Figure 2). It may well be that the rate of adoption is higher than indicated since the questionnaire was specific to the financial year of the survey, and so would miss farm enterprises who regularly tested soil less frequently (i.e. the survey did not ask if the respondent had a soil testing program). Notably, only a small number of indicator tests are routinely used by farmers (e.g. Table 1) although a wide range of soil chemical tests targeting a range of soil functions from nutrient status (fertility) to toxicities (e.g. sodicity), are available as is illustrated for Victoria in Table 2. The same survey showed that soil chemical indicators are primarily used to manage nutrient suppling fertilizers, limes and gypsum, with only a minor proportion of test numbers in the “other tests” category (Figure 2).

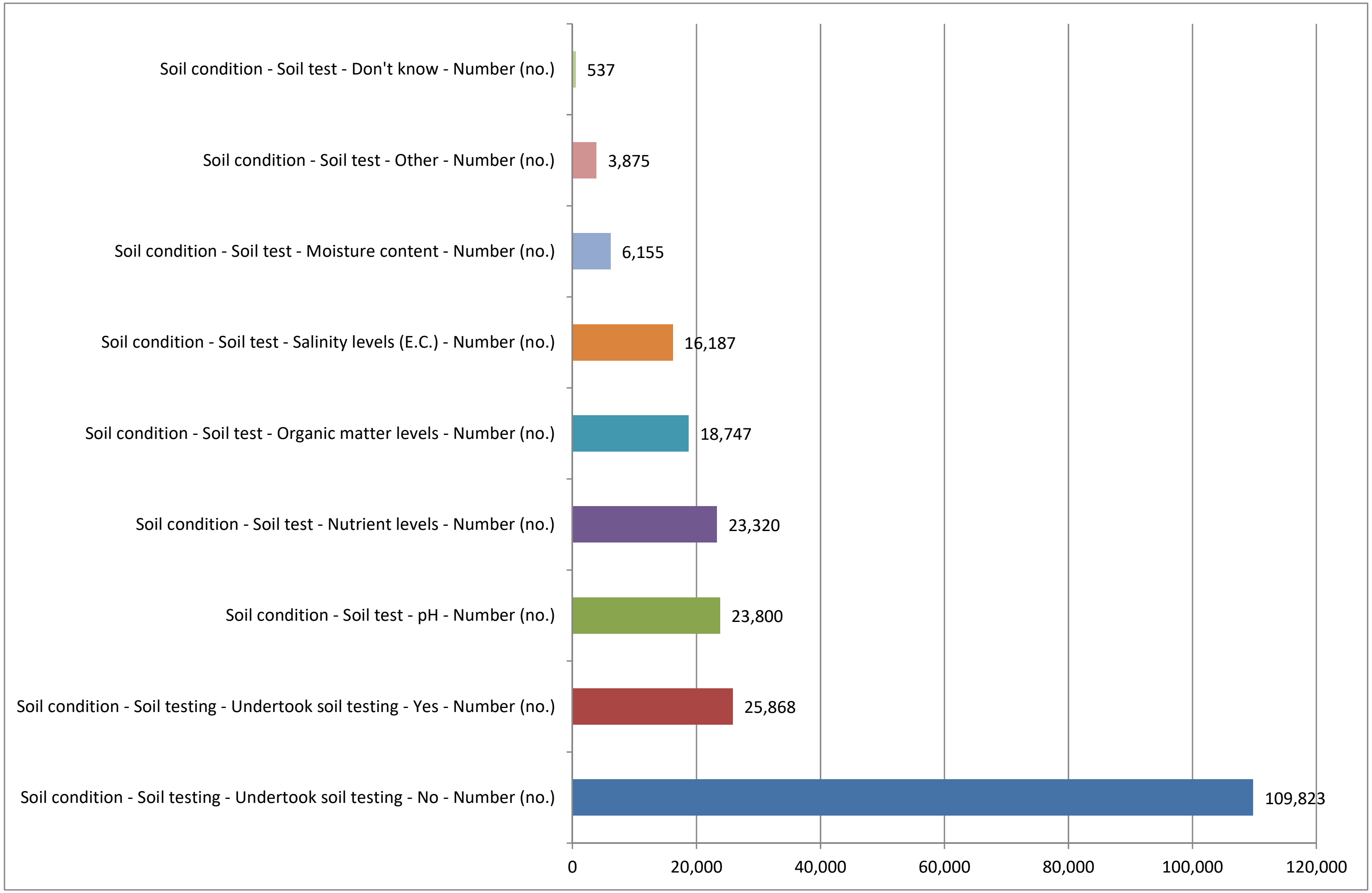

Figure 2. Numbers of farm enterprises using soil testing across Australia. From the ABS survey of farm enterprises (*n* = 135,692) between 2011-2012

Table 2. Chemical indicators of soil health that have been used in Victoria including physical indicators used to interpret chemical indicators

Target variable	Property	Test Purpose	Productivity considerations in Victoria	Range in soil	Critical value	Sample Preparation	Extractive Step	Analyte measurement
Macronutrients								
P	Total P	Used to assess P reserves and baseline data for calculating P fractions. Mainly used in studying natural vegetation and forestry, not agriculture where available P is tested	P deficiencies occur across the state and in all industries	0.02-0.5%		Sample preparation varies, for example, former Soil Conservation Authority (Victoria) used the method of Piper (1942) applied to < 2 mm fraction where as others used a finely ground subsample of the < 2mm fraction	Typically strong acid digestion, e.g. nitric-perchloric digest, boiling in hydrochloric acid	Interferents can have differential effects on analysis of digests
	Available P	Used to indicate the potential response to P fertilizer and from there estimate the P fertilizer requirement.	P deficiencies occur across the state and in all industries	<1-812 mg/kg soil	22 mg/kg soil (Olsen P) 20-40 mg/kg soil (Colwell P)	All on < 2 mm fraction	Typically weak acid extraction. Colwell P and Olsen P; Both methods use 0.5 M $NaHCO_3$ pH 8.5. Colwell uses a 1:100 ratio while Olsen uses a 1:20 ratio, while Colwell shakes for 16 h and Olsen for 30 min	
	P Buffering	Used to understand response to P fertiliser in terms of change in available P	P deficiencies occur across the state and in all industries		NA	< 2 mm fraction	PBI as per available P tests. PBC (Burkitt et al 2002) was based on 17 h	Molybdate Blue, Murphy and Riley 1962 for PBC

Target variable	Property	Test Purpose	Productivity considerations in Victoria	Range in soil	Critical value	Sample Preparation	Extractive Step	Analyte measurement
		soil test values. PBI is calibrated to modify the interpretation of Colwell P values					equilibration with 0.01 M $CaCl_2$ at a 1:10 ratio	
	P fractions	Understand P reserves in mineral or organic fractions and help understand soil P cycle	P deficiencies occur across the state and in all industries		NA	< 2 mm fraction	Various methods on mineral P fractions and organic P fractions based on a variety of methods	
	Oxides of Fe and Al	Inform on P buffering	P deficiencies occur across the state and in all industries		NA	< 2 mm fraction	Extraction by various methods, e.g. acid oxalate, see Rayment and Lyons (2011).	
N	Total N	General fertility but specifically calibrated to assess ley rotation where pasture phase is the main supply of crop N	N deficiencies occur across the state and in all industries	0.02-0.4%	0.08, 0.13% N for ley farming	Fine grind of < 2 mm fraction only	Dumas v. Kjeldahl	Colorimetric titration or gas analysis
	Available N	Nitrate is used to assess pre-sowing N reserves in cereal and oil seed crops to adjust N fertiliser rates nitrate, concentration results are converted into weight/area	N deficiencies occur across the state and in all industries	1-100 mg/kg soil	80 kgNO_3^--N/ha	< 2 mm fraction	1:10 1 M KCl	Colorimetric or titration
	Potentially mineralisable N	Indicate N supply to plant and N cycling	N mineralisation is an important source of N in		Not yet calibrated to predict N fertiliser response	< 2 mm on as received sample. Logistics of sample transport	A range of strong or mild extractants, incubation methods	Depends on matrix and whether nitrate, nitrite

Target variable	Property	Test Purpose	Productivity considerations in Victoria	Range in soil	Critical value	Sample Preparation	Extractive Step	Analyte measurement
			non-legume crops			can drastically affect results	imitating microbial release	or ammonium are measured.
C	Soil Organic Carbon	General fertility indicator on water retention and movement, BD, macro-nutrient reserves, aeration and buffering	Since SOC is the reservoir of N and S and a significant fraction of P, it affects all industries and states	<1-15%	NA	Specific removal of visible charcoal and pre-treatment for carbonates for dry combustion methods	Dichromate digestion or oxygen free dry combustion	Various, effected of interferents
	Labile Carbon (Active Carbon) or Particulate Organic Carbon	Indicate C cycle potential	Not directly related to productivity for which there are better tests		NA	< 2 mm on as received sample. Logistics of between paddock and laboratory door can drastically affect results	Reaction with potassium permanganate for labile C, particulate organic carbon retained when finely ground soil (<0.5 mm) is passed through a 53 µm sieve	
K	Total Potassium	Quantify K reserves	K deficiencies affect the medium and high rainfall zone particularly in the grazing industries	0.04-3%	NA	<2 mm fraction for boiling HCl, otherwise finely ground subsample of the < 2 mm fraction	Strong hot acid digestion, e.g. nitric-perchloric digest, boiling HCl , HF; or XRF spectrometry	
	Available Potassium	Indicate potential response to K fertiliser	K deficiencies affect the medium and high rainfall zone particularly in	1-7200 mg/kg soil	80-200 mg/kg soil	< 2mm fraction	Extraction by weak acid or alkali	

Target variable	Property	Test Purpose	Productivity considerations in Victoria	Range in soil	Critical value	Sample Preparation	Extractive Step	Analyte measurement
			the grazing industries					
S	Total S	Assess S reserves	S deficiencies affect the medium and high rainfall zone particularly in the grazing industries, in cool wet conditions	0.003-1%	NA	Unknown	Boiling HCl v XRF	
	Available Sulfur	Indicate potential response to S fertiliser	S deficiencies affect the medium and high rainfall zone particularly in the grazing industries, in cool wet conditions	1-762 mg/kg soil	4 mg/kg soil	< 2 mm fraction	Calcium phosphate extractants v KCl40	Differences depending whether charcoal used to remove organic S from supernatant
Micronutrients								
Micronutrients	Available Boron	Assess B toxicity in the cropping zone and B deficiency in horticulture	B toxicity in subsoils limit crops in heavy soils in the low rainfall zone, while B deficiency can limit horticulture in highly leached soils	2-100 mg/kg soil	5 and 15 mg/kg soil but varies	< 2 mm fraction	Hot water v mannitol extractable, heating procedure: micro-wave v water bath v jacketed funnel to hold sample vessel	

Target variable	Property	Test Purpose	Productivity considerations in Victoria	Range in soil	Critical value	Sample Preparation	Extractive Step	Analyte measurement
	Available Copper	Assess potential response of plants or animals to Cu treatment	State-wide, all industries but infrequent reports of response to Cu treatment except in highly leached light soils	0.005-1000 mg/kg soil	1 mg/kg soil suggested as a critical value. Requires more research; deficiencies should be identified using plant tissue testing amongst other factors	< 2 mm fraction	Extraction in EDTA or DTPA	
	Available Zinc	Assess potential response of plant to Zn treatment	Deficiencies in NW Victoria in alkaline soils	0.03-1000 mg/kg soil	1 mg/kg soil suggested as a critical value. Requires more research; deficiencies should be identified using soil pH and plant tissue testing amongst other factors	< 2 mm fraction	Extraction in EDTA or DTPA	
	Available Selenium	Assess potential response of animals to Se treatment	Deficiencies in Sthn. Victoria in leached soils	0.1-2 mg/kg soil	Requires more research; deficiencies should be identified using animal tissue testing	< 2 mm fraction	Total or extractable Se	
	Available Cobalt	Assess potential response of animals and plants to Co treatment	Deficiencies in Sthn. Victoria in leached soils	1-94 mg/kg soil	Requires more research; deficiencies should be identified using animal or plant tissue testing	< 2 mm fraction	Total Co, or extraction in EDTA or ammonium acetate	
	Available Molybdenum	Assess potential response of plant to Mo treatment	Deficiencies in Sthn. Victoria in acidic soils	0.2-5 mg/kg soil	Requires more research; deficiencies should be identified using soil pH and plant tissue testing amongst other factors	< 2 mm fraction	Hot water extraction versus 0.275 M NH_4 Oxalate	

Target variable	Property	Test Purpose	Productivity considerations in Victoria	Range in soil	Critical value	Sample Preparation	Extractive Step	Analyte measurement
Fe	Available Iron	Assess response to foliar application of Fe	Infrequent reports of response to Fe treatment except in highly alkaline soils used for horticulture		Requires more research; deficiencies should be identified using soil pH and plant tissue testing	< 2 mm fraction	Extraction in EDTA or DTPA	
Mn	Available Manganese	Assess for potential response to foliar applications of Mn. Also used to research Mn toxicity	Infrequent reports of response to Mn treatment		Requires more research; define in using soil pH and plant tissue testing	< 2 mm fraction	Extraction in EDTA or DTPA	
Soil matrix								
	Texture	To inform on particle size analysis used to classify soil or help understand soil function		0-100%	35% clay, or proportions above and below 2, 20 and 2000 μm	< 2mm fraction or whole soil	removal of binding agents or flocculants including organic matter, salts, lime, gypsum; methods for dispersion of particles, wet sieving	Hygrometer v. plummet balance v. pipette
	Free Fe (for Ferrosols)	Classification of soil	Ferrosols are highly valued due to their versatility for horticulture but are limited in extent		5%	< 2 mm fraction	Citrate/dithionite extractable Fe (Rayment and Lyons 2011)	
	Dispersion	Assess need for gypsum and classify soil	Sodicity affects all industries in the medium to lower rainfall zone, particularly		Slight dispersion	< 2 mm fraction v natural aggregates v field		Emerson v Loveday & Pyle v SCL v field

Target variable	Property	Test Purpose	Productivity considerations in Victoria	Range in soil	Critical value	Sample Preparation	Extractive Step	Analyte measurement
			irrigated agriculture					
	Mineralogy	With texture, provides basic information about soil but sourced from limited data informing local knowledge	Foundation data for understanding soil		NA	< 2 mm v. < 2 micron clay fraction after separation	Prepared using PSA laboratory methods	Elemental composition v clay crystal proportion
	Colour	Classify soil and inform on drainage	State-wide, all industries		Grey or Gleyed colours	Natural fragments v. prepared samples of < 2 mm fraction	Moist v. dry	Manual comparison to Munsell colour chart
	Lime content	Soil classification and land use assessment	Free lime can block soil pores, abundant lime nodules can limit aeration, drainage and water reserves, in NW Victoria		Slight effervescence	<2 mm fraction (laboratory) or whole soil (field)	Gas release v. weight loss after acidification v. effervescence	Volumetric v. infrared v. visual assessment
Soil condition								
Reaction	pH (H^+, OH^- activity)	Assess pH conditions for extremes in deficiency/toxicity, classify soil	Alkalinity in NW Vic and Acidity in Sthn. and NE Vic affect all industries	4-10 (pH_{water}) 3-9.5 (pH_{CaCl2})	6.0, 7.5 (pH_{water}) 5.0, 7.5 (pH_{CaCl2})	Laboratory sample vs. *in situ* measurement	Laboratory methods are based on 1 h shake of a 1:5 ratio suspensions, occasionally 1:1 or 1:2.5 ratio. Field pH is directly assessed on the sample. Little data on direct measurement of soil water bathing the	Suspension in water or 0.01 M $CaCl_2$. Historical research has used 1:1 water in Victoria. Overseas, water, 1 M KCl and 0.01 M $CaCl_2$ are

Target variable	Property	Test Purpose	Productivity considerations in Victoria	Range in soil	Critical value	Sample Preparation	Extractive Step	Analyte measurement
							roots which needs high G force centrifuges to extract	used at other ratios including 1:1 and 1:2.5 including for the Soil Taxonomy. Field kits (Raupach 1950)
	Exchangeable Acidity	Used to help estimate effective CEC in acid sodic soils and calibrated to determine lime requirement	Acidity affects all industries in the medium and high rainfall zones, sodic soils affect a subset of these zones	0-20	NA	< 2 mm	Equilibration in triethanolamine buffer solutions	Titration with acid
	pH buffering	Used to estimate net acid addition and model pH change when liming or soil is acidifying	Acidification affects all soils except where product balance is alkalinising, the rise and fall of alkaline water tables or irrigation water affects soil pH and carbonate dissolution occur		NA	< 2 mm	Depends on the method; equilibration in acid solutions or acid and alkali solutions	Determine pH of supernatant
Salinity, cations	Salinity	Salinity is used to monitor salinization of soil and land	Horticulture and irrigated agriculture	0-2 dS/m	0.16 dS/m	< 2 mm fraction	1:5 suspension is standard but many use saturation	Reporting temperature 22 v 25,

Target variable	Property	Test Purpose	Productivity considerations in Victoria	Range in soil	Critical value	Sample Preparation	Extractive Step	Analyte measurement
and sodicity		under irrigation, or by dryland salinity (primary or secondary), and to check drainage	across the state use EC to assess salinity. Low rainfall zones and coastal zones use this test for salinity.				extract is the reference for assessing plant tolerance. Historically, total soluble salts were used to more crudely assess effect on plants.	mmho/cm v. dS/m, salt mass after evaporation
	Chloride	A mobile anion used to indicate accumulation of salts due to poor drainage or salinity	Horticulture and irrigated agriculture across the state use Cl to assess salinity. Low rainfall zones and coastal zones use this test for salinity.	0.001-8.17 Cl as NaCl%	0.02-0.5%	< 2 mm fraction	1:5 water	Potentiometric (precise) v colorimetric (rough), done depending on EC rule
	Cation Exchange Capacity	Used to calculate sodicity in acidic soils and for classifying soils	Sodicity affects all industries in the medium to lower rainfall zone, particularly irrigated agriculture	1-91 cmol. (+)/kg	NA	< 2 mm fraction	Sum of acid and base cations	
	Exchangeable/extractable cations	For calculating sodicity and classifying soil; also used to calculate Ca:Mg ratios and	Sodicity affects all industries in the medium to lower rainfall zone, particularly	<0.05-60 cmol. (+)/kg	cation balance ratios are not field validated for Victoria; 2 Ca:Mg ratio	< 2 mm fraction	Buffered and unbuffered extraction in salt solutions with or without prewash to remove soluble salts;	

Target variable	Property	Test Purpose	Productivity considerations in Victoria	Range in soil	Critical value	Sample Preparation	Extractive Step	Analyte measurement
		Albrecht cation balance ratios	irrigated agriculture				leaching methods seldom used	
	Sodicity	Assess the need for gypsum and classify soil	Sodicity affects all industries in the medium to lower rainfall zone, particularly irrigated agriculture		6 and 15% ESP			
	Available Aluminium	Originally to assess land for lucerne and guide lime requirement, but now used for other low pH sensitive plants such as canola	Medium and high rainfall zone soils for cropping and lucerne	1-1000 mg/kg soil	Method dependent	< 2 mm fraction	1:10 1 M KCl v. unbuffered extractable cation methods v. 1:5 0.01 M $CaCl_2$	

3.2 Limitations and future directions

Despite this array of chemical 'soil health' indicators, adoption by end-users is patchy (Figure 1). There can be many reasons for farmers to not adopt indicators or discontinue their use (Figure 3). Pannell (2003) provides a review looking at sustainability indicators that equally applies to soil health indicators. Low adoption levels are expected for indicators that are only regionally relevant (e.g. sodicity), specific to an enterprise (e.g. BSES P in sugarcane), are slow to change (e.g. Total carbon), lack adequate remedial management options, are outside the control of the farmer, are no longer necessary (e.g. where a soil property has reached optimal conditions) or are no longer used due to the stage of the farm business (e.g. the farmer is close to retirement).

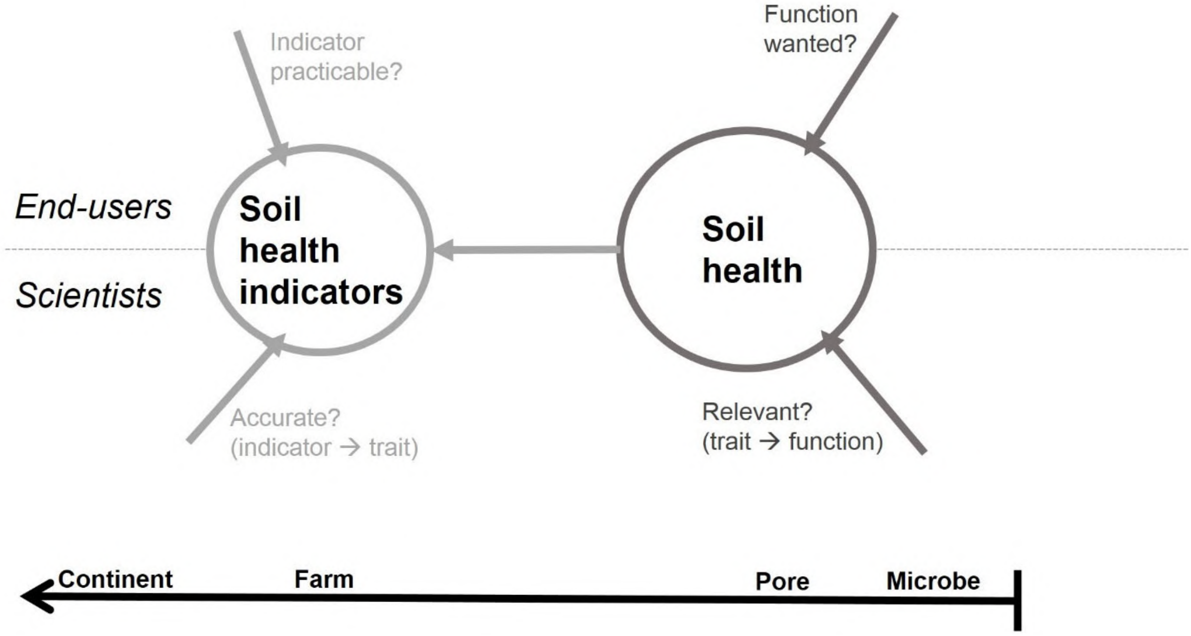

Figure 3. Schematic representation of the challenges in developing soil health indicators. The indicators must be relevant to the targeted soil function or property which vary differently at different scales, but to be adopted by end-users it must also provide accurate information at the farm scale and be practicable (cost effective and with minimal complexity of sample collection and handling).

Importantly for the Soil CRC, low adoption rates of some indicators (e.g. nitrogen, carbon, phosphorus) and technologies to measure indicators can arise either when there is a lack of benefit from using the indicator, whether perceived or real. That is, where the benefits are not evident (i.e. you can't see it on the air, water, soil or plant, or on the balance sheet), result only in intangible benefits (e.g. commodities going to markets that don't require ethical production), or where the indicator has poor awareness amongst users for some indicators, the lack of scientific information curtails any claims of beneficial impacts of soil management.

Addressing adoption of an indicator therefore requires identification of these gaps and limitations arising from a lack of awareness, a lack of feasibility (precision, cost and timeliness of different analytical methods, benefits, opportunity, research data calibrating the indicator), or a lack of accuracy due to variability in the soil (e.g. gilgai) or the analyte (Brown 1993, McBratney and Pringle 1997).

Indicator feasibility gaps can be addressed either through collaboration with the work under Programme 2.2 and Programs 3 and 4, to develop technologies to lower the barriers to adoption. Where the fundamental uncertainties in the relationship between a soil indicator, the soil and soil management practises, represent a gap then further targeted research is needed. Furthermore, changes to farming systems will require recalibration of some indicators, particularly where the fertility profile has changed with the adoption of reduced tillage, deep placement of fertilizers and controlled traffic. In the context of the Soil CRC, low implementation of robust and practicable indicators would be best addressed through collaboration with social scientists in Programme 1 and will thus not be discussed further here.

3.2.1 Improving indicator accuracy by improving sampling resolution

Scale issues are fundamental to the soil-plant system, where heterogeneity exists from the 10^{-6} m to 10^{+6} m. Isotope measures provide some scope to integrate micro-scale variations that might be plant-relevant into plot or field scale measurements (Table 2). We see substantial scope within this CRC to further address this gap for Australian agroecosystems by combining targeted chemical measures of soil function with satellite and/or sensor networks to upscale relationships over time and space.

It is this ‘resolution’ limitation to soil chemical health indicators, combined with technological farming equipment advances, that has enabled cropping farmers to adopt precision agriculture. Fundamental to this approach is shifting thinking away from assuming that the paddock is a single unit. These farmers are prepared to pay to have the paddock either surveyed with EM38 or grid sampled for soil pH and available P and K by commercial service providers. Data is used to apply variable rates of fertilizers, gypsum and lime across the farm. An important value-add has been the improvement of drainage by utilising the elevation data from the differential GPS collected with the EM38 data. This is an area of rapid development that has implications for chemical, physical and biological aspects of soil health. A recent survey of farm enterprises (Australian Bureau of Statistics 2016) found 3,260 farm enterprises using spatial yield mapping, with 3,959 using variable rate application of inputs. Although the survey did not assess the adoption of within-paddock mapping of soil chemical indicators, service providers in this field report significant adoption of within-paddock soil mapping in the cropping industries of south-eastern Australia. Within-paddock soil mapping has been widely adopted for establishment of perennial horticulture, particularly vines, based on convention soil survey at high intensities (e.g. 1:2,500 to 1:5,000 scale). In both cases, the optimal survey frequency for monitoring changes in soil indicators are not yet established. This represents an example where indicators are known to provide farmer-relevant and accurate information, but adoption of a more intensive application is lagging,potentially due to be both cost and the scientific uncertainty that means that no standard procedure is available.

3.2.2 Improving indicator accuracy by better linking ‘indicator’ and ‘function’

While promising, these ‘big data’ approaches will not be able to solve all of chemical soil health indicators ‘accuracy’ limits. This is because there are numerous instances where, although the chemical laboratory methods are sound, the measured parameter does not easily match a functional output in the field. Developing ‘next generation’ soil health indicators therefore requires careful identification of where indicator strength is limited by data quality/ quantity, and where it is limited by a more fundamental chemical/biogeochemical accuracy. For instance, measurements have historically targeted ‘abundant’ (i.e., measurable) soil components, which we now know may not correspond to the biological availability, and thus function, of the compound. There is therefore a need to re-examine soil chemical indicators using the more sensitive and precise techniques now available (see, e.g., (Ros et al. 2011)). Some of the most promising approaches to developing new chemical indicators of soil N, C, and P availability are listed below (Table 2). For N and P these revised tests are aimed at better defining the ‘biologically available’ pools (rather than the measurable pool), while for C these tests are aimed at better defining C stores and turnover.

Systematic validation of these approaches will also provide more information on what is actually feeding plants / soil fertility, and whether these relationships remain constant across the steep hydrologic gradients found within Australia, or whether unique indicator suites are needed for different cultivation zones. The combination of farm, industry, and 'fundamental' research trials that will be carried out under the umbrella of the Soil CRC provides an opportunity to test the utility of several promising emerging techniques for assessing soil health.

Table 3. Prospective chemical indicators of soil health

Target Soil Property	Technique	Test purpose	Sample preparation	Current limitations to application
P	Phosphate stable isotopes ($\delta^{18}O\text{-}PO_4^{3-}$)	Constrain turnover times could enable more accurate connection between the different 'extractable' P pools and the actual plant available P pool (Tamburini et al. 2014)	Prepare soils as for desired P fraction measurement (see Table 1); remove excess organic matter; prepare precipitate; produce AgPO4; measure on IRMS (Pistocchi et al. 2017)	Intensive off-line sample preparation needed, which is currently not performed by any commercial laboratories. Potential for easy-to-interpret data on P fraction turnover, but more research needed to calibrate for different soil types.
	Rhizosphere P?	With growing evidence that manipulating rhizosphere microbes can increase P uptake, need some sensitive approaches for quantifying these effects (Wallenstein 2017)		
N	Isotopic composition of bulk soil N ($\delta^{15}N$-TN)	Provide an integrative measurement of soil N retention v. loss (Stevenson et al. 2010) and long-term soil productivity (Mudge et al. 2013)	Homogenise, dry (40°C), and grind samples; weigh small (<1 mg) into tin capsules; store in a desiccator until analysis IRMS	Easy added value if SOC already being analysed (though note that these samples must NOT be acidified). Data is scalable (Bai et al. 2013) and fairly easy to interpret. Probably significant added value if paired with plant $\delta^{15}N$ analyses (Amundson et al. 2003).
	Compound-specific N isotopic composition (e.g., $\delta^{15}N\text{-}NO_3^-$ and $\delta^{15}N\text{-}NH_4^+$)	Indicators of competing microbial processes affecting N availability (Rock et al. 2011). Potential to measure gross soil N mineralisation when combined with $\delta^{15}N$-TN measurements (Pörtl et al. 2007).	Either collecting soil water from in-situ passive sampling or KCl extracts of fresh soil	Extractions best performed on fresh soil samples (same as for nutrient concentration measurements), labour intensive sample pre-treatment needed before isotope analysis, samples must be analysed on an IR-MS fitted with a gas bench (less common than solid IR-MS / EA). Data requires expert interpretation. Recommended in intensive studies, but not practical for wide adoption by end users.

	Passive samplers of plant available N	Remove ‘extraction’ step from measuring plant available N forms	Insert to rooting depth, collect soil water samples at regular intervals	Not applicable in low-moisture soils
	Organic N compounds	Plants may preferentially uptake organic N forms over the conventionally measured NH_4^+ and NO_3^-, meaning measuring low molecular weight organic N and/or amino acid availability may be a better predictor of plant available N than more conventionally measured NO_3^- (Jones et al. 2005, Farrell et al. 2014)	Either collecting soil water from in-situ passive sampling or KCl extracts of fresh soil. Concentrations can then be measured by FIA or fluorometers, provided appropriate standards and reagents available	Both size fractionation and free amino acid quantification can be performed using standard, reasonably low cost, laboratory equipment (Jones et al. 2002). However, few government or commercial laboratories currently have these methods in place, so might be slow to adopt.
C	Soil C fractions			Differences in sample handling and laboratory methods can make upscaling difficult. Only recommended in combination with ‘standard’ SOC measurements.
	Combining ^{14}C dating of bulk v fractions of the soil organic C pool	Precise soil C turnover times, check assumptions on soil C fraction models (Sanderman and Baldock 2010, Sanderman et al. 2016)		Costly and labour intensive (on the laboratory side), only recommended for validating predictions from other approaches
	$\delta^{13}C$ depth profiles	Determine C mineralisation and stability over time (Diochon and Kellman 2008, Hou et al. 2015)	As per SOC: dry, grind, acidify (if IC present), weigh, and analyse on IR-MS	Straightforward value-added if already measuring SOC. For best results, analyse plant $\delta^{13}C$ to account for mixing effects. Data requires expert interpretation.

In addition to developing sensitive indicators of nutrient availability, substantial scope remains to improve the interpretation of the available chemical indicators through identifying key inter-indicator relationships. For instance, the relationship between soil N content and plant N uptake is mediated by soil water content.

Table 4. Relationships between factors and indicators that need to be built into monitoring systems

Target Soil Property	Regulating factors
P availability	Soil minerals pH Plant roots Moisture (diffusion) C:N:P stoichiometry
N availability	C:N:P stoichiometry Moisture Temperature Sunlight (N fixation)
C availability	Plant biomass Soil minerals Sunlight (photosynthesis) Temperature Moisture C:N:P stoichiometry
Water availability	Precipitation Sunlight Temperature Soil structure Plant community (roots) Salinity
Micronutrient availabilities	Soil minerals Redox pH
Reaction (strongly acid to strongly alkaline range)	Mineralogy of particle surfaces Redox/waterlogging/aeration Soil composition (±calcareous) Salinity and soluble salts

We suggest that a target outcome of this Australasian-wide Soil CRC is to build comprehensive datasets that will allow relationships to be identified and empirically quantified under both the 'big data' umbrella and via more targeted field trials. Specific approaches could include:

- Use sensor networks soil temperature and moisture data to calibrate more 'scalable' indicators of nutrient availability like $\delta^{15}N$ and $\delta^{13}C$
- Develop nutrient availability indicators in parallel to biological indicators to test strength of feedbacks between species and hydrology, nutrients, microbial diversity, etc.

- Use satellite data-based ‘microbial active days’ calculations to predict soil N mineralisation (availability?)
- Expand standard C:N data to C:N:P (Sinsabaugh et al. 2008, Gardenas et al. 2011, Sinsabaugh et al. 2016)

3.3 Specific recommendations for Soil CRC research in the ‘chemical soil indicators’ sphere

- Identify which indicators are ‘data limited’ and/or ‘biogeochemically limited’. This could include collecting high temporal resolution data for specific parameters that are currently in the ‘development’ stage of sensorisation (e.g., NO_3^-) and quantifying the benefit of increased data. This will inform whether future work should continue to focus on sensorisation or instead be refocused on identifying an alternative ‘target compound’ for the desired function.
- As nutrients, are regulated by, and for, soil biology, future work requires synergistic development of ‘biology’ and ‘chemistry’ indicators to improve the accuracy of interpretation.
- Quantitative links between ‘tactical’ and ‘strategic’ indicators. Farmers make management decisions monthly – seasonally – annually based on readily measured parameters, whereas more inter-annual – decadal farm sustainability are reflected in less sensitive parameters like soil C. Can simple and frequent tests be used to predict long-term soil health?
- Chemical indicators have historically been used to make input (e.g. fertilisers and other amendments) decisions. However, there is growing recognition that indicators are also needed to help farmers rapidly identify the impact of management practices on complete ‘soil health’. For instance, to identify the magnitude and breadth of soil compaction across a farm. Based on the inexorable connections between such physical alterations and biological and chemical outcomes, developing indicators across all three domains will strengthen their accuracy and potential use to the farmer.

3.4 Broad recommendations for Soil CRC research in the ‘chemical soil indicators’ sphere

We propose that the Soil CRC work in different indicator domains is summarized in Table 5. These address limitations and opportunities for improving current indicators, replacing indicators of soil properties with indicators of soil functions and replacing measurement methods or sampling approaches.

Table 5. Targeted future development

ID	Soil Property	Measurable parameters	Research, development, and implementation targets		
			Why? (importance)	Functional gaps	Technology opportunities
Nutrient availability					
1	**P availability**	Available P, PBI, Paddock history	P deficiency	-Plant P availability v. measurable and labile P pools -P transformations -Organic P quality and composition	-Infrared spectrometry -Osmotic soil samplers (accounts for physical constraints to plant uptake, removes lab artefacts) -Laser-Induced Fluorescence Spectroscopy (molecular structures) -Lab-on-chip (bioavailability)
2	**N availability**	-Available N (NH_4^+, NO_3^-) -Net mineralisation -Paddock history (basically use of BNF)	N limitation on growth	-Gross transformations (maintenance of fertility) -Plant bioavailability -Quality and composition of the organic N pool	-Osmotic soil samplers (accounts for physical constraints to plant uptake, removes lab artefacts)
			N loss minimisation (both NUE and leaching)		-Land on chip (N availability that minimises artefacts) -Infrared for total N
3	**C availability**	TC and C fractions		-Lability and utilisation of C forms -Interaction biology and C storage -C and soil structure -C and acidity / buffering	-Infrared sensors -Satellite -Laser-Induced Fluorescence Spectroscopy (molecular structures) -CO_2 sensors (C mobilisation and mineralisation)
Soil matrix					
4	**Texture**	Texture	Interpreting other soil tests especially available K, available P, lime and gypsum requirement	Defined effect of soil components on field texture	IR spectroscopy
5	**Soil organic matter**	Soil organic matter content	Lime requirement	Composition of organic matter and pH buffering	IR spectroscopy

ID	Soil Property	Measurable parameters	Research, development, and implementation targets		
			Why? (importance)	Functional gaps	Technology opportunities
6	**Mineralogy**	Clay minerals, lime content, gypsum content, metal oxide content	Soil composition and reaction with nutrients (e.g. P fixation), salinity and pH buffering	Inadequately defined relationships	IR spectroscopy, Laser induced breakdown spectroscopy (LIBS), X-Ray Fluorescence (XRF)
Soil condition					
7	**Reaction (pH, H^+, OH^-, Eh)**	Eh	Redox potential	-Buffering capacity (C and clay etc. affect lab analyses and field performance)	-Lab-on-a-chip -Eh probes -O_2 sensors
		pH, H^+, OH^-	-nutrient availability -phytotoxic ions -need and response to liming -soil acidification	Better define effects on deficiencies, toxicities and pH buffering	-Field kits -Field pH probes -IR spectrometry and pH buffering
		Carbonate content		Better define relationship to pore matrix	-IR spectrometry -Lab-on-a-chip
8	**Salinity**		-Plant toxicity / affects plant growth		-EM application could be improved, e.g. integrated with other mobile sensors and multiple EM sensors -Infrared spectrometry, LIBS/XRF -Connecting hydrology measurements (to bring in time dimension)
9	**Sodicity**		-Plant toxicity -Affects slaking and dispersion	-Issues need to be addressed via dispersion and slaking development (see above)	-LIBS

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4 BIOLOGICAL INDICATORS (BIOINDICATORS) OF SOIL FUNCTION

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4.1 Definition and circumscription of bioindicators of high performance soils

4.1.1 Definitions

In this review and from the broader Soil CRC perspective, high performance soils have the 'capacity to function within ecosystem and land-use boundaries to sustain biological productivity, maintain environmental quality and promote plant and animal (and human) health (Doran and Parkin 1994, 1996). In a wide ranging critical review of soil quality, Bünemann and colleagues (2018) support this definition as it captures the multifunctionality of soils within boundaries set by extrinsic factors such as parent material, climate, topography and hydrology. The use of indicators to assess soils must incorporate baseline or reference values to enable identification of management effects within extrinsic boundaries. The importance of context is therefore critical in assessing and recommending bioindicators (refer to Section 2).

4.1.2 Bioindicators have pluri-facetted utility

1. **Bioindicators can be early indicators of change or disruption**. All soil chemical or physical or biological changes will result in a change of behaviour of a fraction of the soil biota that is specifically sensitive to the specific change occurring. Therefore, the behaviour of those sensitive soil organisms can be used as a timely, sensitive indicator of changes in soil properties. Changes in soil properties, regardless of their magnitude, will trigger a change in the behaviour of these sensitive soil organisms. However, when those changes are of small magnitude, they cannot be quantifiable by measuring chemical and physical soil properties – because the difference between previous and current value is below the detection limit of the method deployed to quantify currently accepted chemical and physical indicators. Yet small changes can have large impacts on many valued properties of a farming system such as plant production, nutrient storage and release, agroecosystem resilience and many others.
2. **Most bioindicators are dynamic and measure nutrient flows.** Most chemical (and some physical) indicators of soil properties quantify the stock/pool size of particular elements such as C, P, and N. At a system scale, the size of flows/fluxes of resources is mostly ignored. To maximise farm efficiency and environmental footprint, the amount of carbon actively circulating between soil, water, plant biomass, animal biomass and the atmosphere might be a more accurate reflection of the farm growth potential and of its resource use efficiency. System-scale assessment of ecosystems rarely include both stocks and flows, because flows are not easy to measure in a manner that is reproducible in time and space. When both stocks and flows are assessed, it is commonly observed that the size of the flows by far exceeds the size of the stocks (see, for example, all recent literature on ecosystems responses to elevated CO_2). Any changes of any magnitude in flow size and direction will cause a change in the behaviour of specific soil organisms. Monitoring their

activity or population size / structure can be used to quantify changes in flow size and direction.

3. **Soil organisms actively drive many soil processes.** For example, a large proportion of soil carbon, nitrogen and phosphorus has been processed and biochemically transformed by specific soil organisms. The popularity of genetic techniques stems from the potential it offers to map activity of multiple and simultaneous processes that occur by virtue of switching on and off gene pathways.

4.1.3 Application of soil bioindicators to outcomes

Soil bioindicators can be applied to achieve several specific outcomes; 1) land-holders need productive land to farm, 2) financial, insurance and food processing sectors require evidence that soils are being maintained in good condition (Brand integrity/social licence), 3) state and federal auditors need to report on the state of the environment and 4) regulators & policy sectors need to protect society from risks.

This review will consider bioindicators that can be applied to soils under existing and novel farming systems in Australian and NZ agriculture to achieve multiple outcomes including improved nutrient and water use efficiency. The information generated will also be applicable to other sectors listed above.

Although land-holders need productive land to farm they have expressed a range of needs other than on-farm profitability (e.g. long-term resilience, low environmental footprint, adaptability to changing environmental and economic climate, resistance to diseases). Adoption of new tests for use on ground is driven by a multitude of motivations (Lobry de Brun et al 2017). Despite the development of many industry and region-appropriate soil quality assessment tools (Herrick et al., 2002; Tugel et al., 2005), their adoption by land-holders so far has been fragmented and generally limited (Herrick, 2000) and because uptake is historically low, one can speculate that land-holders remain unmotivated as needs are not being met.

Whilst program 1 of the Soil CRC focusses on the mechanisms and processes underpinning investment in high performance soils, there is as-yet little cross-program integration allowing progress about the social, psychological and economical drivers of use (or lack of use) of indicators of soils performance. This, in our opinion, is key to developing or validating indicators and sensors that are relevant to end-user groups. Biological indicators are an excellent way of illustrating this point: in New Zealand, a solid assessment of soil biological indicators (other than standard earthworm counts, see Table 3) can be commercially undertaken by only one NZ-based soil testing laboratory and by 2-3 Australian Laboratories. Most of the NZ clients requiring comprehensive biological soil testing are organic - certified farmers (G Grelet, pers.comm.). The type of farmers, their relationship to knowledge (evidence-based using quantifiable data versus qualitative observations, or belief-based versus fact-based knowledge) and their personal values determine why, what and how they farm. This, in turn, determines how much they rely on quantifiable indicators of soil performance versus on other means of assessing the performance of their farms (e.g. qualitative observation). If as a community of researchers, we fail to embrace the diversity of our end users, and we fail to embrace the various ways in which farmers appraise the performance of their soils, we are failing to address the needs of many of our NZ and Australian end-users. Landcare Research recently organised a collaborative 2-days workshop (May 20018) including over 64 attendees, ¼ being researchers, ¾ being farmers, consultants and a small number of government representatives. From this workshop, it was clear that all on-farm decisions, the attitude of farmers towards scientific knowledge, their willingness to trial new technology, their reliance on sensors and soil testing, and their interest in soil biology and soil biological indicators was largely driven by their own personal values, and what personal outcomes they sought from farming (G Grelet, pers. Comm.). The diversity of end-user values must be considered in the design and recommendation of appropriate soil bioindicators.

4.2 A collation of current & emerging biological tests of soil health

This review adopts soil health and soil quality terminology interchangeably and sparingly. It focusses on the capability of soils to perform functions that enhance plant performance, cataloguing soil biological tests that are static, describing largely taxonomic features of communities and dynamic, and/or describing multiple functions of these communities.

The Soil Health Institute uses a tiered approach to categorise soil tests according to whether they are well tested and broadly in-use (Tier-1), are available for use but require further research with respect to applicability, reliability and/or regional variation (Tier-2) or are emerging and require further research (Tier-3). The soil health institute have officially endorsed 19 Tier-1 Indicators in 2016 (http://soilhealthinstitute.org/tier-1-indicators-soil-health). This endorsement was driven by scientists from public and private sectors, farmers, field conservationists, soil test laboratories and many others, to promote a set of common soil health measurements that scientists and farmers can compare and track over time. Except for one, all Tier-1 indicators are chemical and/or physical indicators and have been discussed in the previous sections of this review.

According to the Soil Health Institute, “many Tier-1 measures have proven effective to producers who have achieved high yields for decades such that many of the soil test laboratories and field conservationists are already using these measurements. Tier-2 and Tier-3 tests are largely biological tests. Elevation of these tests to Tier-1 usefulness may involve understanding regional differences in interpretation, establishing thresholds, and developing management recommendations to improve soil functioning; in particular, biological measurements require additional research to interpret their contribution in different climates, soils, and production systems specifically related to multiple associated with suppression of disease, improvement of water quality, building drought resilience, increasing carbon sequestration, and reducing greenhouse gas emissions.

Tier 1, Tier 2 and Tier 3 tests apply to soil samples collected and assessed on farm by land-holders and to soil samples that are collected by landholders and sent to a laboratory for testing.

4.2.1 Tier-1 tests for soil biology

The only existing Tier 1 test available widely in Australia is a pathogen detection test or PREDICTA B [www.sardi.sa.gov.au/diagnostic services/pir] which was developed 30 years ago and is now readily available through SARDI.

PREDICTA B (B = broadacre) is an identity kit for soil borne diseases of grain production systems. It is a DNA-based soil testing service that assists Australian grain producers to identify soil-borne pathogens that pose a potential significant risk to crops prior to seeding and to implement strategies to mitigate the risk of yield loss.

PREDICTA B currently assesses the following pathogens:

- Cereal cyst nematode (CNN)
- Take-all (*Gaeumannomyces graminis var tritici (Ggt*) & *G. graminis var avenae (Gga)*
- Rhizoctonia barepatch (*Rhizoctonia solani AG8*)

- Crown rot (*Fusarium pseudograminearum* & *F. culmorum*)
- Root lesion nematode (*Pratylenchus neglectus*, *P. thornei, P. penetrans & P. teres*)
- Stem nematode (*Ditylenchus dipsaci*)
- Blackspot of peas (*Mycosphaerella pinodes, Phoma medicaginis var pinodella* & *Phoma koolunga*)
- Pythium (*Pythium* spp.)

At the time of writing (June 2018), PREDICTA®B has added new tests for ascochyta blight and phytophthora root rot of chickpeas, yellow leaf spot and white grain disorder of wheat, fusarium stalk rot of sorghum, charcoal rot of summer crops and arbuscular mycorrhizal fungi (AMF).

4.2.2 Tier 2 tests:

These are tests of soil biology that have been used repeatedly for diagnostic or research purposes, and for which some information on spatial and temporal variation exist. Some of these indicators are currently characterised well enough that they could be widely adopted but haven't yet been adopted because they are either unknown or because they do not meet farmers/growers or other end-users needs.

Tier 2 tests represent the most likely group that will be further developed through alignment with other indicators of soil health and with sensor technology.

Table 1. Tier 2 indicator tests for soil biology and the frequency and spatial scale recommended for their use

(Possible) Tier 2 'Indicators' of:	Measure	Method	Reference	Frequency	Spatial scale
energy flow	reduction-oxidation potential (Eh) - ATP	voltameter with platinum electrodes in conjunction with a reference electrode	[1]	monthly	paddock
bioavailable C	permanganate oxidisable C	Digestion followed by colorimetric measurement	[2]	monthly	paddock
	particulate organic matter (POM)	Wet sieving with 200 μm filer	[3]	yearly	paddock
bioavailable N	soil protein vs Illinois soil N Test/Solvita™ labile amino N test vs CO_2 flush	Incubate soil with NaOH for amino N test or water for CO_2 burst, then colorimetric measurement	proprietary	weekly	paddock
	Potentially mineralisable Nitrogen (PMN)	Anaerobic or aerobic method. Soil incubated then $NH4^+$-N measured	[4], [5]	monthly	paddock
	Anaerobic mineralisable Nitrogen (AMN)	Anaerobic incubation then $NH4^+$-N measured	[6]	monthly	sub-paddock
	AMN: total N ratio (commercialised as proportion of'active fraction' organic matter)		https://www.hill-laboratories.com		
earthworm community	weight (g), abundance (m^{-2}) & no species (m^{-2}), no. adults, sub-adults and juveniles to 10cm depth; feeding/burrowing behaviour	Field transect lines; liquid extraction with potassium permanganate, formalin, or mustard water; electrical extraction; hand sorting; soil face studies	[7], [8], [9]	yearly	sub-paddock
ant community	abundance (m^{-2}), no species (m^{-2})	transect lines with pitfall traps or leaf litter samples with Winkler extracter	[10]	yearly	sub-paddock
nematode community	population density; maturity index	flotation/centrifugation, elutriation, sedimentation, then count and examine via microscope; size and shape by sieving then microscope	[11]	monthly	sub-paddock
	feeding groups & biodiversity	Morphological examination of mouthparts by microscope	[12]	monthly	sub-paddock
	Community diversity, genus and species identification	TRFLP, high throughput sequencing with metabarcodes	[13], [12]	Yearly	paddock
protozoa (amoebae,	Abundance	Indirect method, counts of species richness under microscope.	[14]	monthly	sub-paddock

flagellates & ciliates)		Indirect method by enrichment methods then most probable number on petri dish using microscope			
mycorrhizal colonisation of roots	arbuscular mycorrhizal fungal colonisation of roots	clearing and staining of root, microscopic examination	[15]	yearly	paddock
	ectomycorrhizal colonisation	number of root tips colonised, morphotypes recorded	[16]	yearly	landscape
	ericoid mycorrhizal colonisation	clearing and staining of root, microscopic examination	[17]	yearly	landscape
rhizobial symbioses	nodule counts & distribution on root; plant baiting for saprophytic or indigenous rhizobia	staining of root tissue and confocal microscopy root washing, nodule removal and counting most probable number counts of nodules from soil solutions	[18], [19]	yearly	paddock
soil associated pathogens	disease diagnostic services for soilborne crop pathogens	isolation of lesions or cysts on plant, culture and microscopic identification	State Govt	yearly	paddock
	Pathogen bioassays in pot trials	Soil with plant pathogen inoculum planted with crop and disease rated	[20]	monthly	glasshouse
	Predicta B for soil-borne diseases of wheat; (new tests under development)	quantitative PCR of DNA extracted from soil and plant stubble	[21]	yearly	paddock
microbial community & biomass	direct "count" systems (http://www.soilfoodweb.co.nz/index.php/services/)	plate culture, colony counts using microscope	[22]	yearly	paddock
	biomass C, N, P (www.soilquality.org.au)	chloroform-fumigation of soil	[23], [24]	monthly	plot
	grid intercept method + dilution to convert to biomass of bacteria &fungi (http://www.soilfoodweb.co.nz/index.php/services/)				
	biovolumes ratio (total/active/active fungal/bacterial (TA/AFB))	soil suspensions are stained, filtered and examined on agar plates for fungi and on slide for bacteria	[25]	yearly	paddock

microbial C use patterns for community level physiological profiles	BIOLOG™; relies on growth on artificial substrate	inoculate soil suspension or bacteria onto Biolog plate (95 different carbon substrates) assessed by plate reader	[26]	yearly	paddock
	substrate-induced CO_2 respiration (SIR)	soil incubated with glucose and CO2 evolved measured	[27]	monthly	plot
	microresp™ www.microresp.com/BriefProtocol.html; like SIR but isotopic labels to trace CO_2	soil suspension added to microresp plates with different substrates, colorimetric assay measured on plate reader	[28]	monthly	plot
microbial enzyme activity (nutrient release processes)	individual & multiple enzymes (on array) including dehydrogenase, cellulase, chitinase, amylase, phosphatase & phytases	soil is extracted in a buffer, enzyme reagent added, plate incubated then enzyme activity of substrate quantified using a fluorescence reader	[29]	monthly	plot
integrated metrics of biological nutrient dynamics	carbon use efficiency (CUE) (microbial growth/C uptake)	analysis based on enzyme and microbial biomass data	[30]	monthly	plot
	fungal-to-bacterial ratio (based on PLFA/NLFA profiling or direct counts)	PLFA, soil extracted and subject to gas chromatography plant count ratio	[31]	monthly	plot
	microbial quotient	biomass C, N, P/total organic pools	[32]	yearly	landscape
	heterotrophic evenness (measure of diversity)	catabolic response profile technique where CO2 efflux is measured during a 4-h incubation of samples amended with 25 different carbon substrates.	[33]	yearly	landscape
	Shannon diversity (based on range of community profiling techniques; PFLA, T-RFLP, BIOLOG)	equation applied to data	[34] [35]	monthly	paddock
	ecophysiological index (EP) (r:k bacteria or copiotrophs :oligotrophs)	soil suspension plated, bacteria isolated, colonies counted over time to determine copiotrophs and oligotrophs. equation applied to data		yearly	paddock

4.2.3 Tier 3 tests for soil biology

These tests are emerging and as such are currently mostly used mainly for research purposes. These tests are also heavily characterised by the extraction of genetic material (DNA and RNA) directly from soil followed by the sequencing of this material to identify a range of biological traits. These approaches are relatively more complex, detailed and representative of the soil biological community than tier 2 tests but currently provide a challenge in terms of representing practical indicators of soil health.

Table 2. Tier 3 indicator tests for soil biology

Tier 3 'Indicators' of:	Measure	Method (specific method articulated)	Reference (in number format)
whole biotic community structure, richness & diversity	a) gene abundance (q-PCR) of DNA using taxonomic markers 16S rRNA (bacteria, archaea), ITS (fungi), 18S rRNA (eukaryotes) for quantification of organisms	DNA extracted from soil, quantitative PCR for each gene	[36]
	b) gene transcript abundance/gene expression (RT-qPCR) of RNA transcripts 16S rRNA (bacteria, archaea), ITS (fungi), 18S rRNA (eukaryotes) for quantification of active organisms	RNA extracted from soil, quantitative PCR for each gene	[37]
	c) community composition (richness & diversity) from environmental DNA (eDNA) (16S rRNA, ITS and 18S rRNA gene sequences) *who's there?*	DNA extracted, amplified by PCR for each gene, sequenced, and taxonomy identified by BLAST/database annotation; richness and diversity calculated	[38], [39]
	d) community composition (richness & diversity) from eRNA (16S rRNA, ITS & 18S rRNA gene transcript sequences) *who's active?*	RNA extracted, amplified by PCR for each gene, sequenced, and taxonomy identified by BLAST/database annotation; richness and diversity calculated	[54]
	e) direct sequencing of community DNA (whole genome shotgun sequencing; WGS)	DNA extracted, sequenced, and taxonomy identified by BLAST/database annotation	[39]
	Microarray for taxonomic studies of bacteria and archaea, Phylochip 16S rRNA gene array ('lab on a chip')	DNA extracted from soil, hybridised to gene array	[40], [41]
whole biotic community function	a) Microarrays of specific functional gene sequences ('lab on a chip'); examples:		
	particulate methane monooxygenase (pmoA) gene in methanotrophs	DNA extracted from soil, hybridised to gene array	[42]
	Geochip® (nitrogen, carbon, sulfur and phosphorus cycling, metal reduction and resistance, and organic contaminant degradation)	DNA extracted from soil, hybridised to gene array	[43]
	C & N cycle genes (Chapman et al 2012)	DNA extracted from soil, hybridised to gene array	[44]

	b) Stable isotope probing (SIP) (PLFA, DNA, RNA) - Linking substrate utilisation to specific members of soil biotic communities	DNA/RNA and PLFA extracted from soils after labelling with C substrates highly enriched with 13C or Deuterium	[55, 56]
	c) quantitative transcript abundance of specific functional genes using qPCR (eg N, P, S, C cycle gene suites); variable relationships with process rate data	DNA extracted from soil, quantitative PCR for each gene	
	d) direct sequencing of soil DNA (shotgun metagenomes): provides information about the potential metabolic pathways present (metabolic efficiency) or underrepresented in the soil (metabolic deficiency) -mostly biased towards prokaryotes and unless very deep sequencing, may capture only functional genes in high frequency	DNA extracted from soil, library prepared and sequenced, functional genes identified by BLAST/database annotation	[45]
	e) Direct sequencing of total RNA or mRNA (metatranscriptomics, mostly using RNAseq approaches) : provides information about biotic activity – again largely biased towards prokaryotes	RNA extracted from soil (maybe rRNA depleted to increase mRNA), reverse transcribed to cDNA, library prepared and sequenced, functional genes identified by BLAST/database annotation	[46]
microbial C processes	surrogate, predictive measures for soil biology based on correlation with other soil properties eg MIR/NIR	spectral absorption is compared to soil chemical data and microbial biomass, enzymes, respiration	[47]
specific biotic groups (e.g. pathogens, symbionts, environmental tolerance species, disease suppressors; nutrient suppliers & storers)	a) PCR (gene, DNA) and RT-qPCR (transcript, RNA) with species-specific primers for many functional genes (N,C,P, cycles, antibiotics etc)	DNA or RNA extracted from soil, specific gene primers used for quantitative PCR	[48], [49]
	b) DNA sequence-guided detection of indicator taxa	DNA or RNA extracted from soil, specific gene primers used for detection of specific taxa	NA
	c) probe-annealing methods (micro-arrays and nanostring for fluorescence detection)	DNA and RNA based assessment of multiple features of microbial communities selected on the basis of specific primers	
detection of microbial by-products or metabolites	a) detection & quantification of fungal-specific compounds (“glomalin”, Ergosterol)	Detection of specific microbial products associated with soil structural property	[50]
	b) NMR, HP-LC, LC-MS to evaluate agricultural metabolomes	Soil or gas volatiles extracted and subject to metabolite profiling, structural identification, database matching	[51], [52], [53]

Density & integrity of the soil food web	eDNA metagenomic approaches combined with microscopy when possible	eDNA extracted – 16S/18S/ITS amplicon libraries sequenced – network analyses	
whole microbial community resilience	DNA approaches for assessing "Stress-on-Stress" Responses (eg metals & additional stressors, chemical pollutants)	Community changes are assessed before and after experimentally inducing stress	

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4.3 A collation of existing continental & regional soil biological monitoring programs

This review defines a monitoring program as one that follows standardised protocols and enables sites to be revisited (see Figure 1). Figure 1 outlines a scheme for an Australian based soil biodiversity monitoring programme that is being adopted widely. The success of this program is characterised by published protocols and accessibility to a sequence database which includes a world class collection of metadata (including most major physico-chemical variables) and controlled vocabulary to describe landscape features.

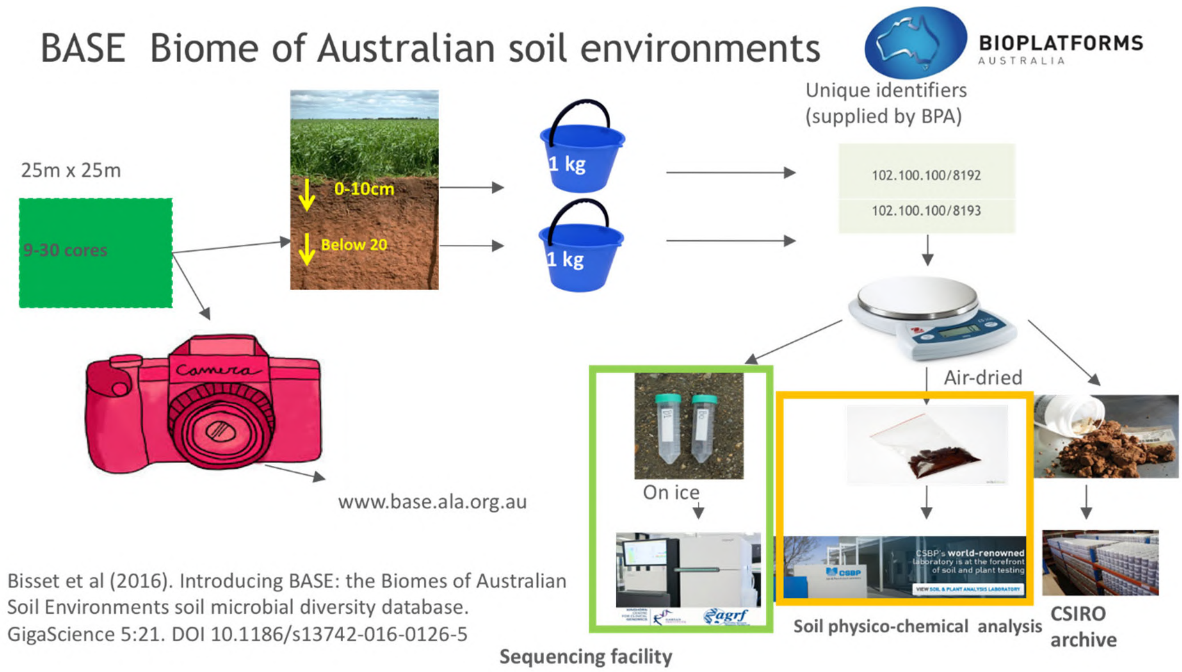

Figure 1. Schematic representation of a standardised National protocol adopted for the Australian soil biodiversity monitoring program (Biomes of Australian Soil Environments; BASE).

Table 3 and the following sections also summarises the existing continental and regional programs (see Table 3) and highlights that there are numerous soil biological programs underway worldwide that utilise emerging bioindicators. Three common features of these numerous programs are; 1) lack of commonality of bioindicators and protocols adopted, 2) lack of temporal datasets although most are set up to be temporal and 3) the large number of programmes currently being established that lack regional context.

Table 3. A collation of global monitoring programmes that headline soil bioindicators

Soil Monitoring Programme &location	Is it climate (C), soil type (S), land-use (LU) specific? Yes (list)/No	Is it temporal? Y/N Sampling frequency?	What soil measures does it use (refs)	What metadata does it use	Sensors used (for what)	Database & accessibility
National						
Biome of Australia Soil Environments (BASE) project - Australia http://www.bioplatforms.com/soil-biodiversity/ *See figure 5.	Yes, C, S, LU	No One sampling event has occurred and no sites have been revisited	Bioplatforms Australia Framework Data Initiative is employing amplicon (bacterial 16S, archaeal 16S, fungal ITS and bacterial 18S) & shotgun metagenomics sequencing) Bisset et al (2016)	Historical, physical and chemical contextual information (including photos): site description climate soil classification soil analysis extreme/unusual properties See: http://www.bioplatforms.com/sample-collection-procedure/ Bisset et al (2016)	Datasets are publicly available & can be linked with other measurements and data such as overland surveys, meteorological data and geological information http://base.ala.org.au/datacheck/	Open access. Data are provided in both raw sequence (FASTQ) and analysed OTU table formats as csv and xlsx https://data.bioplatforms.com/organization/bpa-base https://data.bioplatforms.com/organization/pages/bpa-base/information

MicroBlitz Western Australia Citizen Science collection	No Gridded sampling across 250 million ha WA, 35 cm x 10cm deep.	No One sampling event has occurred Does phase 2 revisit sites?	(Griffiths et al. 2011)	From app or desktop data entry by collector: Location/date/time Photo Additional comments		"back end system for the storage of the data about where the soil samples were taken" https://www.microblitz.com.au/our-research/ https://www.gaiaresources.com.au/project/microblitz/
Europe						
EcoFINDERS (FP7) project Full EcoFinders program overview https://cordis.europa.eu/result/rcn/168040_en.html Webpage and publications: http://projects.au.dk/ecofinders/	Y; C,S,LU Wide range of soils across Europe of varying climate, land use and management. Sites selected had a consistent agricultural management history over several years; were characteristic of recognised European climatic zones; consisted of at least three, independent, replicated plots of two contrasting treatments which varied in	Y; Two seasonal collections per site across 2012 - 2013	The EcoFINDERS (FP7) project was set-up in 2011 to identify soil threats, harmonize methods for measuring biodiversity and to generate European datasets of soil biodiversity and ecosystem function. There is a broad list of soil measures (lead partner Teagasc) . See list of indicators at: Table 1. Biological indicators applied in Long-Term Observatories and Transect sites across Europe. http://projects.au.dk/ecofinders/ltos/ and details at Griffiths et al 2016a	Site location, climate type, date sampled, GPS cords, physico-chem, landuse, landuse intensity Organic C, pH, texture, cation exchange capacity (CEC) and base saturation. (Other relevant data for broader program objectives)		All data arising from the project have been deposited in a bespoke EcoFINDERS database containing biodiversity and soil data from each geo-referenced an unique numbered sample for long term data storage (reported in D1.2). There does not appear to be data reposited for public access at http://eusoils.jrc.ec.europa.eu/

	intensity of management					
EU FP7 EcoFINDERs Griffiths 2016b This is an extension of Griffiths 2011 (UK study)	Y; C,S,LU Sampled across a range of sites spanning a gradient of soil properties (principally pH, organic matter and texture), climatic zones, and land uses (grassland, arable, forest) were targeted for sampling following examination of EU wide datasets. Arctic to Southern Mediterranean climes. 76 samples across 11 countries.		Bacterial communities were examined using TRFLP as described by Griffiths et al. (2011) Relationships between soil pH and bacterial community structure (NMDS, including diversity) regressions tested against Griffiths UK TRFLP (2011) then predictions across larger spatial scales via interpolation using LUCAS EU wide soil datasets Strength of model using worldwide modelled pH data at the global scale was also tested (SoilGrids: soilgrids.org, Hengl et al., 2014)	Additional measurements made on collected soils: volumetric moisture content, pH (in water), texture, and total/organic carbon (C) and nitrogen (N) contents See supplementary material for site locations, S1 (Griffiths 2016). (includes Maps and graphs – raw data, layers etc not provided)	Not directly (possibly for pH modelled data)	Soil data available but microbial/modelled data/layers not apparent. LUCAS soil datasets were downloaded subject to agreements from the JRC European Soil Portal (http://eusoils.jrc.ec.europa.eu/) Modelled global pH at SoilGrids: soilgrids.org, Hengl et al., 2014
CreBeo Soil Biodiversity Project in Ireland (Schmidt, last accessed 2018-02-22)	Y; C,S,LU 61 sites including the inclusion of major vegetation/land-use classes and	Y; 12 of the 61 sites sampled in 2006 were re-sampled in 2007 to examine	Diversity of microorganisms (bacteria and fungi), root-associated fungi (mycorrhizas), nematodes (microscopic worms),	Location and baseline soil property data from the National Soils Database (Kiely et al., 2009).		All earthworm records have been entered into the Earthworms of Ireland database by A.M. Keith (University College Dublin and Centre for Ecology & Hydrology, Lancaster), which contains published and unpublished earthworm species

	soil types in proportion to their known frequency in Ireland and geographical spread. 12 of those sites sampled in 2006 were re-sampled in 2007 to examine temporal variability	temporal variability	earthworms, micro-arthropods (mites) and ants Fungi - Bait plants for AMF, ERM and ECM. From soils : Molecular biology techniques were used to assess AMF, ERM and ECM diversity (internal transcribed spacers-ITSs). Bacteria: intergenic spacer (IGS) regions Nematodes, earthworm, microathropods, soil-dwelling ants: hand-sorting/count to species level and/or functional groups			records, including this survey. This database has been submitted to the National Biodiversity Data Centre, Waterford, and is available via the online biodiversity database and mapping tool (see http://maps.biodiversityireland.ie).
Global Soil Biodiversity Initiative: Collection of working groups worldwide collating, interpreting and disseminating knowledge on soil biodiversity, links to ecosytem services and sustainable management	Global: Collation of resources (Global Soil Biodiversity Atlas) including x2 modelled global maps.		Global soil biodiversity maps: 1)Based on modelled soil carbon and distribution maps of microfauna to give a soil biodiversity index 2) the Soil Biodiversity threats showing the potential	Metadata including modelled soil carbon, microfauna and threats found at: https://esdac.jrc.ec.europa.eu/content/global-soil-biodiversity-maps-0 (European Soil Data Centre (ESDAC),	Potentially from models that these models are based on (Indirect)	Maps downloadable a GIS files (in .lpk format): https://esdac.jrc.ec.europa.eu/content/global-soil-biodiversity-maps-0

			rather than the actual level of threat to soil organisms based on mapped threats and corresponding proxies Orgiazzi et al (2016). There are a number of other microbial related modelled maps available	esdac.jrc.ec.europa.eu, European Commission, Joint Research Centre)		
A global atlas of the dominant bacteria found in soil.						Delgado-Baquerizo et al.. Science (2018) 359, 6373 pp 320-325
African Soil Microbiology Project	Seven sub-Saharan African countries to undertake a broad-scale survey of soil microbiology across the entire African continent,		Latest next-generation DNA sequencing and computational technologies. Contact Prof Don Cowan			Locality map of data collected http://www.teatime4science.org/data/map/ Individual regional reports http://www.teatime4science.org/publications/#science
The teabag index http://www.teatime4science.org/	2014-2016, collected data from about 2000 locations, with a rather equal spread across different vegetation types around the globe		To construct a global soil map of decomposition rates using citizen science - burying tea bags Keuskamp et al. (2013)	Metadata including principal invesigator, affiliate, research purpose, contact, country, reulting publication APA. Other data collected for model inlcudes common dat, location		

				codes and sample data, based on reasoning in Keuskamp et al 2013		
Gluseen http://www.gluseen.org/	Carried out in several habitat types associated with urban and urbanizing landscapes on a global scale 5 cities, 4 biomes, across range of temperature/me oisture regimes and soil order/parent material		Counting and identifying earthworms Decomposition - teabag method (Keuskamp et al 2013) Pouyat Introducing GLUSEEN: a new open access and experimental network in urban soil ecology. Journal of Urban Ecology, Volume 3, Issue 1, 1 January 2017, jux002,https://doi.org/10.1093/jue/jux002	Teabag metadata as in Kuscamp Condition: Remnant, turf, ruderal and remnant. Need to log on ScriServer to see		The collaborative website is using the Elgg framework (www.elgg.org) data infrastructure, based on the SciServer architecture (http://www.sciserver.org/ data visualisation interface interface developed using d3.js (http://www.d3js.org).
Soil organic matter functions	Three long-term trials across Australia (NSW, Qld and WA).		The project assessed the long-term impacts of different farming systems (tillage intensity, stubble and fertiliser management, cropping sequences) on SOM and soil physical, chemical and biological functions/indicators across three climatic	Site locations, soil type, a range of basic characteristics, land use and management history, a range of physical, chemical and biological properties	MIR predictions of soil physical, chemical and biological indicators	- All data generated from the project have either been published in scientific journals and technical articles. - some manuscripts are under review e.g. MIR predictions of soil biological properties; Impact of integrated crop residue-nutrient management on the relationships between soil organic carbon priming and soil biological measures (copiotrophs, oligotrophs, enzyme activity/stoichiometry)

			regions in Australia. Soil biological functions/indicators assessed were: microbial community structure, abundance and diversity (QPCR) Enzyme activities (C, N, P, S) Micro-Resp (profiling microbial respiration on contrasting substrates) Labile and stable SOM pools Plant available N, P and S PMC			- In preparation (by WSU colleague - linking ecosystem multifunctionality to soil biotic and abiotic properties under different crop/soil management systems) - Data stored in the NSW DPI system and are accessible on request.
Canada National Soil Quality Monitoring Program http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/sag3364 http://agrienvarchive.ca/nscp/sqep.html	Yes. Twenty-three benchmark sites across Canada. Sites selected based on 7 criteria to represent typical farm-production systems on dominant landscapes within major agro-ecological regions.		Total carbon (C), inorganic C ($CaCO_3$ equivalent), total nitrogen (N), exchangeable cations and cation exchange capacity, pH ($CaCl_2$), available P and K, cesium-137 content, electrical conductivity and soluble salts, particle size distribution, aggregate size distribution, clay mineralogy, surface area, and total elements. biopore counts, earthworm counts	Soil map at a scale of 1:2000 with surface-texture phases; topographic data; climate monitoring with automated weather stations installed in eight of the 23 benchmark sites; Site history, including land-acquisition date; first cultivation date; early years' land management; major changes in agronomic practices; crop rotation; tillage system; crop yields and quality; commercial	Weather stations	No data available to public. Established in 1989 to 1992 with 10-12 year sampling time frame yet program finished 1997.

			done *in situ* and crop yields. (Wang et al 1997)	fertilizers, organic fertiUzers and soil conditioners; chemical pesticides/herbicides; and soil degradation problems		
NZ https://www.landcareresearch.co.nz/science/portfolios/enhancing-biodiversity/next-generation-biodiversity-assessment	S LU Not C	No			None	Data not yet open access. Open access to data is scheduled once all papers have been published. Dedicated web server allowing querying of datasets (metadata and DNA data) will be set up within NZ's NSC-Bioheritage challenge
RMQS Réseau de Mesures de la Qualité des Sols = French Soil Quality Monitoring Network, 2176 soils covering all the French territory with a systematic grid of sampling	Yes to all: climate, soil properties, landuse recorded		Particle- size distribution, bulk density, C, N, pH, trace elements, etc. and a complete description of the soil profile. Bacterial communities (structure, composition, diversity)	information about past activities, the environment, etc. + other soil quality evaluations and monitoring, e.g. persistent organic pollutants (pesticides, dioxins, organochlorides, PAH, etc.).		DONE- SOL database for soil properties and metadata. See Jolivet C, Arrouays D, Boulonne L, Ratie´ C, Saby NPA. Le Re´seau de Mesures de la Qualite´ des Sols de France (RMQS). Etude Gest des Sols,. 2006; 13: 149–164. Several publications: Ranjard, L., Dequiedt, S., Jolivet, C., Saby. N.P.A., Thioulouse, J., Harmand, J., Loisel, P., Rapaport, A., Fall, S., Simonet, P., Joffre, R., Chemidlin N, Prévost Bouré P, N., Maron, P.A., Mougel, C., P. Martin, M.P., Toutain, B., Arrouays, D. and Lemanceau, P., 2010. Biogeography of soil microbial communities: A review and a description of the ongoing French national initiative. Agronomy for Sustainable Development 30: 359–365. 10.1051/agro/2009033.

						Terrat S, Horrigue W, Dequietd S, Saby NPA, Lelièvre M, Nowak V, et al. (2017) Mapping and predictive variations of soil bacterial richness across France. PLoS ONE 12(10): e0186766. https://doi.org/10.1371/journal.pone.0186766
National Soils Inventory for Scotland (NSIS1+ NSIS2)	Climate, Landuse, soil type recorded	2 sampling events at 25 years interval (1978 to 1988 with 10km grid And 2007-2009 with 20km grid interval).	All commonly used chemical and physical measurements were taken. For NSIS2, fungal and bacterial communities were also assessed using eDNA-based methods. Description of sites, methodologies, measurements can be found here: http://www.hutton.ac.uk/about/facilities/national-soils-archive/resampling-soils-inventory	Vegetation composition data	no	Chemical and physical data available via web interface. Biological data published and available by request to authors. Many publications, including: Powell JR, Karunaratne S, Campbell CD, Yao H, Robinson L, Singh BK. Deterministic processes vary during community assembly for ecologically dissimilar taxa. Nat Commun. Nature Publishing Group; 2015; 6: 8444.

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CANADA: Fox, C.A., Topp, E., Mermut, A. and Simard, R., 2003. Soil biodiversity in Canadian agroecosystems. Canadian Journal of Soil Science 83 (Special Issue): 227–336.

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WORLDWIDE examples of Mapping/modelling of soil biology indicators

Attempts to map soil microbial properties at national and regional scales, using molecular methodologies applied to nationwide soil monitoring schemes (such as rasterised maps providing georeferenced data which can feed wider ecological, climatic or biogeochemical models)

Bru, D., Ramette, A., Saby, N.P.A., Dequiedt, S., Ranjard, L., Jolivet, C., Arrouays, D.,Philippot, L., 2011. Determinants of the distribution of nitrogen-cycling microbial communities at the landscape scale. ISME J. 5, 532–542.

Dequiedt, S., Thioulouse, J., Jolivet, C., Saby, N.P.A., Lelievre, M., Maron, P.-A., Martin, M.P., Prévost-Bouré, N.C., Toutain, B., Arrouays, D., Lemanceau, P., Ranjard, L.,2009. Biogeographical patterns of soil bacterial communities. Environ.Microbiol. Rep. 1, 251–255.

Dequiedt, S., Saby, N.P.A., Lelievre, M., Jolivet, C., Thioulouse, J., et al., 2011. Biogeographical patterns of soil molecular microbial biomass as influenced by soil characteristics and management. Glob. Ecol. Biogeogr. 20, 641–652.

Geostatistical approaches can be used to predict a variable of interest at unsampled locations based on known relationships between the dependent variable and other predictor variables (e.g. climate, soil type, land cover) - e.g. historical change in soil bacterial biodiversity due to land use at regional scales

Fierer, N., Ladau, J., Clemente, J.C., Leff, J.W., Owens, S.M., Pollard, K.S., Knight, R., Gilbert, J.A., McCulley, R.L., 2013. Reconstructing the microbial diversity and function of preagricultural tallgrass prairie soils in the United States. Science 342, 621–624.

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EcoFINDERS project (FP7-264465). Soil biodiversity and DNA barcodes: opportunities and challenges. Alberto Orgiazzi, Martha Bonnet Dunbar, Panos Panagos, Gerard Arjen de Groot. Soil Biology & Biochemistry 80 (2015) 244-250

UniEuk: Universal taxonomic framework and integrated reference gene databases for Eukaryotic biology, ecology, and evolution http://unieuk.org/

Fierer, N., Leff, J.W., Adams, B.J., Nielsen, U.N., Bates, S.T., Lauber, C.L., Owens, S., Gilbert, J.A., Wall, D.H., Caporaso, J.G., 2012. Cross-biome metagenomic analyses of soil microbial communities and their functional attributes. Proc. Natl. Acad. Sci. U. S. A. 109, 21390–21395.

Life under your feet: http://lifeunderyourfeet.org/en/default.asp

Census of soil invertebrates: http://www.annelida.net/earthworm/

4.4 Current on-farm soil health assessment approaches that incorporate soil biological tests

This following list of soil health assessment frameworks have been designed to meet the needs of growers associated with the grains, pasture, mixed farming, sugar and horticulture industries. It draws upon examples from alternative industries to illustrate how measures are selected based on constraints from those industry groups.

- Soil quality assessment: www.soilquality.org.au
- Soil Health and Watershed Function - DiDi Pershouse 2017 - www.soilcarboncoalition.org/learn
- https://www.dpi.nsw.gov.au/agriculture/soils/testing/health-card
- http://www.handfortheland.com/about-us
- Visual Soil assessment [https://www.landcareresearch.co.nz/__data/assets/pdf_file/0003/28677/VSA_Vol2_smaller.pdf]
- BRIX degrees using a refractometer (Caruso et al. Rootstock influences the fruit mineral, sugar and organic acid content of a very early ripening peach cultivar. Journal of Hort Science 71:931-937

4.5 The future of Tier 2 and Tier 3 bioindicators

The main considerations required to determine choice and integration of tier 2 and 3 bioindicators:

- knowledge of constraints to adoption (Programme 1)
- financial challenges (cost of assay): Characteristic soil chemistry measurements usually in the range of US$10-20 and typically includes: pH, available N, P, K, calcium, magnesium and organic matter. The assembly of biology-based sensor systems might be a challenge at this price point.
- engineering challenges
  - the design and construction of autonomous land-based drones for both sensor deployment and soil sampling
  - aerial mapping (and spraying) of target areas is now a commercial reality and is becoming more mainstream (see for example: https://www.dji.com/mg-1)
- scalability in the context of space and time
- scalability in the context of on farm diversity & diversification
- surrogacy (linkages to other indicators; see machine learning approaches)
- bioindicators data IS BIG
  - training and user interfaces: considerable thought must be given to the design and 'user approachability' of control and management software (and hardware)
  - upload, storage and access requirements

- o how to integrate field sensor and testing data into commercial Farm Management Information Systems (and if applicable, State and Federal records)
- o facilitation of data flow between aerial and land-based drones and control hubs/software.
- o design and implementation of wireless/radio sensor networks for remote monitoring, data transfer and systems control.
- o interoperability and modelling capability (https://www.soil-modeling.org/; http://anzsoil.org/anzsoilml/)
- o bioinformatics and machine learning capability
- o interpretability & information feedback: What do the results mean for my bottom line? If soil health is deemed less than ‘ideal’ what is the corrective treatment and what is the per unit area cost? Who do I talk to?
- o knowledge sharing (e.g. Africa Soil Health Consortium. http://africasoilhealth.cabi.org/; South American Mycorrhizal Research Network. https://southmycorrhizas.org/ Land PKS Data Portal https://portal.landpotential.org/; Map of life: https://mol.org/; http://www.cerdi.edu.au/ including Soil Health Knowledge Base)

- the potential of bioindicators to reflect behaviour of soils under particular constraints (drought, salinity & legacy contamination from agricultural amendments (biocides, heavy metals, organic contaminant)

4.6 Recommendations for the application of bioindicators of high performance soils

This living document highlights the importance of:

1. Identifying and calibrating (within boundaries of soil types, farming systems and ecoclimatic regions) bioindicators that are better suited at quantifying fluxes/flows of resources – i.e. fluxes of carbon, nitrogen, water, phosphorus. Biological indicators would be the best candidates for this, as they are both responsive and drivers.
2. Identifying and calibrating indicators of stress tolerance, stress resistance, plasticity and/or resilience. Again these might have to be calibrated within boundaries of soil types, farming systems and ecoclimatic regions.
3. Developing a qualitative and/or quantitative indicators framework that enables translation between “intuitive/observational” indicators and western-science-based indicators. “Intuitive/observational” indicators could include indigenous (Maori, Aboriginal) and / or commonly-used “intuitive/observational” indicators used by farmers applying biodynamic / biological / holistic principles. Some of these indicators have been cross-validated (e.g. Emmett-booth et al. 2016) but not many of those are biological indicators, despite wide usage by farmers (e.g. BRIX test).
4. Developing and adopting a systems-thinking approach to the use and choice of indicators. Farms are complex (as opposed to complicated) systems and one of the limitations of the current set of indicators might be their failure to embrace this complexity. There is a comprehensive existing body of knowledge, upon which we could draw, that have explored the systems behaviour of networks, and also of natural ecosystems. Such systems-thinking underpins the development of the concept of “ecological integrity”. Ecological integrity is defined as “the capacity of the ecosystem to support and maintain a balanced, integrated,

adaptive biological system having the full range of elements and processes expected in the natural habitat of a region" (Karr and Dudley 1981). Whilst this concept, and associated quantification framework - Index of Biotic Integrity (IBI) - has been widely used in the study and monitoring of natural ecosystems, it has received little interest in the study and monitoring of productive ecosystems. Yet a similar approach could be adapted to productive agroecosystems, by including economic- and human-driven processes and elements. Such an approach has already been discussed in the context of organic agriculture (Tybirk et al., 2004), and for debating adoption or exclusion of GMO (Heink et al., 2012).

5. Establishing relationships between researchers and end-users to ensure the development of practical and adoptable indicators of soil health. This must address the diversity of end-user values and aspirations.
6. Challenging the current soil science paradigms that have emerged from the green revolution and associated tertiary Agricultural science degrees. By capturing greater diversity of end-user values (see 5) and scientific disciplines (e.g. related to an ecosystems view of soils) a much needed paradigm shift will ensure that better and more tailored indicators of soil performance will emerge.

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5 SOIL INDICATOR WORKSHOP OUTCOMES

Authors:

Peter Dahlhaus (Federation University Australia)

Megan Wong (Federation University Australia)

5.1 Introduction

A significant part of this Scoping Study was a workshop of project participants and invited stakeholders, held over three days, at the AgriBio Research Centre at Bundoora, Melbourne. The intention of the workshop, held from Monday March 26th to Wednesday March 28th, 2018, was to ensure that the outputs of this scoping study would be a true consensus of the industry and research perspectives, as well as ensure that the research findings and recommendations would be pragmatic for industry and relevant to the future projects within the Soil CRC.

To save on cost duplication and excessive stakeholder engagement, it was logical to run workshops for this review on soil indicators and the concurrent review on soil sensors sequentially at the same venue (since indicators will inform sensors) because many of the same people would likely attend both workshops (especially the academic and government participants). The review on soil sensors is co-led by Marcus Hardie of the University of Tasmania and John Bennett of the University of Southern Queensland.

The workshop was designed to present the work to date by the teams involved in the Scoping Study literature reviews, and then using small group discussions, explore the gaps and potential needs for future Soil CRC research projects. Commencing after lunch on day one, the indicators review was completed by the afternoon of the second day, after which the sensor review took the remaining time. On day three, some time was given to presentations by the Soil CRC Chief Executive Officer and Program 2 Research Leader. The workshop closed mid-afternoon on day three to give participants time for travel. The workshop agenda and list of attendees is appended (Appendix 3).

5.2 Workshop outcomes

Thirty eight people attended the workshop, representing the following organisations:

- Agriculture Victoria Research
- Australian Organics Recycling Association
- Burdekin Productivity Services
- Federation of Victorian Traditional Owner Corporations
- Federation University Australia
- Griffith University
- Herbert Cane Productivity Services
- Holbrook Landcare Network
- Manaaki Whenua Landcare Research
- NSW Department of Primary Industries
- Soil CRC
- Southern Cross University
- Southern Farming Systems
- University of Newcastle
- University of Southern Queensland
- University of Tasmania
- WA No Tillage Farmers Association

The presentation of the literature review on indicators and the subsequent discussions led to four small group discussions: two groups exploring soil indicators for farmers, one group discussing soil indicators for public good, social licence and natural capital; and one group discussing soil indicators for indigenous land management.

The groups reported back using their collected thoughts as dot points written on 'butchers paper' to guide them. The consensus was recorded on a white board (Figure 1 below) and agreement sought from all on the recommended projects.

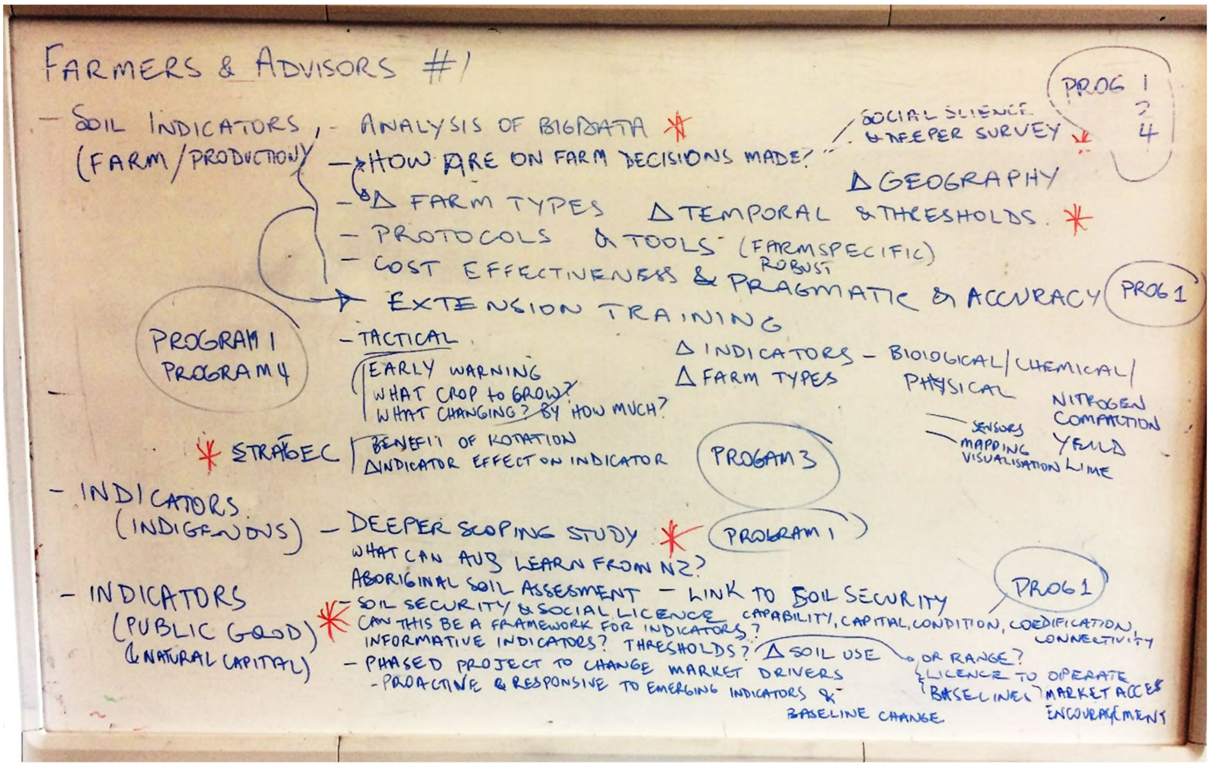

Figure 1. The record of the discussions on indicators

5.2.1 Proposed research projects

The top recommended projects by consensus of those present at the workshop are:

Project 1 (farming/production focus): Analysis of (big) data combined with a deeper social science survey (i.e. questionnaires, interviews, focus groups – perhaps in collaboration with Program 1 researchers) to determine which indicators are best suited to which farming systems over what timeframes in which geographies, and what are the thresholds for those indicators. The intention here was to fully explore what farmers are already using and why they have chosen those particular indicators. In other words, to learn from the experience of farmers.

Project 2 (farming/production focus): Research on the relationship or response that one indicator has on another, especially applied to the benefits of rotation in timeframes suited to strategic decision making. This is particularly important for the rise in prominence of biological indicators of soil performance and farm productivity, and the response that soil biology might have to chemical and physical conditions. As examples, soil biology is likely to be impacted by soil compaction, soil moisture, soil temperature, soil chemistry and so on.

Project 3 (indigenous land management focus): A scoping study to explore the potential to exchange learnings between the indigenous peoples of New Zealand and Australia on the development of methods, tools and frameworks for assessing soils and soil health. This may result in the selection of a suitable framework, or modification of a framework, for adaption and application by Indigenous Australians to manage and monitor soil health and support decision-making. Ultimately, an indigenous indicators framework of soil health developed by traditional land owner groups that sits alongside traditional science-based methods serves a two-fold purpose:

- Incorporating indigenous values and traditional science-based measures into a framework specifically to strengthen the management of indigenous lands, and
- By building two-way capacity, traditional science-based approaches can be strengthened by indigenous knowledge and worldviews.

Project 4 (public good/natural capital focus): Sustaining soil security, soil ecosystem services and the natural capital of our landscapes is of growing importance in many public and private sector services. These include catchment managers, municipal planners, environment protection agents, produce marketers, brand marketers, realtors, and bankers and financiers to name a few. A project to research and develop or adapt a framework for informative indicators and thresholds for soil security and social licence to develop various soil types for different soil uses is required. Ideally, the framework would consider baselines, capability, condition, capital, codification, connectivity and market encouragement.

Other recommended projects included:

Project 5 (farming/production focus): As a follow-on from project 1) above, once the indicators are recommended, what protocols and farm-specific and robust tools can be used to measure the indicators, that are also cost effective, pragmatic and accurate to the level required.

Project 6 (farming/production focus): For tactical decision making, including early warning, crop selection, and monitoring short-term soil change frequency and amplitude, research what indicators would be best suited to different farming systems in different locations. Emphasis may be given to sensors, mapping and visualisation of nitrogen, compaction, yield, lime (acidity) and moisture.

Project 7 (public good/natural capital focus): Research how best to proactively respond to emerging indicators, baseline changes, and changing market drivers.

6 CURRENT PERCEPTIONS OF SOIL INDICATORS: A SURVEY

Authors:

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Peter Dahlhaus (Federation University Australia)

6.1 Introduction

A key component of this Review Project 2.1.01 was an online survey used to collect data from agricultural industry practitioners, which was intended to compliment the information gathered by the collaborating researchers from the published research literature. The study allowed a comparison of perceptions of soil quality across agricultural systems, as well as exploring the perceived value of indicators across the roles of agricultural practitioners and the geographies in which they operate. It is significant because analysis of published surveys (e.g. MacEwan 1997; Lobry de Bruyn and Abbey 2003; Kelly et al. 2009; Bennett & Cattle 2013) shows that they have typically targeted one type of actor (e.g. farmer) in one type of role (e.g. cropping), or one geographic location. This survey targets different actors (farmers, agronomists, consultants, industry representatives and researchers), across Australia in a variety of agricultural industries (cropping, livestock, horticulture, viticulture, etc.).

The overarching aim of this project is to review which soil properties (physical, chemical and biological) would provide pragmatic indicators of soil health and function, for farmers, agronomists and advisors to translate into practical management of the agricultural resource, meeting profitability and sustainability expectations of land managers and government. Hence a critical part of the research is a survey to ascertain:

- What data farmers, agricultural advisors and researchers are collecting, why they collect it, whether they use it and what data they would ideally like;
- What tools and methods (indicators) farmers, agricultural advisors and researchers are already using to assess their soil performance; and
- The current availability of soils data and the usefulness and limitations of this data

6.1.1 Survey design

The design of the survey was heavily influenced by the desire to reach as many practitioners as possible, especially to explore the differences in perceptions of soil indicators from people working in different roles. For example, whether the perception of soil performance indicators by farmers matched that of agronomists and consultants, and that of researchers. Hence the initial question formed the basis for a branching survey, with questions being tailored slightly differently for each role identified. While the initial questions were used to categorise the respondent, the emphasis in the survey remained on the perceptions of what farmers believed were important. For example, a researcher or agricultural advisor were asked what they thought a farmer would consider an important indicator, rather than what they thought.

The survey was submitted to the Human Research Ethics Committee (HREC) at Federation University Australia in early February 2018 and Ethics Approval granted on 27 February 2018 (# A18-007). A separate report on the survey and all the results is available online (Appendix 4).

The survey was designed to take around 15 minutes to complete and was anonymous.

6.1.2 Survey distribution

Recruitment for the survey included inviting members of the Soil CRC to distribute, via email to their stakeholders, an invitation to participate in the online survey. Fourteen organisations agreed and provided a letter to the HREC indicating their willingness to do so. These included:

- Wimmera Catchment Management Authority
- MacKillop Farm Management Group
- Central West Farming Systems Inc.
- Manaaki Whenua Landcare Research
- Herbert Cane Productivity Services Ltd.
- Holbrook Landcare Network
- Society of Precision Agriculture Australia
- Liebe Group
- SA Grain Industry Trust
- Birchip Cropping Group
- Landmark
- Landmark
- Gillamii Centre
- Hart Field-site Group Inc.
- Southern Cross University

Most of the above listed member organisations distributed the link to the online questionnaire via their organisation's newsletter, social media channels or website. In addition, an email was sent to dozens of research and industry contacts inviting individuals to participate in the survey. Links to the survey were placed on social media channels, as well as the CeRDI website. Participants were expected to include farmers, agronomists, farm and soil consultants, agricultural service providers, agricultural product providers (e.g. fertiliser, compost and machinery), agricultural extension officers, government agricultural research agency staff, university researchers and soil scientists. The target was a sample size of 1,000 participants in the survey. There was no capacity to identify participants in this process.

All participants for this research will have received information about the project through the Plain Language Information Statement which was provided prior to data collection. Participants were asked at the conclusion of the survey if they wish to state their name and email address indicating that they volunteer to be part of potential aligned research projects at a later date. If they chose to do so, they were directed to another one question survey.

6.1.3 Survey limitations

Because of the very tight timelines for the project and budget limitations, input to the survey design from skilled social scientists was not possible. As a result, the survey design suffered from too many variables in some questions, and therefore the analyses of the results could be more complex than presented in this section. However, the overall intention of the survey remained valid, in that there was the opportunity to analyse the variation in results from participants in different roles.

The software used for the online survey also has some limitations in the ability to make the survey intuitive to complete. This restriction, when combined with the complexity of the questions, resulted in some questions having a low response rate as participants simply skipped over the question.

Another limitation was in the timing of the survey distribution, which coincided with numerous other surveys that were concurrently being distributed to the same organisations and participants from other research organisations. Therefore the response was generally poor, with anecdotal evidence that the inundation of concurrent surveys discouraged many from participating.

6.2 Profiles of the survey respondents

In total, there were 122 survey respondents, well short of the target 1000. The initial series of questions were aimed at delineating the respondent's role in agriculture, their age group, their farming system focus and the general size of farming operation, and their geographic location.

Of the 122 respondents, farmers made up the majority of respondents (38%, n = 46), followed by agronomists/consultants (30%, n = 36) and researchers (16%, n = 20). Advisors/extension officers made a total of 10% respondents (n = 12) and industry representatives 7% (n = 8) (Appendix 4, Question 1).

Respondents were mostly engaged in dryland grain, oilseed and pulse production either as a primary farming enterprise (farmers 16%) or where most of work or research time is spent (agronomists/consultants 23%, researchers 18%, respectively) as highlighted in red in Table1 (and Appendix 4, Question 4).

A total of seven respondents across all groups had certification of some form (e.g. organic, biodynamic) (Appendix 4, Question 6).

The age classes, secondary farming enterprise focus and size of main farming enterprises of the respondents are reported in Appendix 4 in Questions 2, 5 and 7, respectively.

Because of the relatively low response, a fine-grained analysis of the data is not possible. For example, delineating between respondents in different roles, of a certain age group, who are working with particular sized farming systems, in a specific geographic region, would reduce the sample sizes to meaningless numbers. For that reason, the analysis remains relatively generalised, in which we simply focus on the use and views of indicators of soil performance of and between the roles of respondents with meaningful sample size. To do so we have combined the responses into three broad, but significant groups: farmers, agronomists/consultants and researchers, making up 102 respondents or 84% of the survey pool.

Table 1. The count and percentage of respondents by role and their primary focus of main enterprise. Colour ramping of red through to orange, yellow and green indicates the highest through to lowest percentage of grand total respondents by role and enterprise.

Role of respondents and primary focus of main enterprise	Count of Role	Percentage of grand total
Farmer	***46***	***45%***
Dryland	35	34%
Beef cattle	8	8%
Dairy (cows)	1	1%
Grain, oilseed, pulses	16	16%
Horticulture: permanent plantings	1	1%
Prime lamb	4	4%
Wool (sheep)	5	5%
Irrigated	10	10%
Beef cattle	2	2%
Dairy (cows)	2	2%
Horticulture: permanent plantings	3	3%
Rice	1	1%
Sugar	1	1%
Viticulture	1	1%
No answer	1	1%
No answer	1	1%
Researcher	***20***	***20%***
Dryland	18	18%
Grain, oilseed, pulses	18	18%
Intensive (e.g. feedlots, greenhouses)	1	1%
Dairy (cows) (e.g. feedlots, greenhouses)	1	1%
Irrigated	1	1%
Sugar	1	1%
Agronomist and Consultants	***36***	***35%***
Dryland	30	29%
Beef cattle	3	3%
Dairy (cows)	3	3%
Grain, oilseed, pulses	23	23%
Sugar	1	1%
Irrigated	4	4%
Grain, oilseed, pulses	2	2%
Horticulture: annual crops	1	1%
Horticulture: permanent plantings	1	1%
Rangeland	2	2%
Beef cattle	2	2%
Grand Total	**102**	**100%**

6.3 The data and information used to make farming decisions

Farmers, agronomists and consultants and researchers source information and data used for management decisions across a range of areas including weather, terrain, soils, production and agribusiness. Here we highlight the percentages of farmer respondents collecting this data and information, the percentage of consultants and agronomists using this data or information to advise on farm management, and researcher's beliefs on the data used to make on farm decisions. The survey questions and a more detailed breakdown of how often the data or information is used within each role can be found in Appendix 4 (Question 8).

6.3.1 Weather information and data

- Responses within the role of researchers reflects the importance of the categories of rainfall, temperature and seasonal variation to both farmers to make management decisions (up to 98%, rainfall) and to agronomists to advising on on-farm management decisions (up to 89%, rainfall) (Figures 1 a, b and e).
- Whilst wind is used by farmers to make management decisions (76%), the percentage of agronomists that advise on wind less (42%) and researchers may underestimate it's use in farm management decisions (50%) (Figure 1d).
- Frost information is used slightly less within farmer respondents (63%) than the percentage of agronomist and consultant respondents that advise on frost (81%) (Figure 1c).

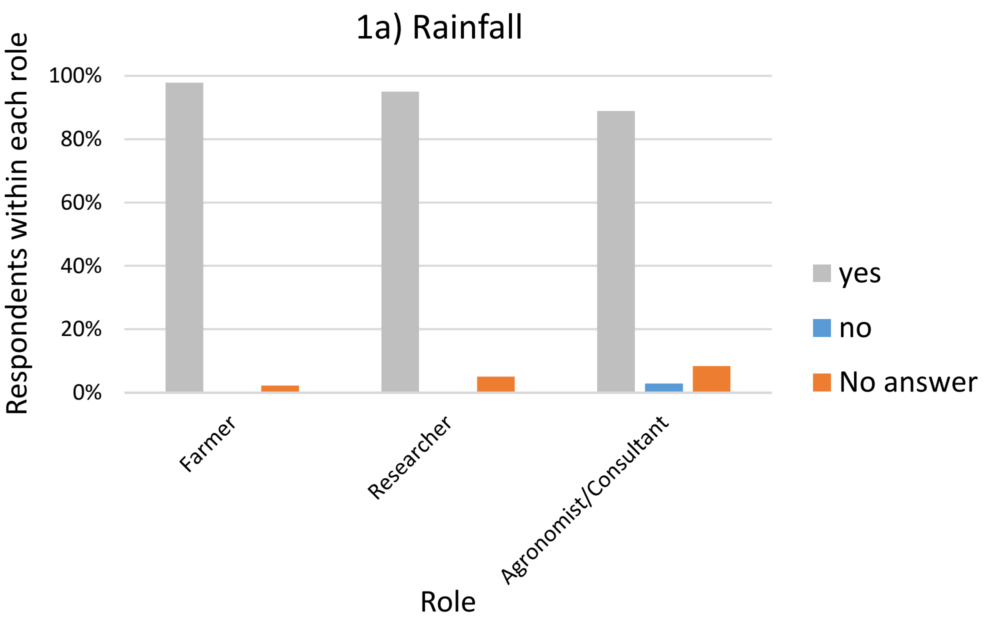


Figure 1. Weather data or information farmers use to make management decisions, agronomists and consultants use to advise clients about management decisions and what researchers believe are typically used to make on-farm management decisions: a) Rainfall, b) Temperature, c) Frost, d) Wind and e) Seasonal Forecasts. (Farmer *n* = 46, agronomist/consultant n = 36, researcher *n* = 20)

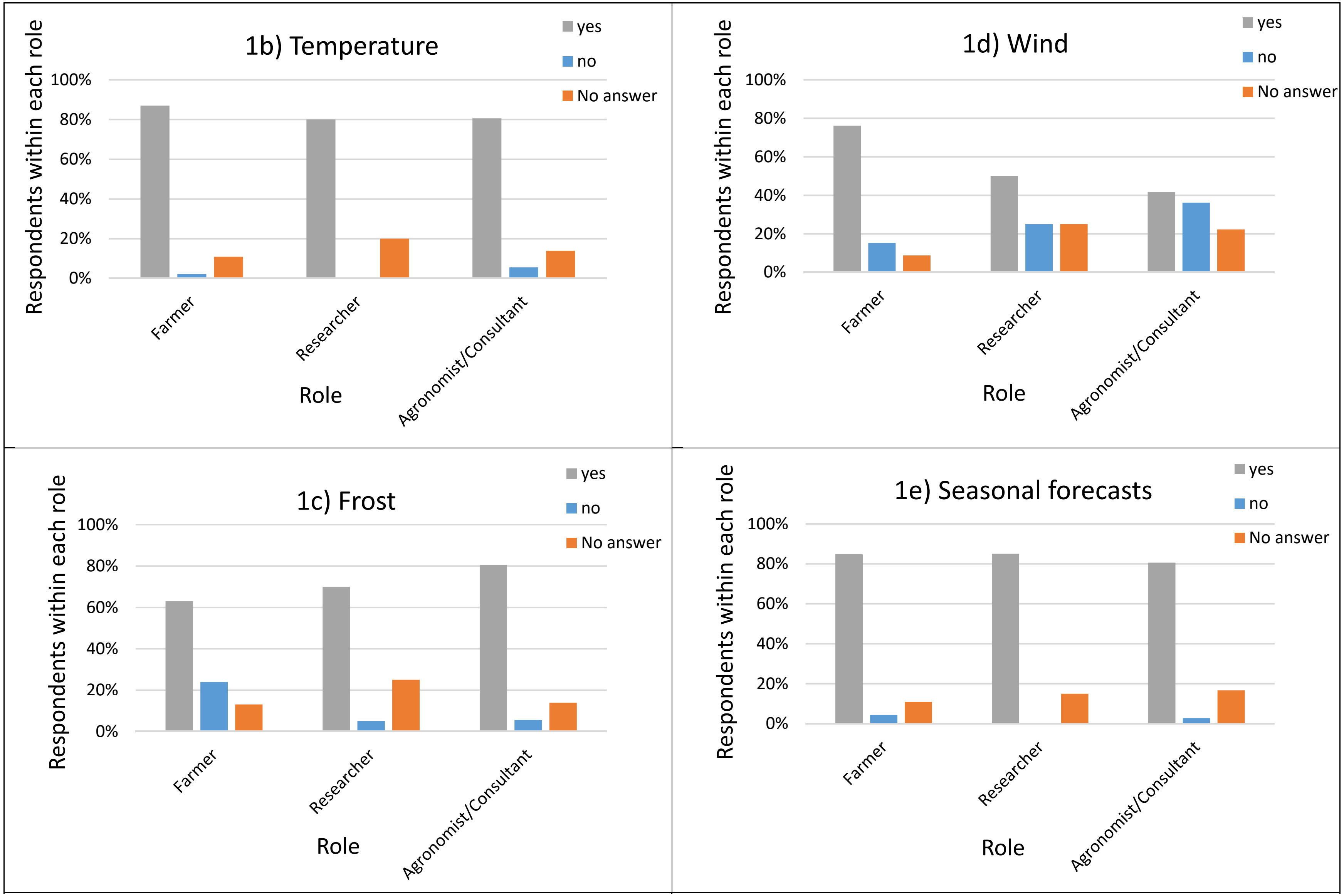
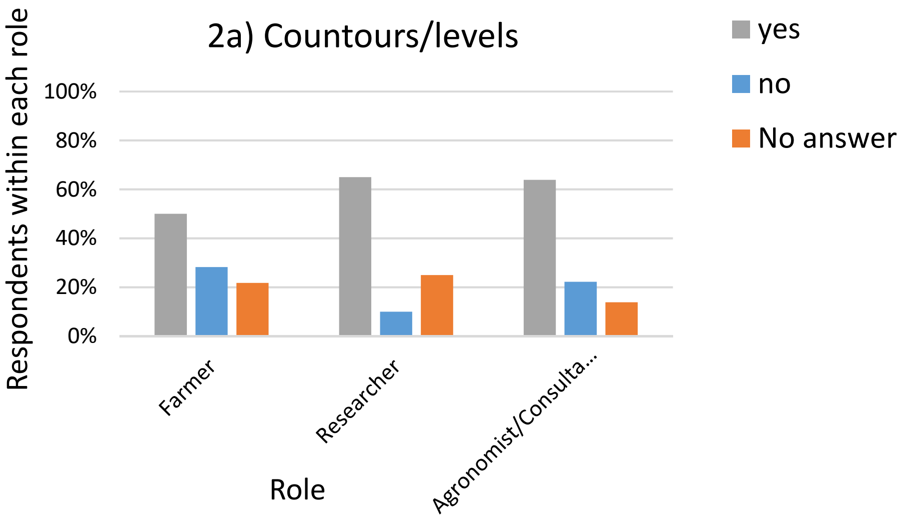


Figure 1. Weather data or information farmers use to make management decisions, agronomists and consultants use to advise clients about management decisions and what researchers believe are typically used to make on-farm management decisions: a) Rainfall, b) Temperature, c) Frost, d) Wind and e) Seasonal Forecasts. (Farmer *n* = 46, agronomist/consultant n = 36, researcher *n* = 20)

6.3.2 Terrain information and data

- The percentage of farmer respondents that use contours and levels to make management decisions (50%) is slightly less than the percentage of agronomists advised on (63%) and researchers believed this information was used (65%) (Figure 2a).
- Whist 83% of agronomists used drainage and/or waterlogging information or data to advise clients, a lesser percentage (65%) of farmers report using this data for management decisions (Figure 2b).



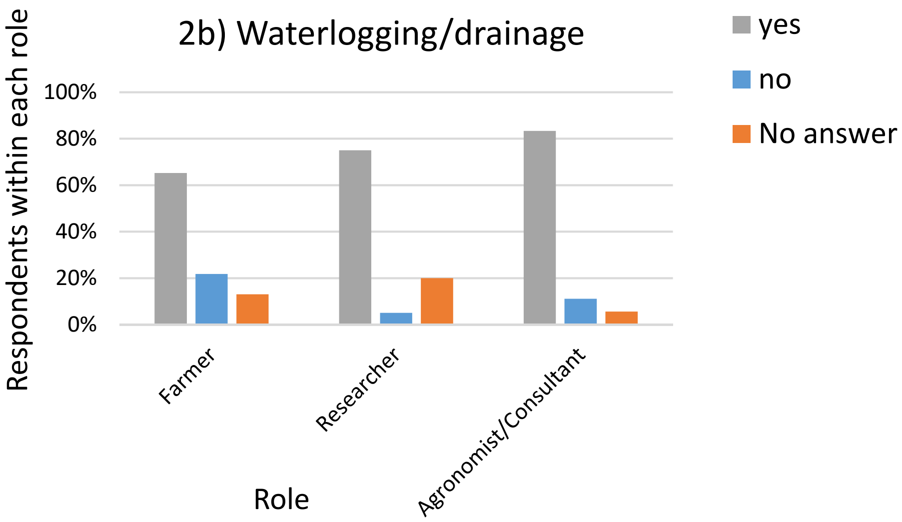


Figure 2. Terrain data or information farmers use to make management decisions, agronomists and consultants use to advise clients about management decisions and what researchers believe are typically used to make on-farm management decisions: a) Contours/levels, b) Waterlogging/drainage. (Farmer *n* = 46, agronomist/consultant n = 36, researcher *n* = 20)

6.3.3 Soils information and data

- Soil type and variability, soil moisture, soil chemistry, including nutrients and soil structure were all used by a high percentage of farmers to make management decisions and for agronomists to advise on. This was also reflected in the researcher's view of the use of the data and information provide to farmers for management decisions (Figures 3 a-d).
- Researchers underestimated use of soil biology by farmers to make management decisions, with 88% of farmers using soil biology to make management decisions, and only 55% of researchers believing that soil biology was used by farmers to make management decisions (Figure 3e).

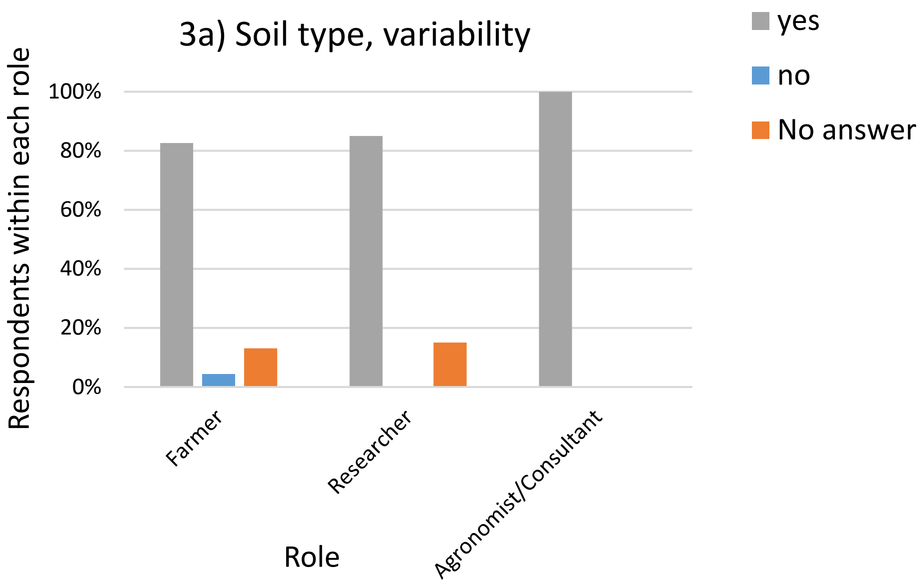


Figure 3. Soil data or information farmers use to make management decisions, agronomists and consultants use to advise clients about management decisions and what researchers believe are typically used to make on-farm management decisions: a) Soil type, variability, b) Soil moisture, c) Soil chemistry, d) Soil structure and e) Soil biology.

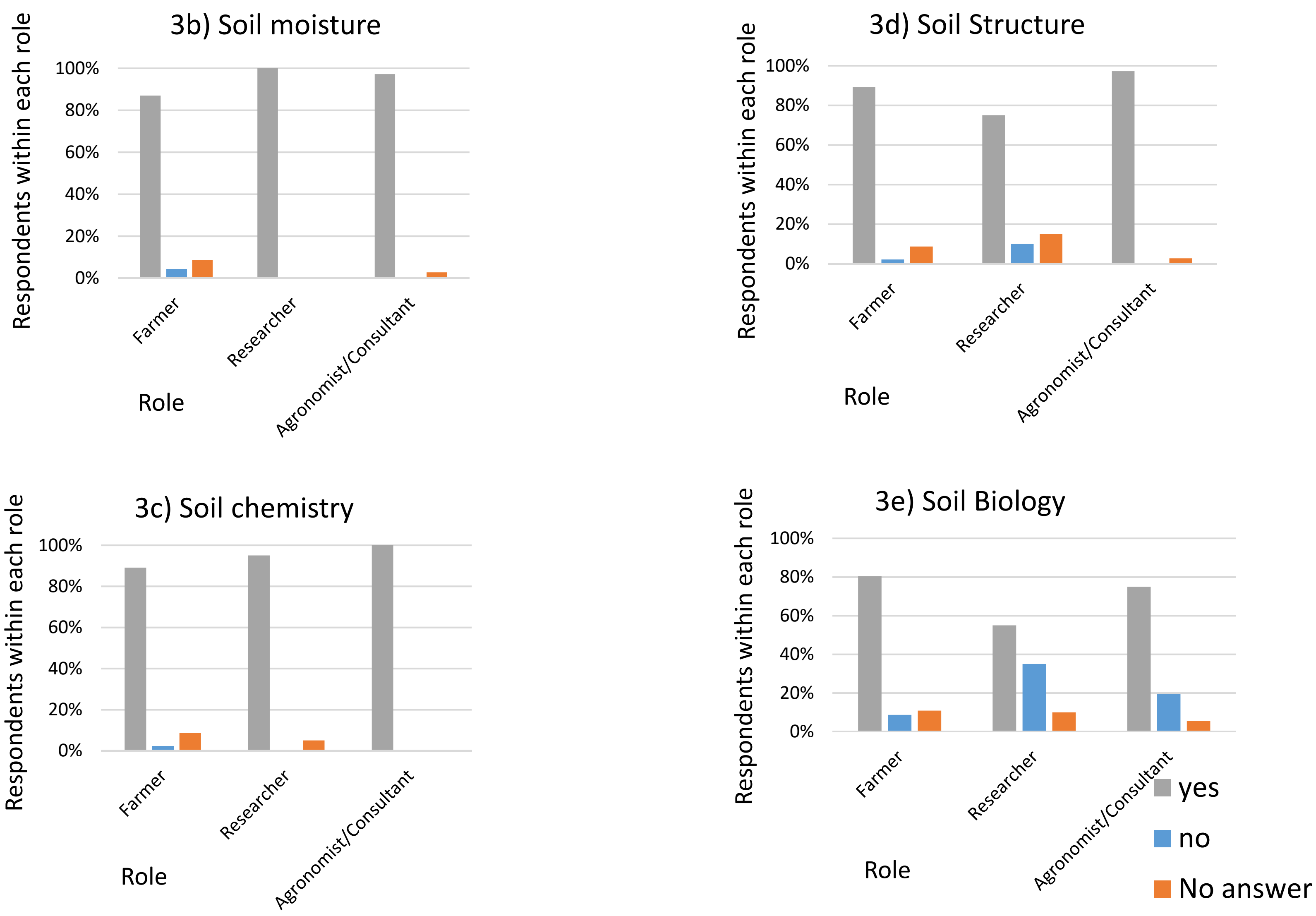
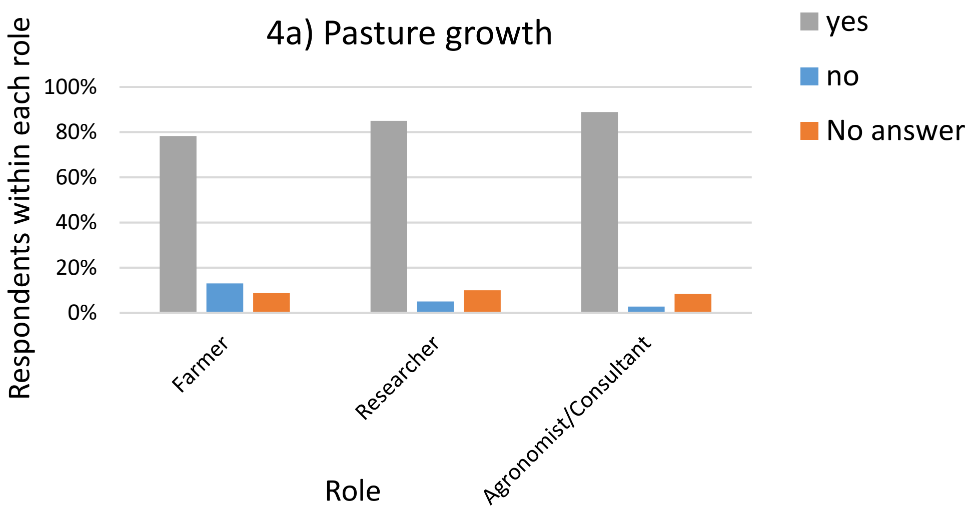
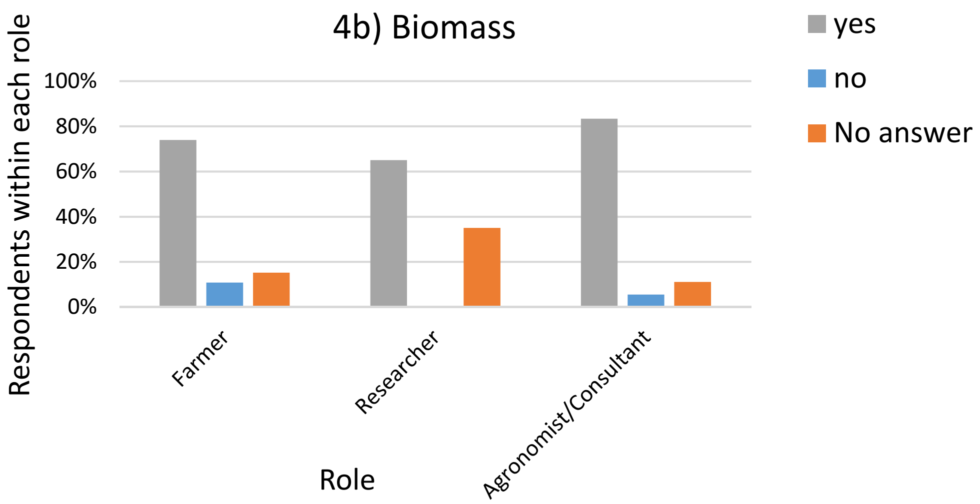


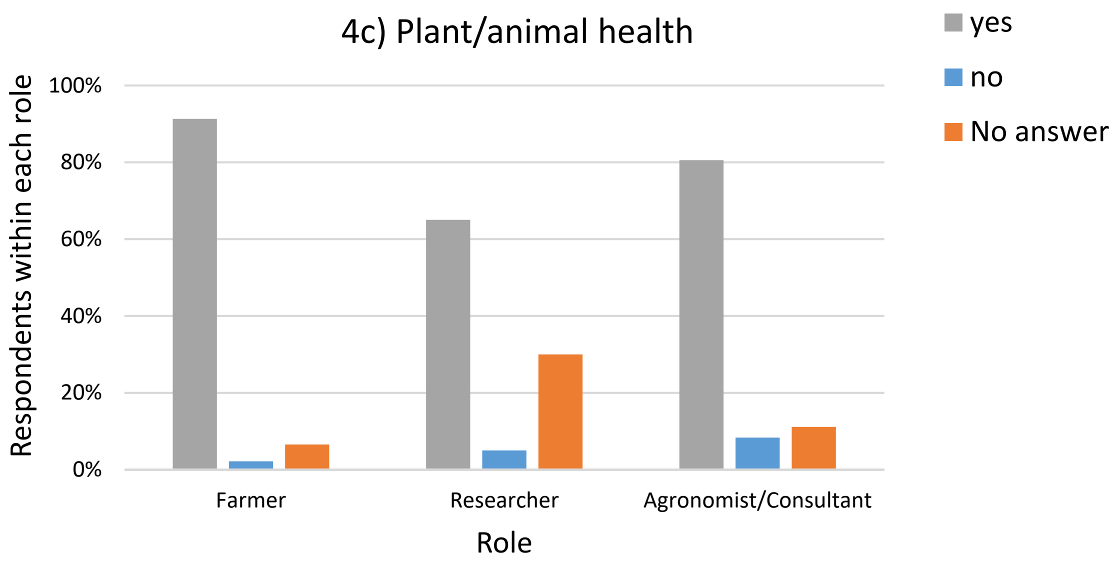
Figure 3. Soil data or information farmers use to make management decisions, agronomists and consultants use to advise clients about management decisions and what researchers believe are typically used to make on-farm management decisions: a) Soil type, variability, b) Soil moisture, c) Soil chemistry, d) Soil structure and e) Soil biology.

6.3.4 Production information and data

- Production is important to both farmers and agronomists in making, or advising on, farm management decisions (Figures 4 a – d). Greater than 90% of farmer respondents use plant/animal health (Figure 4c) and yield (Figures 4d).
- Whilst the importance of this data was generally reflected by both the agronomists and researcher respondents, researcher's 'no answer' were 35% for biomass, 30% for production and 15% for plant and animal health.







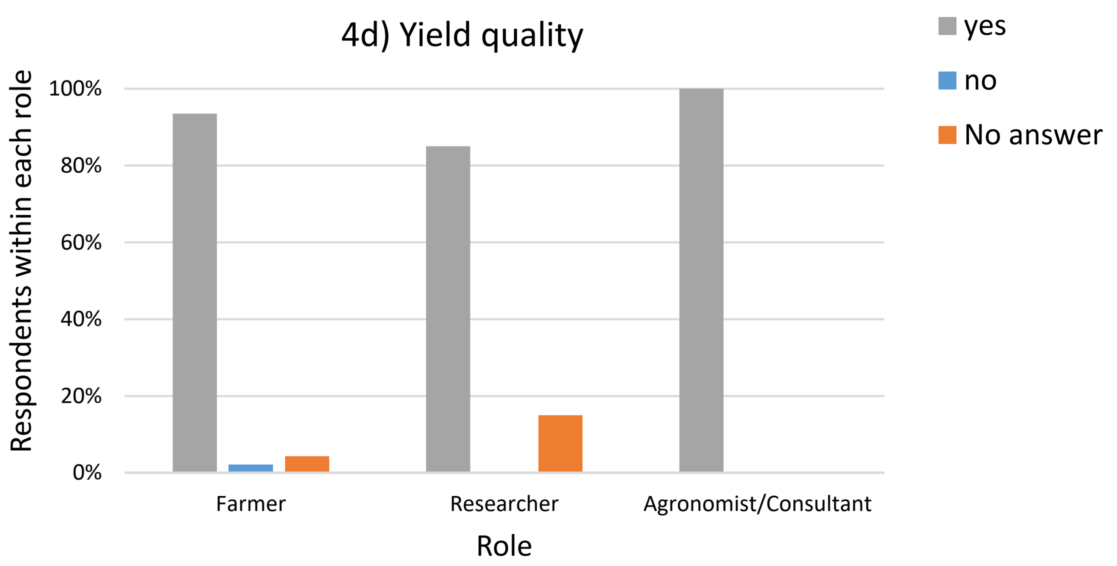
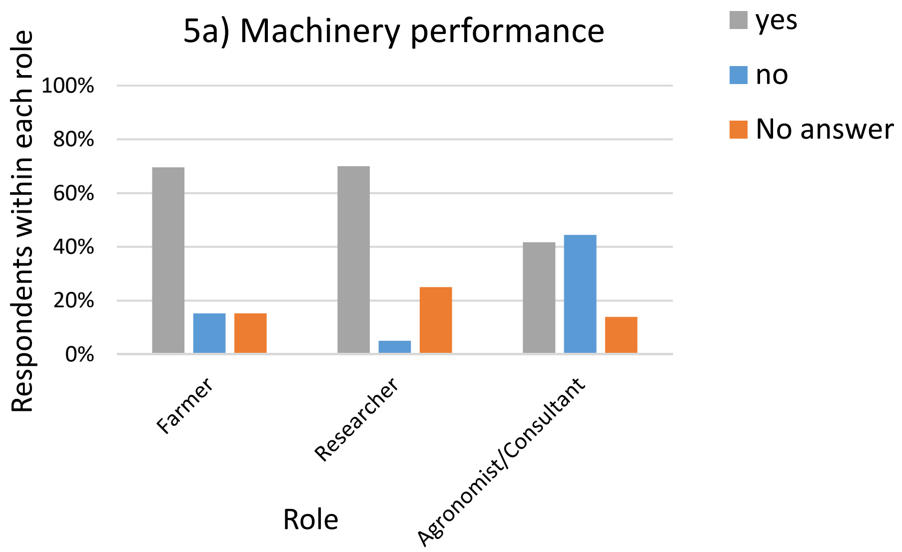
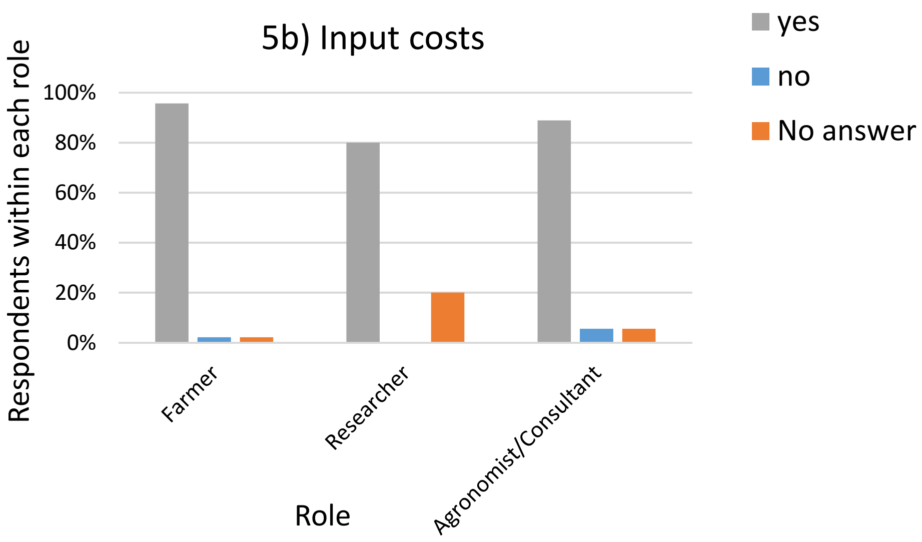


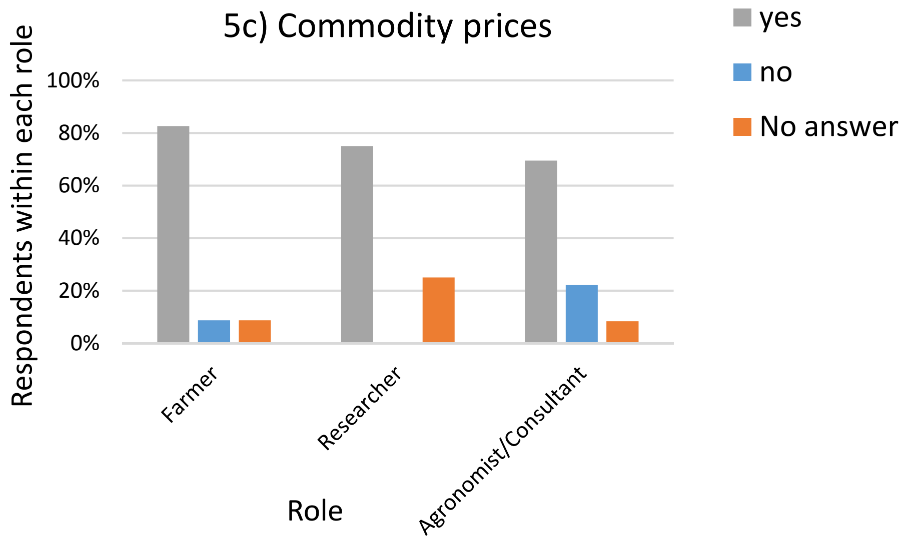
Figure 4. Production data or information farmers use to make management decisions, agronomists and consultants use to advise clients about management decisions and what researchers believe are typically used to make on-farm management decisions: a) Pasture growth, b) Biomass, c) Plant/animal health and d) Yield quality. (Farmer *n* = 46, agronomist/consultant n = 36, researcher *n* = 20)

6.3.5 Agribusiness information and data

Agribusiness data or information is important to farmers for management decisions, particularly input costs (96%, Figure 5b). The percentage of agronomists/consultants that used machinery performance data to advise on farm management decisions (42%) was less than the percentage of farmer respondents that used the data (70%) (Figure 5a) and a similar pattern was seen for market forecasts (farmers 74% to agronomists 56%, Figure 5d). Whist researchers views generally reflected this use of agribusiness data and information for on-farm decision making, there were 'no answer' responses of each agribusiness category of between 20 to 25%.







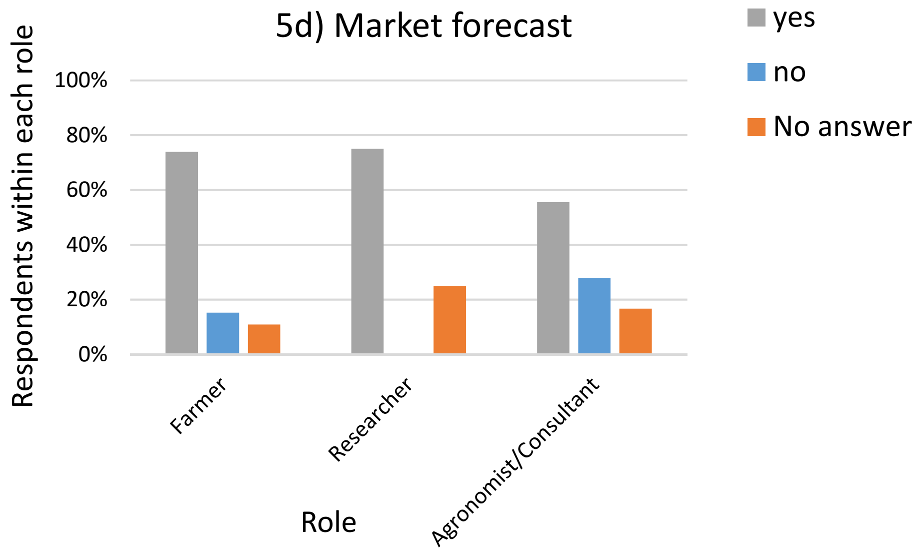


Figure 5. Agribusiness data or information farmers use to make management decisions, agronomists and consultants use to advise clients about management decisions and what researchers believe are typically used to make on-farm management decisions: a) Machinery performance, b) Input costs, c) Commodity prices and d) Market forecast. (Farmer *n* = 46, agronomist/consultant n = 36, researcher *n* = 20)

6.4 How soil information and data is sourced

Farmers, agronomists, consultants and researchers were asked where they normally source their information about soil on their main farming enterprise, their client's farms, or their agricultural research site. Here we compare the responses of the main roles (Figure 6, Question 9 in Appendix 4).

- A sizable percentage of respondents sourced soil information about their farm (farmers), their clients farm (Agronomists/consultants), or their research sites (researchers) on-site manually, either through themselves or through farmers (87%, 83% and 80%, respectively) (Figure 6a).
- A smaller percentage of farmer respondents source their site information or data from in-field sensors (15%) in comparison to researcher respondents (40%) (Figure 6b).
- A lower percentage of farmers and agronomists/consultant respondents source their soil information and data from their own database (Figure 6c) or their colleagues, friends, family or neighbours than the percentage of researcher respondents (Figure 6d).
- The percentage of farmers that source site soil data or information from research is much lower than the percentage of researcher respondents that do (farmers, 40%; researchers 75%, Figure 6f).
- More farmer respondents sourced their site soil data and information from extension activities (farmers 50%, agronomists/consultants 36% and researchers 35%, Figure 6e) than both researcher and agronomist/consultant respondents, and similarly for paid advisors/consultants (farmers 40%, agronomists/consultants 14% and researchers 10%, Figure 6g) and paid subscriptions or memberships (farmers 35%, agronomists/consultants 36% and researchers 35%, Figure 6h).
- A lower percentage of agronomists/consultants respondents source their information feely from the internet (22%) as compared with farmers (41%) and researchers (55%) (Figure 6i).
- Researchers were the highest users of mobile applications to source site soil information or data (25%), with a small number of farmer respondents using this technology for this purpose (7%) (Figure 6j).

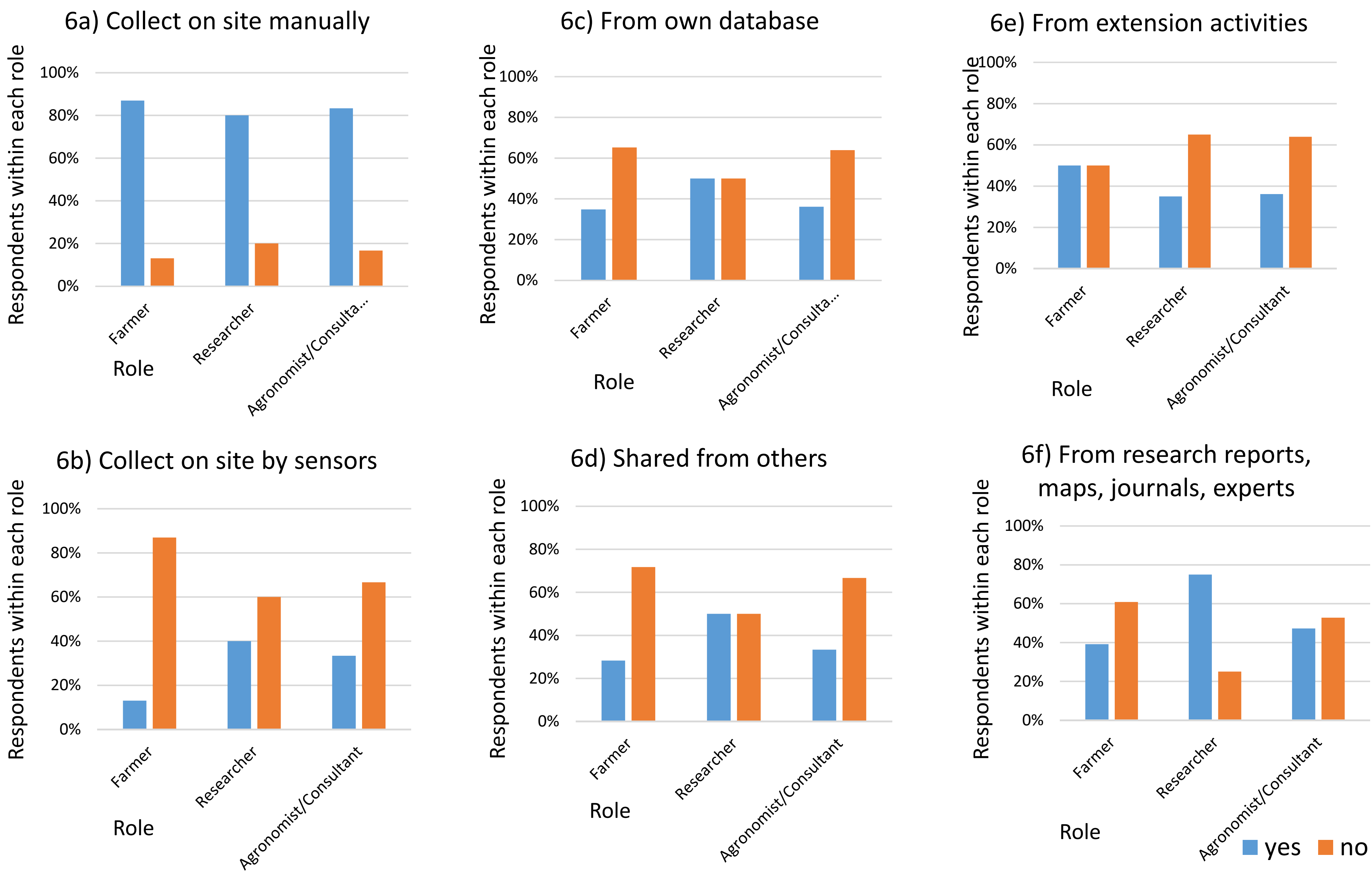


Figure 6. Where farmers, agronomists/consultants and researchers would normally source their information about the soil on their farm, their client's farm or their research site. (Farmer *n* = 46, agronomist/consultant n = 36, researcher *n* = 20)

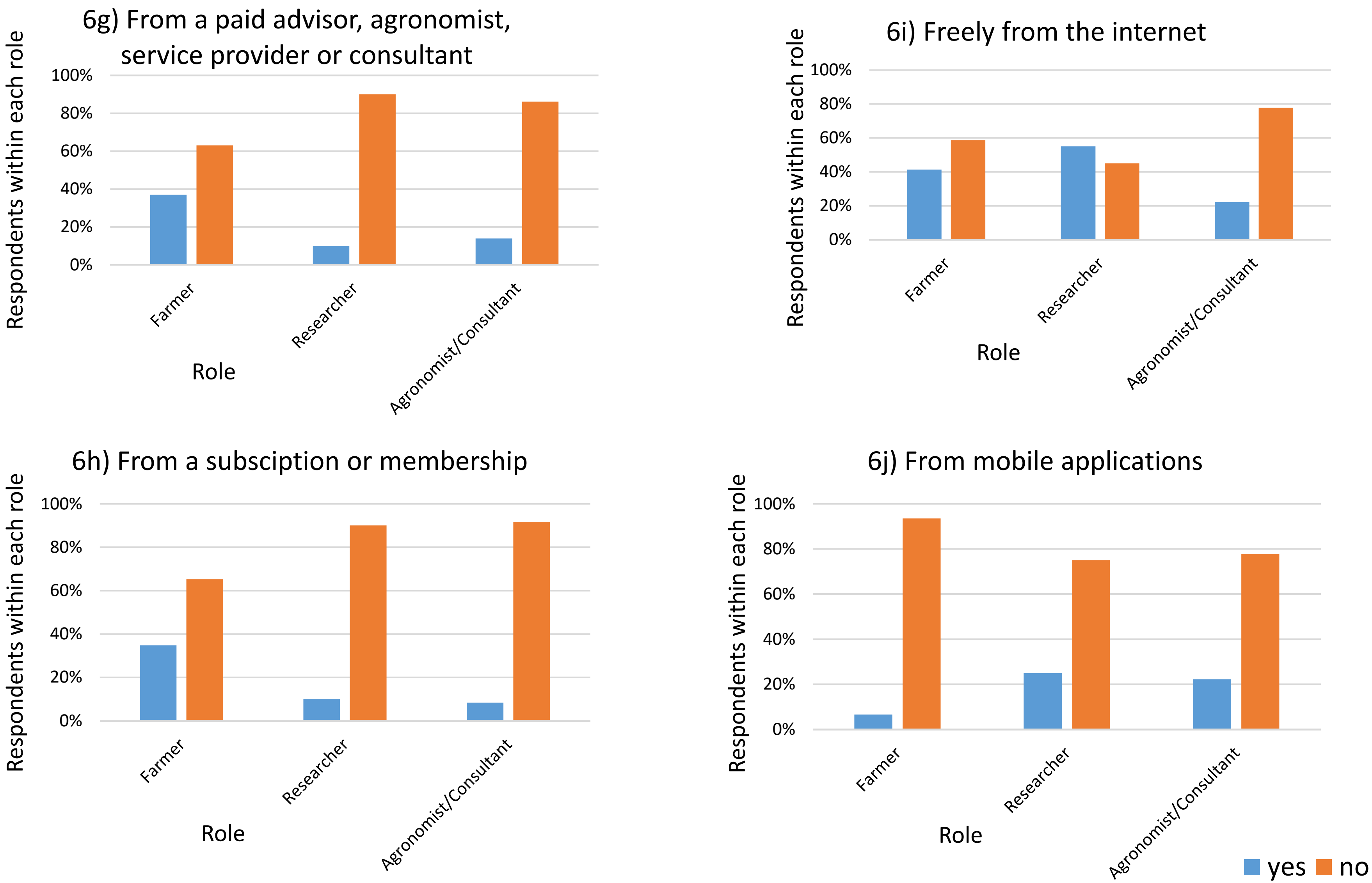


Figure 6. Where farmers, agronomists/consultants and researchers would normally source their information about the soil on their farm, their client's farm or their research site. (Farmer *n* = 46, agronomist/consultant n = 36, researcher *n* = 20)

6.5 Soil observations that are used to judge the performance of soils

Farmers, agronomists and consultants and researchers were asked what **soil observations** they use to judge the performance of soils on their farm, their client's farm, or their agricultural research site (Question 10 in Appendix 4). Here we compare the percentage responses of each role (farmers, agronomists and consultants and researchers) (Figure 7). For a further breakdown of the responses by how often the observations are made see Appendix 4, Question 10.

- A sizable percentage of respondents use soil observations to judge the performance of soils at their farm (farmers), client's farm (agronomists/consultants) or site (researcher). These percentages range from 60% (research respondents using soil-borne pests and disease) through 90% (researchers using colour, texture and feel).
- The one contrast between respondent groups was the use of the smell and taste of soil, with 61% of farmers using this observation as an indicator of soil performance in contrast with 31% of research and 42% of agronomist/consultant responses.
- Agronomists/consultants returned the highest percentage of 'no response' to all observation categories (25% organic matter observations through to 33% smell and taste).

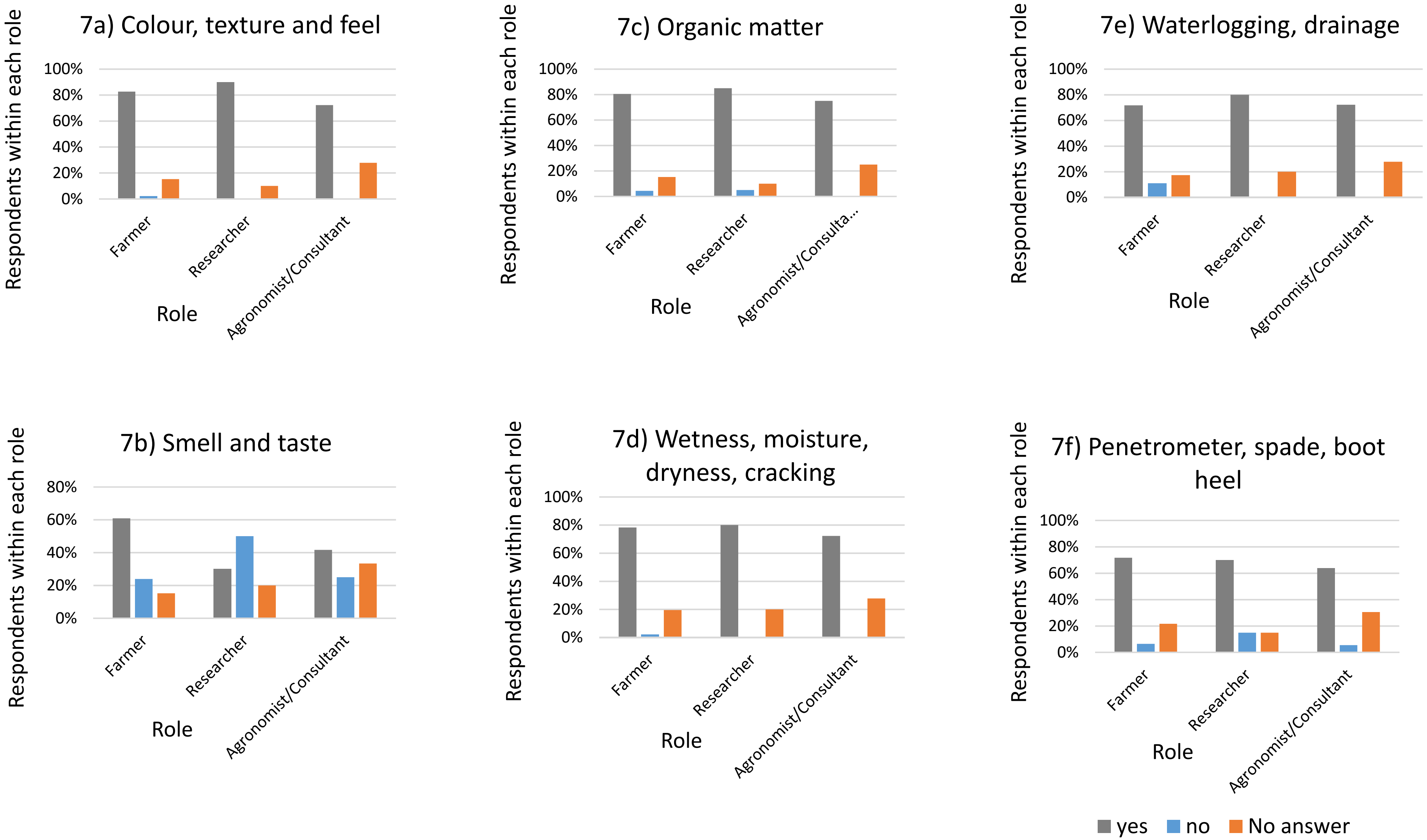


Figure 7. Soil observations farmers use to judge the performance of soils on their farm, agronomists and consultants on a client's farm, and researchers on an agricultural research site. (Farmer *n* = 46, agronomist/consultant n = 36, researcher *n* = 20).

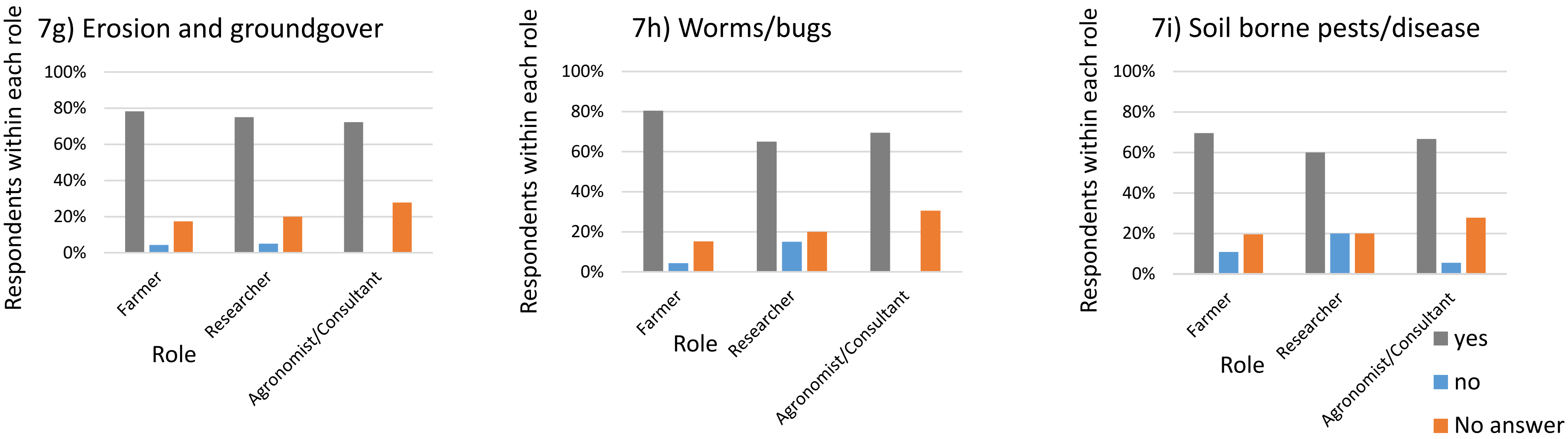


Figure 7. Soil observations farmers use to judge the performance of soils on their farm, agronomists and consultants on a client's farm, and researchers on an agricultural research site. (Farmer *n* = 46, agronomist/consultant n = 36, researcher *n* = 20).

6.6 Soil tests that are used to judge the performance of soils

Farmers, agronomists and consultants and researchers were asked what **soil tests** they use to judge the performance of soils on their farm, their client's farm, or their agricultural research site (Question 11 in Appendix 4).

6.6.1 Soil physical

- Soil moisture and soil structure are used by a high percentage of respondents in all groups to judge the performance of soils, from 64% (agronomists/consultants, soil structure, Figure 8c), to 75% (soil moisture, researchers, Figure 8a).
- Soil physical strength and temperature are used to a slightly lesser extent within roles, from 50% (agronomist/consultant and researcher, soil strength, Figure 8d) to 67% (farmer, soil temperature, Figure 8b).
- There was a reasonably high number of all respondent groups that replied 'no answer' to soil structure and soil strength (20% researcher response to 'soil structure', to 36% agronomist/consultant response to 'soil strength' Figures 8c and 8d).
- The one notably different response between groups is that only 17% of farmer respondents use EM38 (electromagnetic) surveys to judge the performance of soils, in contrast to agronomists/consultants (47%) and researchers (60%) (Figure 8e).

6.6.2 Soil chemical

- A high percentage of all respondent groups use soil chemical tests to judge performance including soil tests for; available nutrients, including N, pH and EC in 1:5 water. Percentage of use ranged from 67% for farmers for soil EC to monitor soil salinity to 90% for researchers using soil pH (Figures 9a – 9d).
- The percentages of respondents using soil contaminants and toxicity as an indicator of soil health were lower across all groups (agronomist/consultant 44%, farmer 46% and researcher 50%). The numbers of 'no response' are notably high (consultants 36%, researcher 30% and farmer 24%) (Figure 9e).

6.6.3 Soil biological

- For most of the types of biological test surveyed there were a greater percentage of respondents within each group that *did not* use biological tests as an indicator of soil performance than did (Figure 10). This contrasts with the soil observation and soil chemical and physical test categories (Figures 8 and 9).
- The percentage of 'yes' respondents within each group ranged from 20% for farmers using DNA based tests to 46% for farmers using worm counts (see Figures 10b and 10c).
- More farmer respondents used worm counts (46%) than agronomists/consultants (36%) and researchers (25%) (Figure 10c) with a similarly for bug counts (44% farmers, 22% agronomists/consultants, 30% researchers) (Figure 10d).
- Contrasts between respondents could also be seen for DNA based tests, with 57% of farmers not using these tests to judge the performance of their soil, whilst 41% of agronomists are (Figure 10b).
- Again, the high number of 'no answer' responses within the soil biological category should be noted and in some cases they are as high as the percentages of 'no' and 'yes' responses within groups.

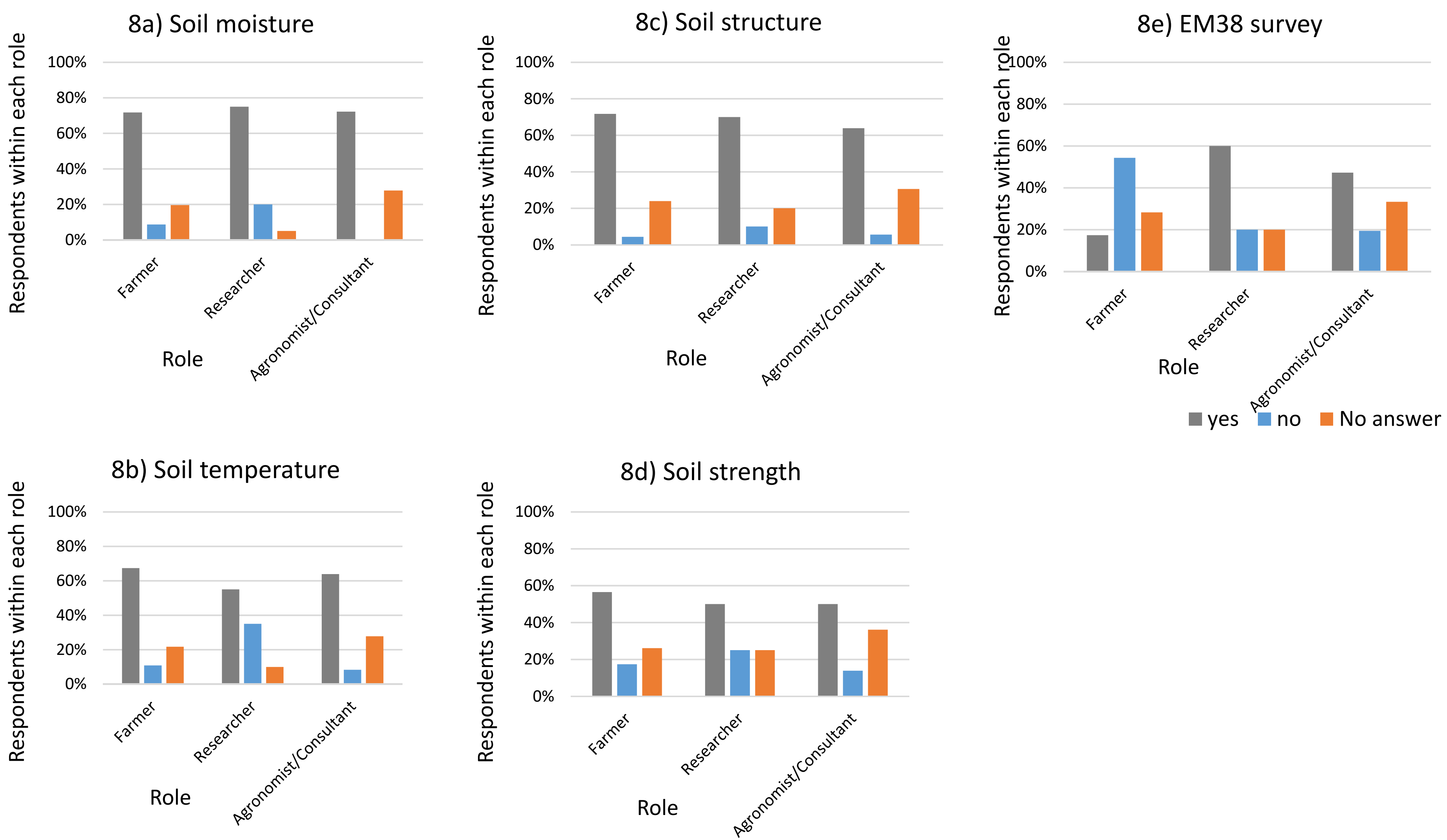


Figure 8. Soil physical tests that farmers use to judge the performance of soils on their farm, agronomists and consultants on a client's farm, and researchers on an agricultural research site.

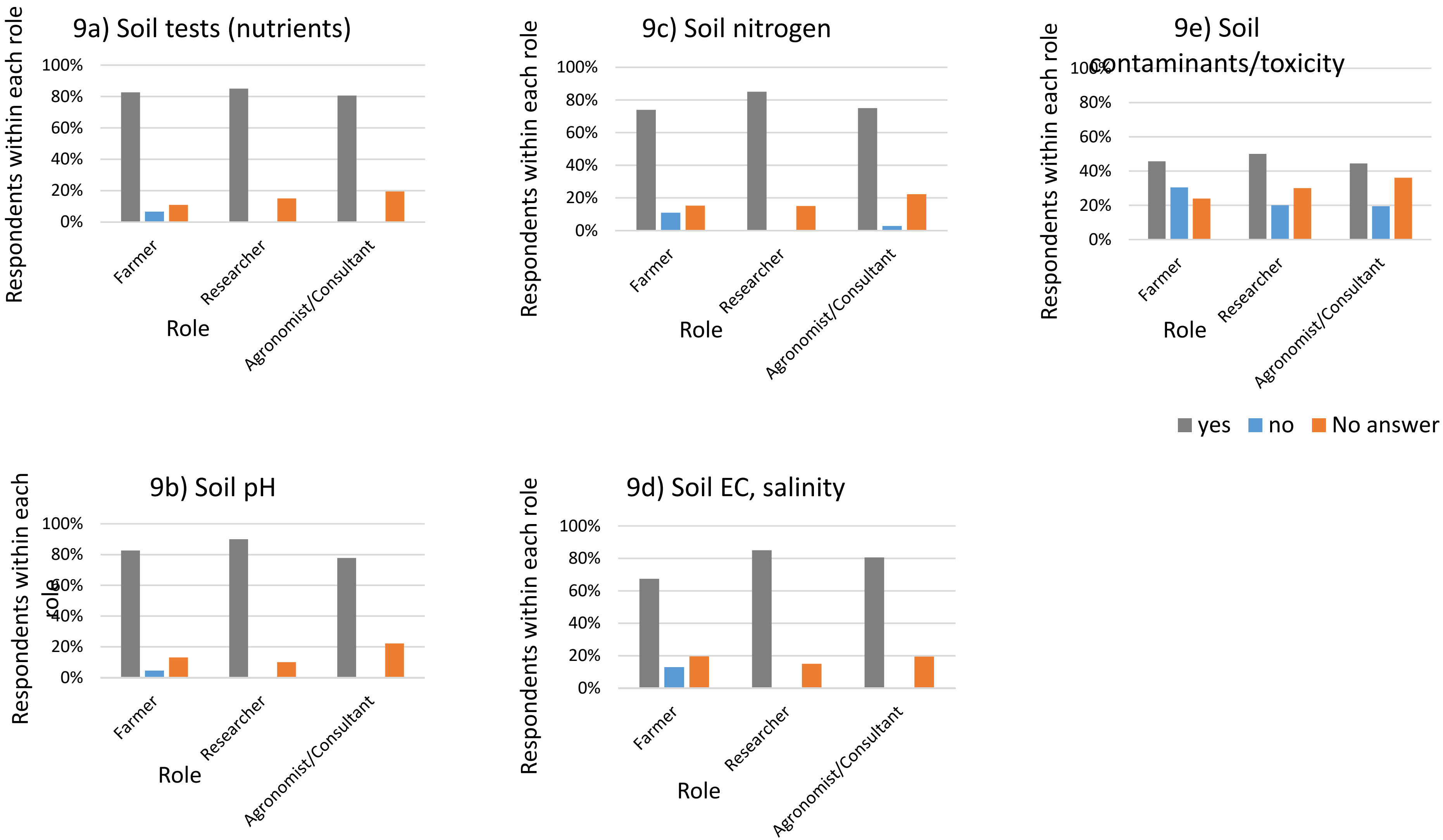


Figure 9. Soil chemical tests that farmers use to judge the performance of soils on their farm, agronomists and consultants on a client's farm, and researchers on an agricultural research site. (Farmer *n* = 46, agronomist/consultant n = 36, researcher *n* = 20)

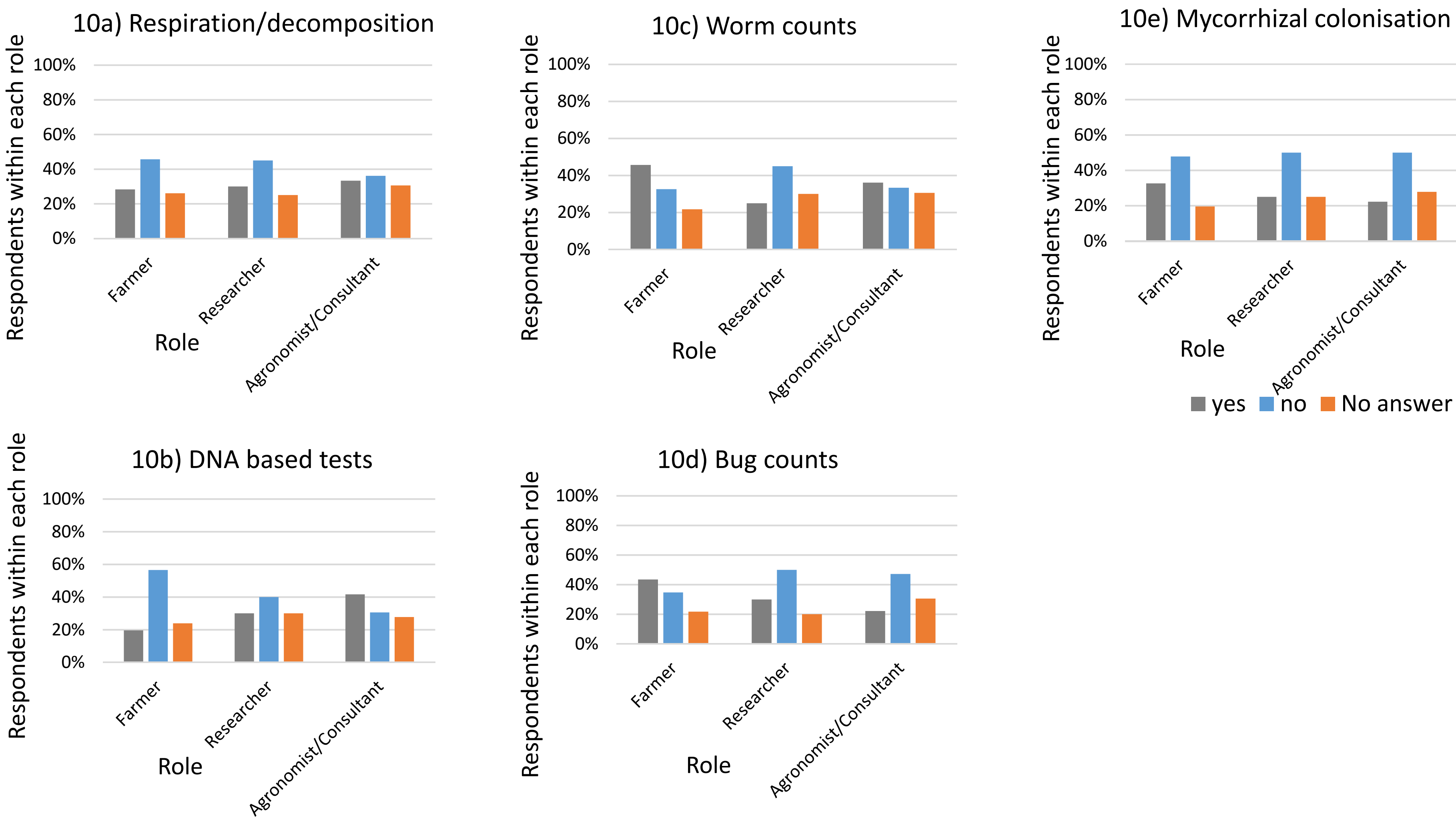


Figure 10. Soil biological tests that farmers use to judge the performance of soils on their farm, agronomists and consultants on a client's farm, and researchers on an agricultural research site. (Farmer *n* = 46, agronomist/consultant n = 36, researcher *n* = 20).

6.7 How often past soil information, observations or tests are looked back on to make decisions

Respondents were asked how often they looked back on their past soil information, observations or tests to make farming decisions (farmer respondents), advise client farming decisions (agronomists/consultants) or in their research (researchers) (Figure 11 and Question 12, Appendix 4).

Few respondents across all categories look back at their data more than yearly (i.e. monthly). Farmer (59%) and agronomists/consultant (58%) respondents look back on their data yearly with percentage of researchers that look back at their data yearly being lower (35%). There are more research respondents that look back on their data every 2 to 5 years (25%) or hardly ever (20%) than the farmer and agronomist/consultant respondent categories.

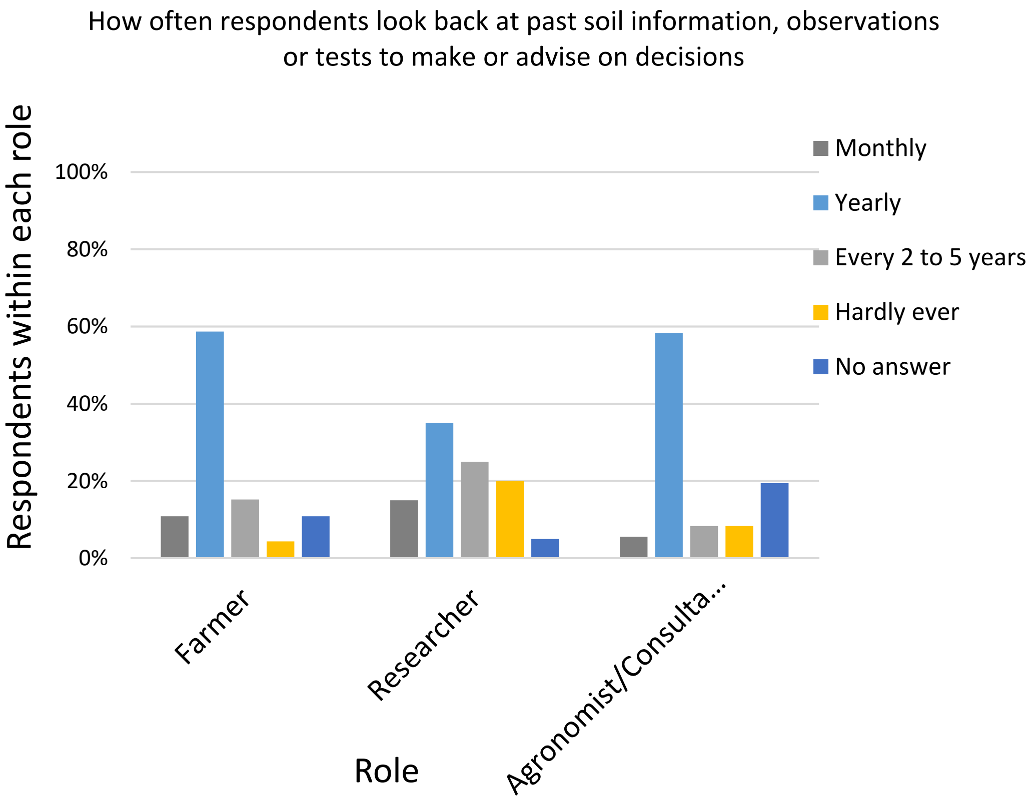


Figure 11. How often respondents looked back on their past soil information, observations or tests to make farming decisions (farmer), advise client farming decisions (agronomists/consultants) or in their research (researchers). (Farmer *n* = 46, agronomist/consultant n = 36, researcher *n* = 20).

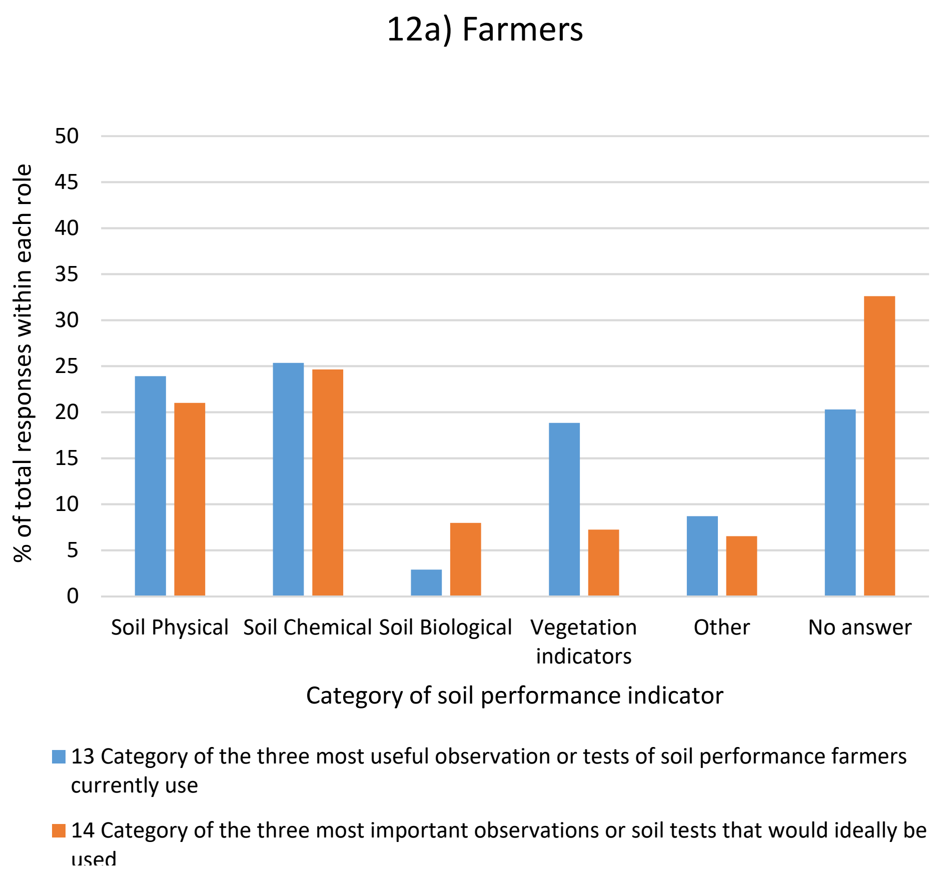
6.8 The most useful and the most ideal observations of soil performance

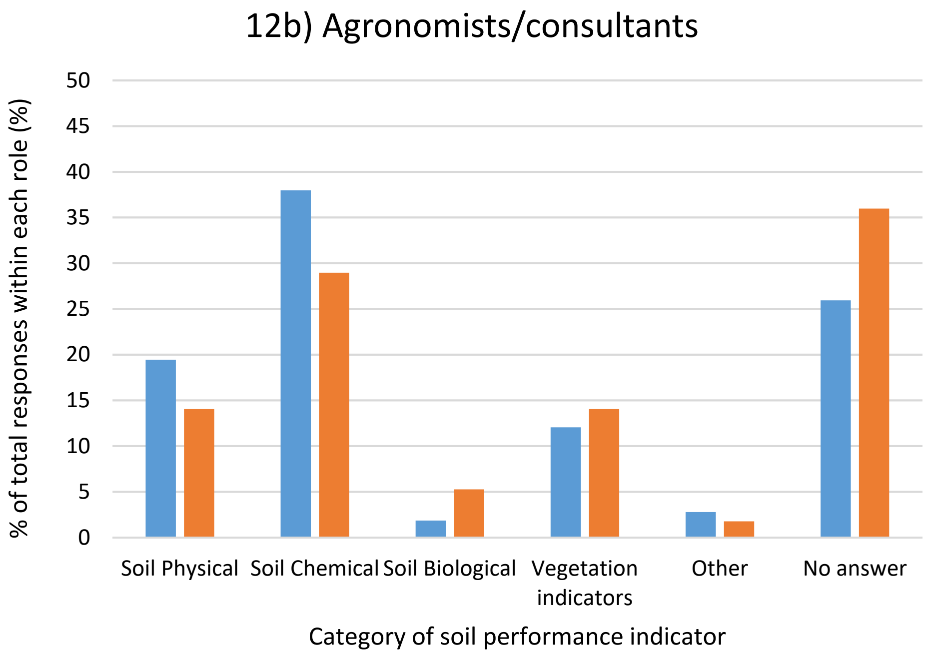
Respondents were asked which are the three most useful tests of soil performance that they use; 1) directly i.e., farmer, 2) that they use to advise their clients i.e., agronomists and consultants, or 3) that they believe farmers currently use i.e., in the opinion of researchers. They were all then asked what, in an 'ideal-world', they would like to use or advise their clients to use (Figure 12 and Questions 13 and 14, Appendix 4).

Between the three respondent groups, soil biology is lower than physical and chemical. Within the farmer, agronomist/consultant and researcher categories however, the percentage of biological indicators was higher as an indicator of soil performance that should ideally be used.

Many respondents answered that measures of vegetation growth and health were the most useful observations or tests of soil performance, in particular farmers (19%). Again, the number of 'no answers' should be noted which was as high as 33% for farmers and 36% for agronomists/consultants.

Word frequency queries were run in inVivo 12 Pro (excluding the word 'soil') with results shown in Figures 13, 14, 15 and Table 2. There are no clear differences between what respondents use as the ideal indicator, and what they would ideally like to use as the ideal indicator and there are no clear differences between the groups observable at this low sample number. We do, however, get an indication that the most useful indicators of soil performance common between the groups are moisture levels, organic matter content, soil pH and macro nutrients (phosphorus and nitrogen).





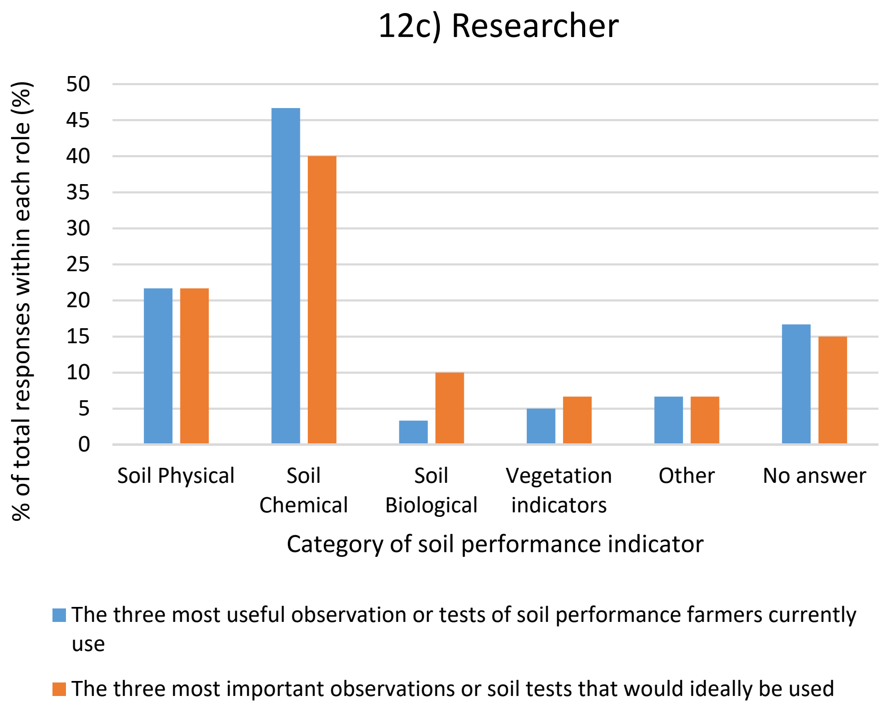
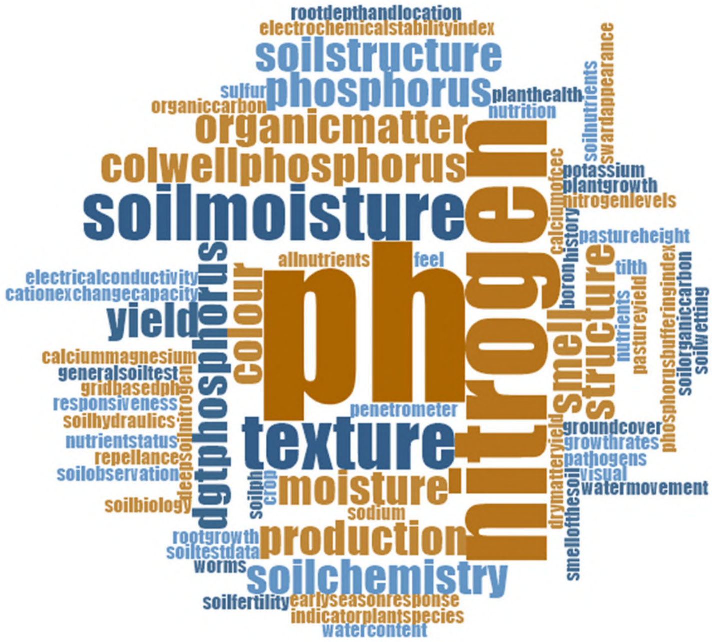


Figure 12. The three most important observations or tests of soil performers that 12a) farmers currently use (blue bars) and would ideally like to use (orange bars) 12b) agronomists/consultants use to advise their clients (blue bars) and ideally like to advise their clients (orange bars) and 12c) researchers think farmers use (blue bars) and would like to see farmers use (orange bars). (Total number of responses: Farmer n = 138, agronomist/consultant n = 108, researcher n = 60).

Figure 13. What farmers view as the most useful (top diagram) and what they would ideally like to use as (bottom diagram) indicators of soil performance.



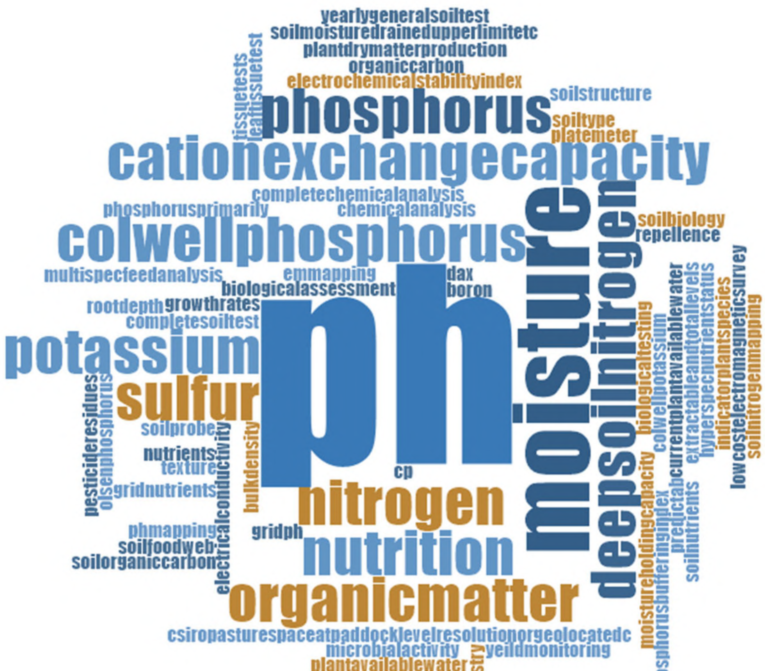


Figure 14. What agronomists and consultants view as the most useful (top diagram) and what they would ideally like to use as (bottom diagram) indicators of soil performance

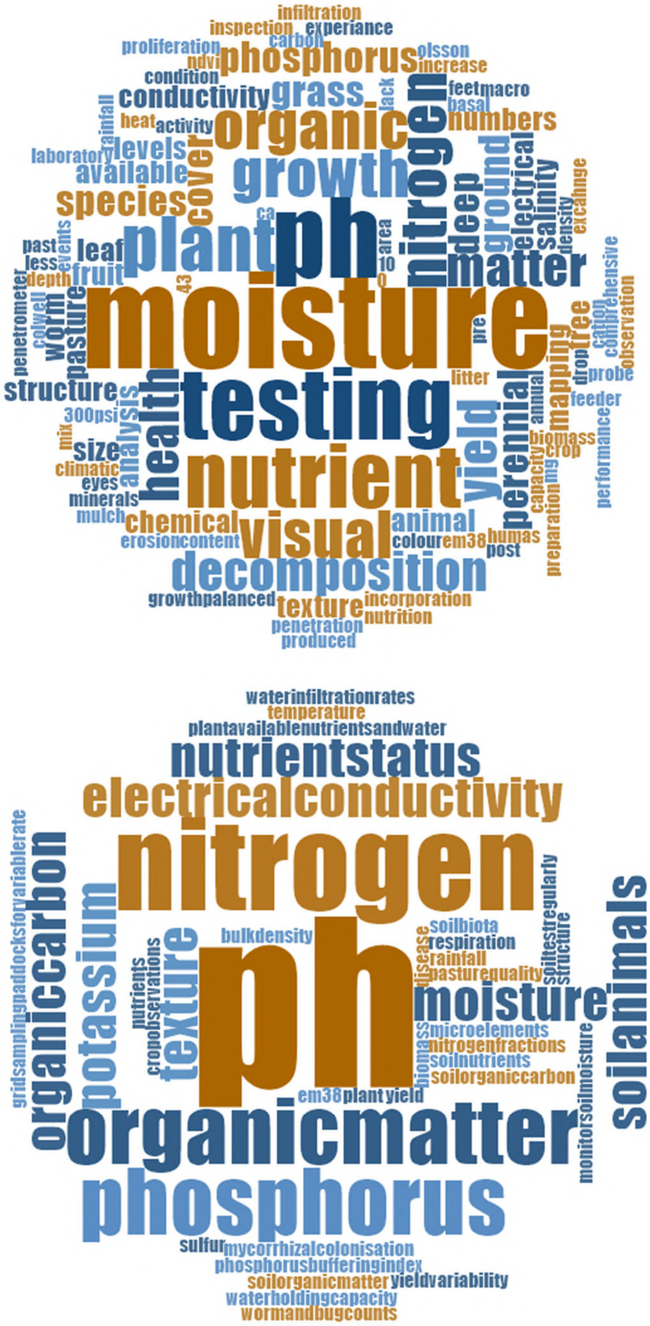


Figure 15. What researchers view as the most useful (top diagram) and what they would ideally like to use as (bottom diagram) indicators of soil performance

Most ideal used			Would like to use		
soil test or observation	**count**	**weighted precentage**	**soil test or observation**	**count**	**weighted percentage**
Farmers					
ph	7	5.79	ph	5	4.95
moisture	6	4.96	organic matter	4	3.96
organic matter	3	2.48	moisture	3	2.97
soil moisture	3	2.48	nitrogen	2	1.98
soil tests	3	2.48	soiltest	2	1.98
visual	3	2.48	yield	2	1.98
animal health	2	1.65			
deep nitrogen	2	1.65			
electrical conductivity	2	1.65			
groundcover	2	1.65			
growth	2	1.65			
nitrogen	2	1.65			
salinity	2	1.65			
soil nutrient	2	1.65			
soil structure	2	1.65			
yield	2	1.65			
Agronomists and consultants					
ph	8	8.33	ph	7	8.43
nitrogen	5	5.21	moisture	3	3.61
soil moisture	3	3.12	cation exchange capacity	2	2.41
texture	3	3.12	colwell phosphorus	2	2.41
colour	2	2.08	deep soil nitrogen	2	2.41
colwell phosphorus	2	2.08	nitrogen	2	2.41
DGT phosphorus	2	2.08	nutrition	2	2.41
moisture	2	2.08	organic matter	2	2.41
organic matter	2	2.08	phosphorus	2	2.41
phosphorus	2	2.08	potassium	2	2.41
production	2	2.08	sulfur	2	2.41
smell	2	2.08			
soil chemistry	2	2.08			
soil structure	2	2.08			
structure	2	2.08			
yield	2	2.08			
Researchers					
ph	9	15.52	ph	7	11.48
nitrogen	6	10.34	nitrogen	4	6.56
phosphorus	4	6.90	organic matter	3	4.92
moisture	3	5.17	phosphorus	3	4.92
electrical conductivity	2	3.45	electrical conductivity	2	3.28
nutrients	2	3.45	moisture	2	3.28
organicmatter	2	3.45	nutrient status	2	3.28
phosphorus buffering in	2	3.45	organic carbon	2	3.28
potassium	2	3.45	potassium	2	3.28
soil moisture	2	3.45	soil animals	2	3.28
temperature	2	3.45	texture	2	3.28

Table 2. Respondents were asked what the three most useful observations or tests of soil performance are that they use (famers), that they use to advise their clients (agronomists/consultants) or that they believe farmers currently use (researchers). They were also asked what, in an ideal world, they would like to use (farmers), like to use to advise their clients (agronomists/consultants) or would like to see farmers use (researchers). Counts and weighted averages are shown here, excluding answers that were only given once.

6.9 Summary of survey findings

This survey provided insight into what soil information, data, tools and indicators practitioners are using, or would like to use, to assess their soil's performance. It draws on the knowledge of individual farmers, agricultural practitioners and researchers. The complexity of the branching survey and some of the survey questions to categorise the respondents combined with the relatively small number of respondents means that only broad scale conclusions can be drawn. Once the analysis starts to break the responses into finer categories (e.g. farmers of a certain age in a particular farming system in a geographic location) the number of respondents becomes statistically insignificant. Nevertheless, the overall intention of the survey still holds in that there are useful observations that can be made about the more generalised results. There were 122 survey respondents, predominantly working within dryland grain, oilseed and pulse production as a primary farming. Industry representatives n = 8 and advisors and extension officers n = 12 were discounted and removed from the analysis in this section, due to low respondent rates. Comparisons were made using percentage responses within the roles of farmer (n = 46), agronomist/consultant (n = 36) and researchers (n = 20).

6.9.1 Main findings

Observations that could be used by the Soil CRC to guide the delivery of practical, real world tools and knowledge for on-farm soil management decisions include:

- Farmers and agronomists draw their data and information from a wide number of sources to make or advise on farming decisions. Soil moisture, chemistry, soil type, variability and structural information may be used as often as rainfall, temperature, seasonal forecasts, input costs and yield quantity and quality. The view of researchers broadly reflects the importance of this data or information to on-farm decisions making. From this sample size there is an indication that the most useful indicators of soil performance common between farmers, agronomists/consultants and researchers are moisture, organic matter, pH and major nutrients (phosphorus and nitrogen);
- Farmers and agronomist look back at their past soil information, observations and tests for their farms or client's farms more regularly (mostly yearly) than researchers look back on their data for research;
- Some information and data that agronomists and consultants are using to advise on management decisions may not be being used by farmers to make on-ground management decisions, or conversely farmers are using data and information not being provided by agronomists and consultants;
- Most farmers, consultants/agronomists and researchers source their soil information and data in-field;
- The internet, their own database, field days extension activities, paid advisors/consultants and farming/interest groups are sources of soil information and data for farmers, whilst very few respondents use mobile applications as a source;
- Whilst farmers and agronomists/consultants source soil information and data from research, this considerably less than accessed by researchers;
- Soil observations, soil physical and chemical tests are used as indicators of soil performance. In this survey, the use of these indicators ranged from between 55% (researchers using soil temperature) to 90% of respondents (researchers using pH and soil colour, texture and feel);

- Soil strength and soil contamination/toxicity are used to a lesser extent within all groups as an indicator of soil performance;
- Soil smell and taste is an indicator of soil performance is used more by farmers than agronomists and consultants, and even less so by researchers;
- EM38 and in field sensors are used to a lesser extent by farmers than by researchers and agronomists and consultants;
- Vegetation indicators are almost as useful an indicator of soil performance to farmers as soil chemical and soil physical properties;
- Whilst soil biology indicators are used to make management decisions, they are viewed as less useful indicators of soil performance on-farm relative to vegetation, soil chemical and soil physical indicators to farmers, researchers and agronomists/consultants. However the responses suggest some interesting practitioner viewpoints regarding soil biology:
  - Researchers may underestimate the number of farmers using worm and bug observations to judge soil performance;
  - Farmers use soil biological counts (worms and bugs) as an indicator of soil performance more than both researchers and agronomists/consultants;
  - Whilst agronomists/consultants advise on soil biology using DNA methods, few farmers use DNA methods as an indicator of soil performance and
  - The number of stakeholders that would *ideally* like to use these indicators is higher than those using biological indicators.

6.9.2 Insights for Soil CRC research and development

This report highlights challenges for the Soil CRC to embrace in the delivery of practical, real world tools and knowledge for on-farm soil management decisions through research and development:

- Determining exactly why, as seen here, some tests are used as measures of soil performance more than others, including how information on the test is sourced, how it is used to make management decisions, whether there is a stronger understanding of the relationship to soil performance for certain indicators, test cost/availability, interpretability and industry specific uses;
- Weather, production, machinery performance and agribusiness decisions is as important in making management decisions as soil data and information highlighting value in multi system approaches;
- Understanding how farmers and agronomists look back on their own databases and records to make or advise on soil management decisions;
- Understanding why more technology dependent such as EM38, on-farm sensor and microbial DNA technologies seem to have a lower usage by farmers than agronomists/consultants and researchers including understanding cost-benefit, routes to market, links with soil performance and extension support available;
- Consideration of how indicators of soil performance used by farmers more than other practitioners could add value to research and development outputs, for example vegetation indicators and more sensory measures of soil performance such as soil smell and taste and worm and soil bug observations;
- Whether biological indicators can be strengthened as useful indicators of soil performance

and

- The communication of soil data and information beyond the traditional channels of researchers through farmer-used channels including the internet, field days extension activities, paid advisors/consultants and farming/interest groups.

6.10 Works cited in this section

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7 SOIL DATA AND DATA MANAGEMENT

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7.1 Introduction

This component of the Scoping Review Project 2.1.01 considers the following items:

- the current availability of soils data and the usefulness and limitations of this data,
- a review of the current initiatives (international, national, state and regional) that are doing the same thing,
- models of current soils and sensor data collection, storage, management, etc.,
- conceptual models for interoperable (on-the-fly) data federation, manipulation, modelling and visualisation, and
- overcoming the barriers, e.g. capability, value proposition, IP management, business cases, data longevity, etc.

7.2 Soil data availability

In Australia, soil data availability has changed considerably over the past three decades. Up until the late 1980s State government agencies (departments of agriculture or equivalents), were the main custodians of soil data repositories. These repositories were built up over the previous half-century or more when governments undertook soil surveys and soil series mapping for agriculture or land capability assessments (e.g. Leeper et al., 1936, Downes, 1949, Skene, 1963, Pitt, 1981, etc.). With the widespread adoption of economic liberalisation policies from the late 1980s and the move to smaller governments, the functions of the public service have changed, generally resulting in less collection of soils data.

Concurrently, the past three decades have seen the move into the New Digital Age (Schmidt and Cohen, 2013) and Era of Big Data (Mayer-Schönberger and Cukier, 2013), resulting in more data being collected on the Earth's landscapes than at any previous time in history. Hence, the volume of digital data in agriculture has grown exponentially, much of it collected by sensors (Keogh and Henry, 2016, Stubbs, 2016). In addition, data availability has vastly improved as governments in many countries adopt open data policies, including Australia (Productivity Commission, 2016, Welle Donker and van Loenen, 2017).

However, much of the soils data, including the new digital data, is being collected in the private sector. As an example, Precision Agriculture P/L, a precision agriculture service provider based in Ballarat, Victoria, have collected over 90,000 soil tests in the past two years (2016-2017), all spatially located via an accurate global positioning system (Ben Fleay, 2018 pers comm).

The issue of agricultural data supply, big data and its transformation into knowledge was recently reviewed by an international team of researchers, and published as a series of papers that investigated the *'Next Generation Data, Models and Knowledge Products'* (Antle et al., 2017b). Their research generally concluded that:

- Current agricultural decision models are direct descendants of research undertaken three or four decades ago, and do not fully exploit the potential of the new digital age (in both their technology and data).
- Historical agricultural systems models are usually limited by their domain and vary widely depending on farm system, scale, purpose and research motivation. Recent trends towards multidisciplinary collaboration and eResearch has set the stage for the next generation of databases, models, knowledge products and decision tools.
- Current common limitations in system models for decision support are: 1) data scarcity (quantity, resolution and quality) and 2) inadequate knowledge systems to effectively communicate the results to the end-user. These limitations are greater obstacles to use of the tools than gaps in theory or technology.
- The greatest data challenge is to obtain reliable data both for on-farm management decision making and policy decision making. Seamless automated data collection (from both public and private sources), data interoperability and the federation of multidisciplinary data (plant, animal, soil, land, climate, weather, machinery, farm business, economics, marketing, trade, etc.) are required, preferably utilising open cloud-based systems for data storage and open standards for data exchange.
- A logical approach is linking interoperable data federation and model development (a "pre-competitive space") to commercial development of applications, products and services (a "competitive space") through private-public partnerships (Figure 1).
- Virtually all stakeholders want access to model outputs, rather than the models. Hence tools are required to serve model outputs and provide analytical capability to visualise and interpret the outputs for decision making.

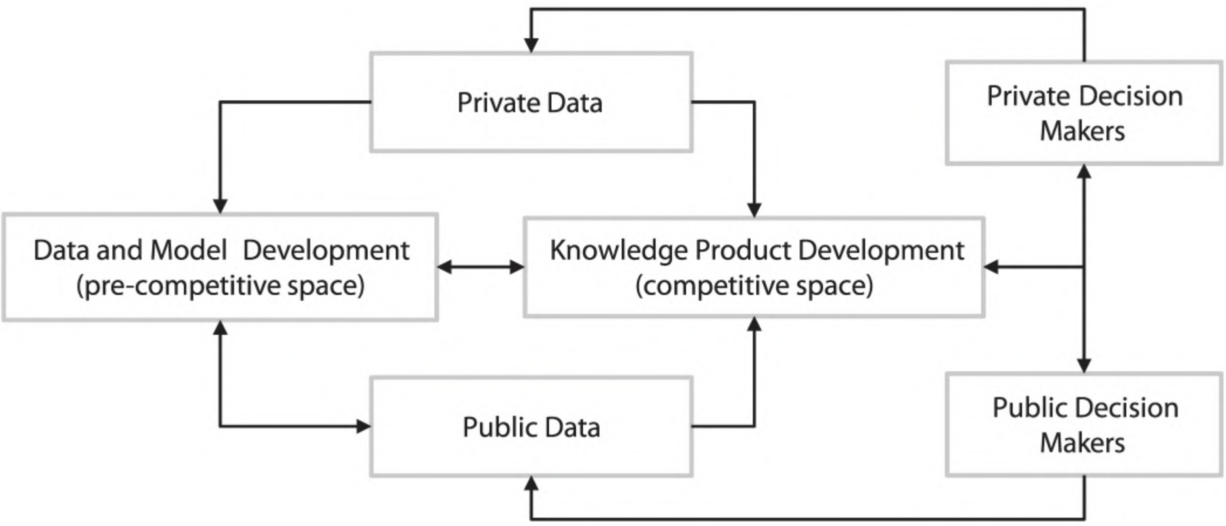

Figure 1. Logical linkages in making agricultural data more available (Antle et al., 2017a).

However, collecting more data and increasing its availability is only part of the solution to the major challenges, as there are limitations in how to transform this data into improved understanding of soil science and agricultural productivity. These limitations are largely due to the distributed custodianship and heterogeneity of soil data, making it difficult for the end-user to discover, access and harmonize the data (Dahlhaus et al., 2017).

7.3 Soil data systems

Although advances in farm technology have led to a huge increase in the collection of soil and related agricultural data by farmers, agronomists, researchers and industry, the potential to use these richer combined data sets in decision support systems remains limited. These data are not always accessible or interoperable, and therefore not able to be easily integrated, especially with datasets from other domains (such as weather, climate, water, transport, commodity markets, etc.). Seamless automated data collection (from both public and private sources), data interoperability and the federation of soil data is required, preferably utilising open cloud-based systems for data storage and open standards for data exchange.

Data interoperability is usually specified as a series of levels that provide increasing complexity (Brodaric and Gahegan, 2006), viz:

- **technical interoperability** requiring the use of communication protocols such as HTTP (hypertext transfer protocol);
- **syntactic interoperability** achieved through the use of common data formats such as XML (extensible mark-up language);
- **schematic interoperability** requiring the adoption and use of an agreed common information exchange models; and
- **semantic interoperability** achieved through the use of common vocabularies.

A comprehensive discussion by Box et al. (2015) outlines different models for interoperable spatial data frameworks (Figure 2), which include:

1. anarchic (or point to point) – direct producer and user interaction;
2. centralised - centralised production of data by a single organisation;
3. aggregated - aggregation and integration of data by an intermediary;
4. brokered - centralised broker transforms heterogeneous supplied data to a common form;
5. federated - federated data supply using common community models.

The choice of framework and level of interoperability are linked, with an increasing proportion of effort required by the data provider as the sophistication increases (from anarchic to federated). However the effort for each option is proportioned between different actors in the data supply chain (Figure 3), with the relative cost shifting between the provider, intermediary and user (Box et al., 2015). In other words, the easiest solution for the data provider is to simply supply their data 'as is' (i.e. anarchic model). In that case, the consumer (user) has the task of understanding the meaning of the data fields and values, integrating and harmonising data from different users, and storing the data for their bespoke use. At the other end (i.e. federated model), the large proportion of effort is borne by the providers, who collaboratively develop the data stewardship and governance model, the community data schema, map their data to the model and stand up web services to deliver the data. The consumer (user) then gets standardised data supplied with explicit metadata via standardised web services (on-the-fly), ensuring data currency.

Naturally, the costs also vary according to the number of providers and users. For each additional user and provider joining the system, the costs for the anarchic model increases linearly, whereas for the brokered and federated models, the costs for each additional user remain the same, and the cost for each additional provider proportionally reduce.

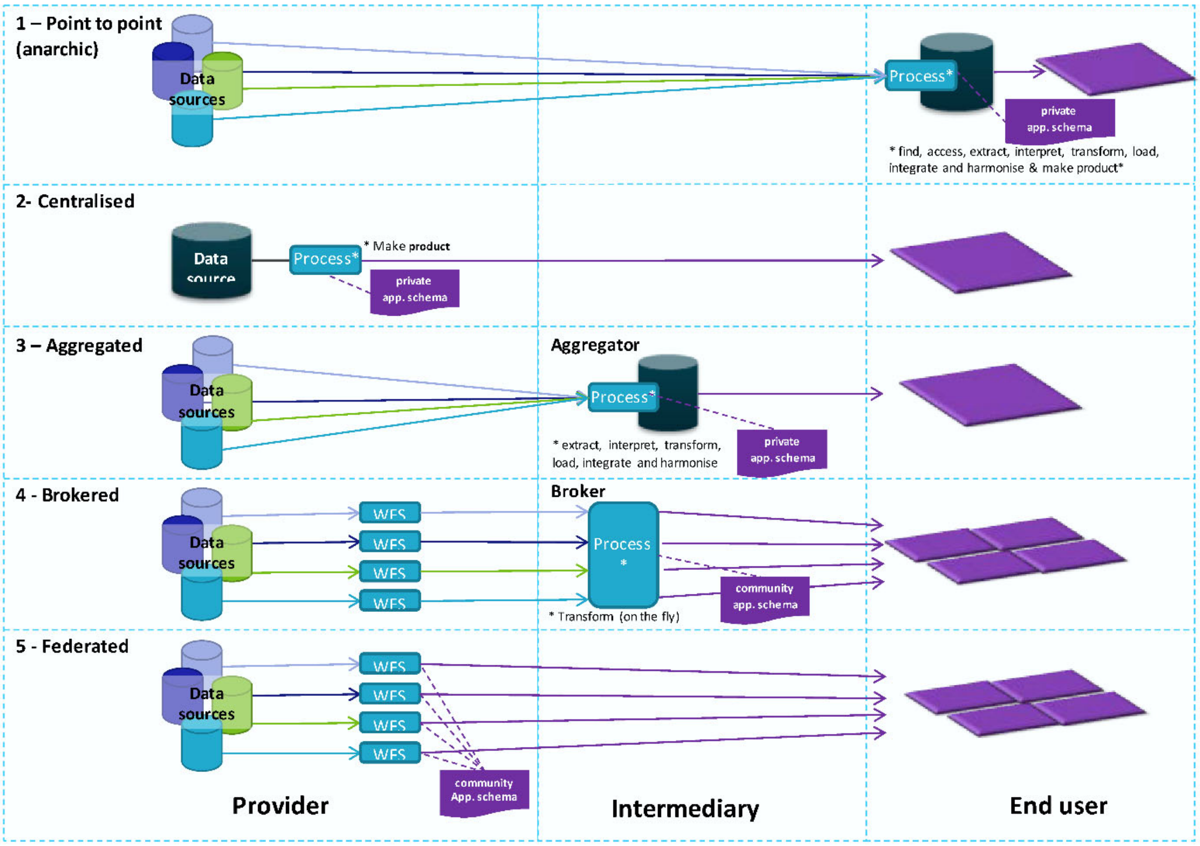

Figure 2. Geospatial data supply chains (source: Box et al., 2015)

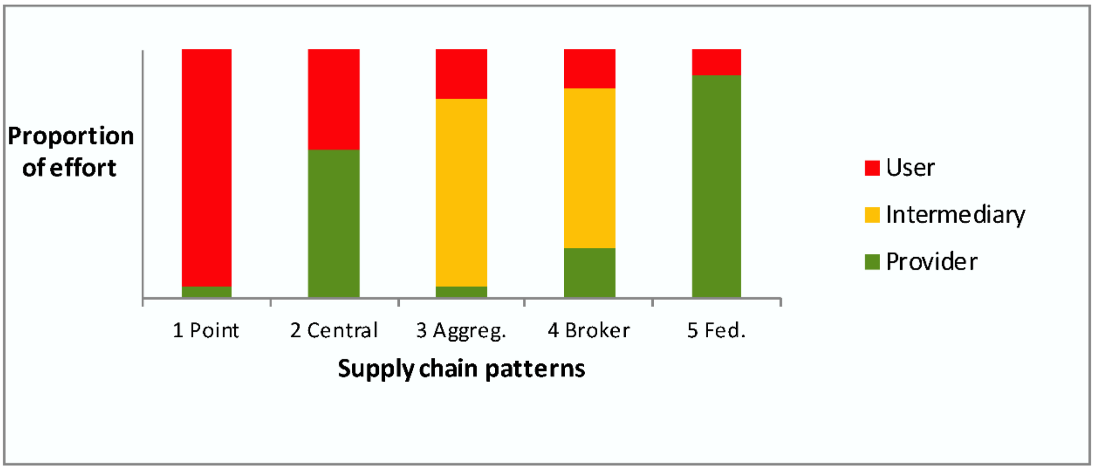

Figure 3. Relative effort (cost) of data for each supply chain (source: Box et al., 2015)

As a result of the exponential increase in the availability of global soils data, the capability of technology to deliver those data, and the desire to use the data to generate useful products for end-users of soils data, there are a number of initiatives that have emerged in recent years that are relevant to this Scoping Study.

7.3.1 International initiatives

The Global Soil Partnership (GSP) is an initiative of the Food and Agriculture Organisation (FAO) of the United Nations established in December 2012 with the key objective "to improve the governance and promote sustainable management of soils." (FAO, 2018a). One of the intended outputs of the GSP is the establishment of national soil information systems. The GSP is organised into five 'pillars of action' with GSP Pillar 4: *Enhance the quantity and quality of soil data and information: data collection (generation), analysis, validation, reporting, monitoring and integration with other disciplines* and GSP Pillar 5: *Harmonization of methods, measurements and indicator for the sustainable management and protection of soil resources* being of particular relevance to this review.

GSP Pillar 4, chaired by Neil McKenzie (CSIRO Canberra), has made some progress in the production of global soil maps, most notably the Global Soil Organic Carbon map - GSOCmap (FAO, 2018b). The interactive map is a collaboration of 110 countries, has statistic calculations, can be cropped and downloaded, and accessed using web services. Where Pillar 4 deals with data availability, GSP Pillar 5, chaired by Rainer Baritz (FAO), deals with data harmonisation and standardisation.

The GSP selected ISRIC – World Soil Information to host their Soil Data Facility, developed under Pillar 4, in July 2017 (ISRIC, 2018). ISRIC hosts a number of soil portals that allow the exploration and discovery of global soil data, including the World Soil Information Service (WoSIS), with over 100,000 geo-referenced sites with over five million soil records; a collection of over 8,000 digitised maps with 15,000 reports and books; the world soils and terrain database program (SOTER); the World virtual soil museum, and much more

The Global Open Data for Agriculture and Nutrition (GODAN) supports a Soil Data Working Group to promote the sharing of soil-related data through web services (GODAN, 2018). The Working Group was established in Barcelona in April 2018 and has the vision "to become the key driver for building a soil e-infrastructure looking at various aspects of the soil data life cycle."

The Agricultural Data Interest Group (IGAD) of the Research Data Alliance (RDA), was formed in 2013, and has since developed interoperable data standards for wheat, rice, agrisemantics and on-farm data (IGAD, 2018). The RDA is sponsored by the European Commission, the US National Science Foundation and other US agencies, and the Australian Government. Although attempts have been made by IGAD to establish soils standards, there has been little progress to date.

The European INSPIRE system is widely recognised as leading the world in in the use of model driven approaches to interoperable delivery of environmental data, including soils data (van Liedekerke and Panagos, 2014). The system supports the European Union's Common Agricultural Policy (CAP), including the new legal framework to promote agricultural practices beneficial for the climate and environment (Tóth and Kučas, 2016).

The International Organisation for Standardisation (ISO) has also been working towards a standard for Soil quality – Digital exchange of soil-related data (ISO, 2018). The standard – ISO 28258:2013 – proposes syntactic interoperability through the development of an XML specifications, which references other ISO standards for soil quality. The standard is currently under review.

International standards for geospatial data that are widely adopted are those of the Open Geospatial Consortium (OGC). The OGC is a not-for-profit organisation with around 520 members from around the globe who contribute to the development of community standards for the exchange of spatial data in every conceivable field (OGC, 2018). The OGC established an Agriculture Domain Working Group (AgDWG) with a mission to develop new geospatial interoperability standards, including for soils data (OGC, 2017). The existing OGC standards for web-delivery of interoperable data are already widely used in agriculture, such as the Sensor Web Enablement suite of standards, including for soils data (e.g. Phillips et al., 2014).

The International Union of Soil Science (IUSS) Soil Information Systems Working Group (WGSIS), chaired by Peter Wilson (CSIRO Canberra), has the longer-term goal of maximising soil data availability by developing soil data standards for interoperable soil data exchange. The initiative, commenced in Berlin in June 2011, intended to bring together the various global community standards (e.g. INSPIRE, GEOSS, ISO, OGC, EGU) into a common SoilML (soil markup language) data schema.

7.3.2 The international Soil Data Interoperability Experiment

The international soil data interoperability experiment (Ritchie et al., 2016, Schaap et al., 2017) has been the only tangible result to date that demonstrates true interoperability of international soils data. The experiment (known as the Soil ML IE), organised by the OGC AgDWG and the IUSS WGSIS, was demonstrated in December 2015 (Figure 4). The experiment illustrated dynamic access to soil databases, in New Zealand, Australia, and The Netherlands (ISRIC).

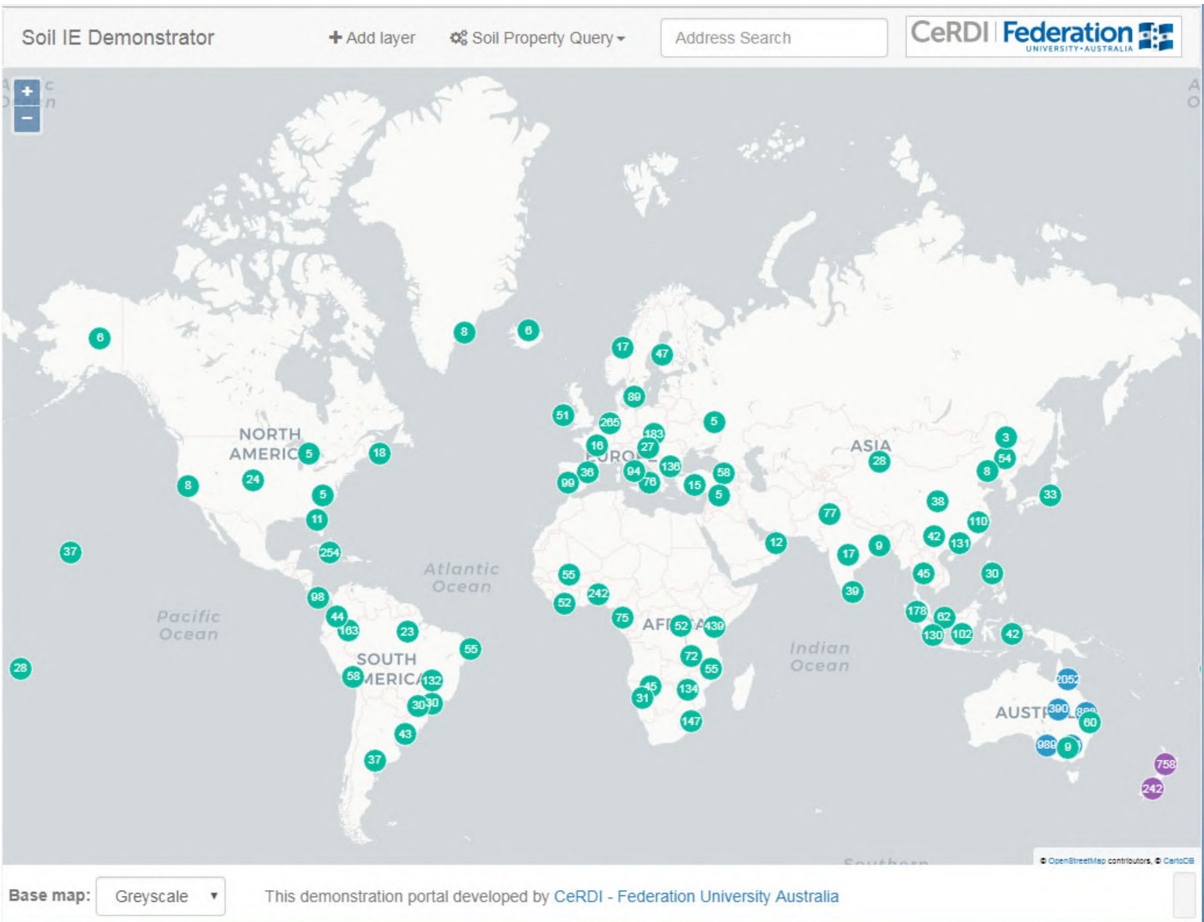

Figure 4. The portal illustrating the international soil data interoperability experiment.

The SoilML IE was led by Landcare Research and Horizons Regional Council in New Zealand and included CSIRO and Federation University in Australia, ISRIC (The Netherlands), US Department of Agriculture and US Geological Survey, and the European Commission. The experiment deployed services and web clients that demonstrated the delivery and integration of soil sampling and sensor data from across the globe. One of the most exciting features was the ability to view current data from disparate databases in different countries and then send it to a web processing service (hosted by ISRIC) to be modelled by pedotransfer functions (contributed by a colleague in Italy), with the modelled data also delivered in standard formats. This ability to dynamically access and model soil data was an international first.

7.3.3 National initiatives

At the national level, there are a number of soil data sets that are open:

Australian Soil Resource Information System (ASRIS) is probably the most well-known. ASRIS claims to provide online access to 'the best available soil and land resource information in a consistent format across the country' (ASRIS, 2018). The data is categorised in hierarchal tiers, from Level 1 at continental scale to Level 7 at site scale.

Soil and Landscape Grid of Australia (SLGA) is a continental scale digital soil map of Australia's soil and landscape attributes (Grundy et al., 2015). The SLGA provides web services of open data soil attribute and landscape information, with their modelled uncertainty, at 90 x 90 metre cells. Soil attributes are: organic carbon content; available water capacity; clay content; depth to rock; depth of soil; pH; silt content; sand content; bulk density; total nitrogen content; and total phosphorus content. Landscape attributes are: Solar radiation; multi-resolution valley bottom flatness (MrVBF); slope, relief, curvature and topographic position; topographic wetness index; and aspect. The grids are available from the Terrestrial Ecosystem Research Network (TERN) portal.

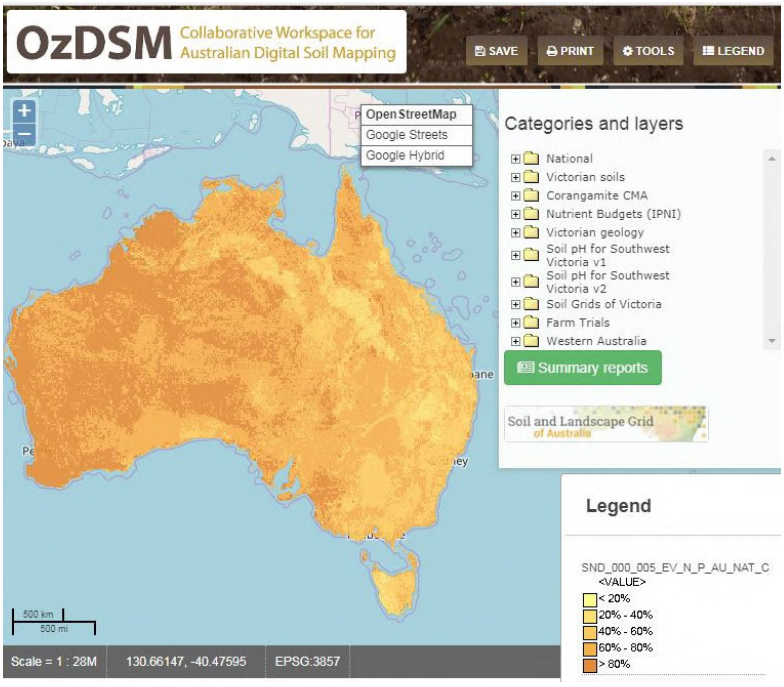

Figure 5. A grid from the SLGA (sand at 0-5cm) displayed in the OzDSM portal.

The CSIRO National Soil Archive is located in Canberra and contains more than 70,000 soil specimens collected from 9,500 sites across Australia (Figure 6). The mission of the CSIRO National Archive is to provide facilities and protocols for conserving the long-term scientific value of soil specimens and associated soil data, and to make these specimens and their data available for public research, both now and into the future (ACLEP, 2018).

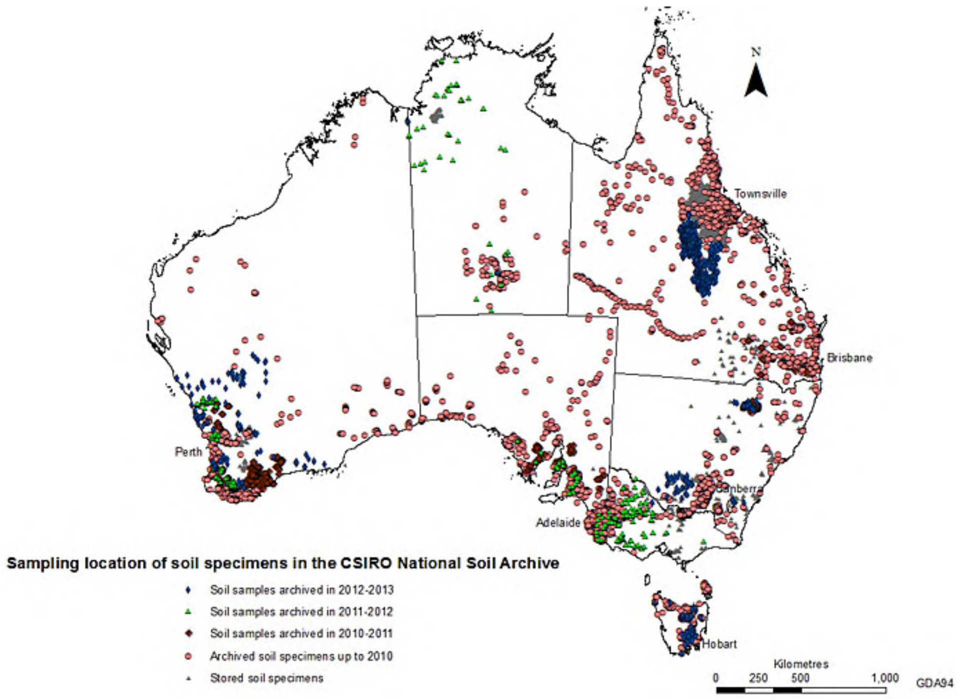

Figure 6. Sampling locations of the soil specimens in the CSIRO National Soil Archive

Australian Collaborative Land Evaluation Program (ACLEP) provides a focus for the national delivery of soil and landscape data. ACLEP is funded by CSIRO and the Australian Government Department of Agriculture and Water Resources, with strategic direction from the National Committee on Soil and Terrain (NCST). States and territories provide significant resources in support of ACLEP projects and activities. ACLEP manages several activities including ASRIS, the National Soil Archive, SLGA, and digital soil mapping.

More informal soils data are available through the Australian Government open data portal (data.gov.au) and the Australian National Data Service (ANDS) Research Data Australia (RDA) portal. At the time of writing, there were 393 soil datasets on data.gov.au, varying widely from economic limitations, soil condition, soil nutrient status, land use potential and modelled pre-1788 properties to name a few. The RDA portal shows 2740 records for soil data sets, which includes all of those on data.gov.au plus many from the CSIRO, Universities and State agencies. Almost all data sets are spatial GIS files or grids of soil parameters, with hundreds of maps and site-scale studies.

Other portals include OzDSM, a collaborative workspace for Australian Digital Soil Mapping (www.ozdsm.com.au) which consumes interoperable data from SLGA and many other sources.

Across the Tasman, the New Zealand National Soils Database contains descriptions of around 1500 soil profiles together with analytical data on their chemical, physical and mineralogical characteristics (MWLR, 2018). Associated soil data includes S-map Online which allows free access to soil maps at 1:50,000 scale for around 56% of New Zealand; SINDI – Soil Quality Indicators is a web-based tool to assist interpretation of soil quality under a particular land use; and New Zealand Land Resource Inventory – Soil, one of the five physical factors of land resource assessment (the others being rock, slope, erosion, and vegetation cover).

7.3.4 State initiatives

Each Australian State and Territory has also adopted open data policies, which includes soil data. An exhaustive review of these has not been attempted, but the more accessible open data sources include:

Victoria:

The Victoria Resources Online (VRO) portal (vro.agriculture.vic.gov.au) is an excellent information portal providing detailed soils data and resources. Among the available resources is the soil and land survey directory that provides access to legacy government reports. The VRO currently does not support data downloads or interoperable web services.

The Victorian Open Data Directory (data.vic.gov.au) lists 31 datasets for 'soil', including the Victorian Land Use Information System (VLUIS) legacy layers and various soil maps. These data are freely downloadable in various formats. The Victorian Soil Information System (VSIS) has not yet been made openly available.

New South Wales:

The eSpade portal (www.environment.nsw.gov.au/eSpade2WebApp) is a comprehensive web mapping portal to access a wide variety of maps and over 70,000 individual soil observations. The portal allows limited downloads in keyhole markup language (KML). The portal connects to both the eDIRT data collection system and SALIS the NSW Soil and Land Information System (both closed (login only) systems).

The Data.NSW open data portal (data.nsw.gov.au) shows 245 results for 'soil', 230 of which are those sourced from the abovementioned Office of Environment and Heritage (OEH) data.

Tasmania:

The List is the equivalent open data portal in Tasmania (www.thelist.tas.gov.au) that shows 61 results for 'soil'. Digitised soil maps are also available from the Department of Primary Industries, Parks, Water and Environment (DPIPWE).

Queensland:

The Queensland Government has data from around 150 soil and land resources mapping projects in the Soil and Land Information (SALI) database, accessible through the open data portal (data.qld.gov.au) where 27 datasets are listed; the Queensland Spatial Catalogue. Showing 280 results (qldspatial.information.qld.gov.au), and the Queensland Globe (qldglobe.information.qld.gov.au).

South Australia:

The South Australian Government makes soils data available through a variety of portals, including their Nature maps portal (spatialwebapps.environment.sa.gov.au/naturemaps) and the South Australian Government Data Directory (data.sa.gov.au) where 102 datasets are available.

Western Australia

Western Australian soils data is available through the open data portal (data.wa.gov.au) showing 63 datasets for 'soil'. The Department of Primary Industries and Regional Development (DPIRD) also has a number of online tools, including soil tools (MySoil and Soil water tool)

Northern Territory and Australian Capital Territory

Both territories have soil data available under their open data portals. In the Northern

Territory, the NR Maps (nrmaps.nt.gov.au) provides limited soils data. In the ACT, soils is available either through the open data portal (www.data.act.gov.au) or NSW portal.

7.3.5 Regional initiatives

The development of soil databases at the regional scale is not uncommon, although few are delivering open data, so most remain inaccessible to the public. Regional databases are typically established as standalone instances by natural resource management authorities, municipalities and agricultural industry groups. Rare examples such as the Soil Health Knowledge Base developed in the Corangamite region, Victoria, federate open data, community contributed data, and farmer contributed data (Dahlhaus et al., 2017, Dahlhaus et al., 2018). In the Corangamite portal, the detailed private data is accessible to the data custodian, but not the public, who can nevertheless access the deidentified and averaged private data aggregated with the public data to explore soil properties in the landscapes. The Soil Health Knowledge Base is freely accessible at www.ccmaknowledgebase.vic.gov.au/soilhealth.

7.3.6 Research sector initiatives

Few of the agricultural Research Development Corporations (RDCs) have databases that include soil data, such as the Grains RDC Online Farm Trials portal (www.farmtrials.com.au). However an initiative of the RDCs is the ***Accelerating Precision Agriculture to Decision Agriculture (P2D)*** project which has three aims (CRDC, 2018):

- Facilitating the development of digital technology in Australian agriculture.
- Fostering the establishment of appropriate legal frameworks, data systems and access to critical datasets.
- Identifying the data communications systems required to deliver the benefits of digital agriculture to the Australia farm and agribusiness sectors.

The P2D project, funded by the Rural R&D for Profit programme involves all the RDCs. After an extensive evaluation in the first round of funding, the project made 13 recommendations:

1. Develop a Data Management Policy for Australian Digital Agriculture.
2. Develop a voluntary Data Management Code of Practice and a Data Management Certification or Accreditation Scheme.
3. Policy and investment to improve telecommunications to farms and rural businesses.
4. New investment models including public/private investment.
5. RDC's develop Digital Agriculture Strategy's and implementation roadmap.
6. Big Data Reference Architecture and Data Management Implementation Plan.
7. Establish, review and refine foundational data sets.
8. Establish a Digital Agriculture Taskforce for Australia (DATA) headed by the Chief Digital Agricultural Officer – to deliver outcomes.
9. Establish a Digital Agriculture Taskforce for Australia Working Group (DATAWG) – to provide guidance.
10. Provide education and capacity building to increase digital literacy in the agricultural sector.
11. Establish baseline patterns of data usage and a national mobile network coverage (data speed and volume) database.

12. Digitise and automate data collection including for regulatory compliance activities.
13. Execute a cross Industry Survey every three years to identify producers' needs and issues in digital agriculture.

The next step is that all RDCs co-invest in the recommendations with the Australian Government. Support the establishment of Digital Agriculture Taskforce for Australia (DATA) and Working Group (DATAWG) (Leonard et al., 2017).

The 2016 National Research Infrastructure for Australia (NCRIS) roadmap aligned the work being undertaken by ANDS, the National eResearch Collaboration Tools and Resources (Nectar) and the Research Data Services (RDS) entities, into a single ***National Research Data Cloud (NRDC)***: to *"Enhance existing capability through the integration of existing capability – ANDS, NeCTAR and RDS to establish an integrated data-intensive infrastructure system, incorporating physical infrastructure, policies, data, software, tools and support for researchers."* (DET, 2017). A component in the NCRIS roadmap is to support the National Science and Research Priority focus area of soil and water, and the Australian Agricultural Research Data Cloud project is in development.

In the international peer-reviewed literature, there are dozens of examples of the development of syntactic, schematic and semantic standards for agricultural data interoperability. These include suggested standards for Precision Agriculture Markup Language (PAML) (e.g. Murakami et al., 2007) and Farm Markup Language (FarmML) (McAllister et al., 2013). Arguably the most developed are those from Wageningen University in The Netherlands, that resulted in rmAgro, a model suite that includes a domain reference model (drmAgro) that includes crop models (drmCrop), animals (drmAnimal), etc., etc. (Goense, 2017). Despite all of the research and development work to date, none have emerged specifically for soils.

7.3.7 Private sector initiatives

Soil databases in the private sector are prolific, typically assembled by agronomists, agricultural consultants, soil testing services and fertiliser suppliers, for example. Increasingly agricultural industry groups and grower groups are also exploring data collections, including data co-operatives (Box et al., 2017, Guthrie, 2017). In some cases, soils data is made available online (e.g. Southern Farming System's soil moisture probes probetrax.sfs.org.au) with subscriber logins for access to more detailed data. In other cases, data sharing websites are operated by third parties on behalf of grower groups (e.g. Data Farmer www.datafarmer.com.au) to allow data uploads and data sharing subject to the data custodian's consent.

Private data exchanges are also growing in number, such as the North American AgGateway (www.aggateway.org), a not-for-profit consortium of over 200 agribusinesses. The vision of AgGateway is to provide a trusted forum for developing resources for their members to realise the benefits of digital agriculture at the global scale. AgGateway has invested a considerable effort in developing data standards, including XML schemas.

Data Linker (www.datalinker.org.nz), was developed by Rezare Systems Ltd. (New Zealand) for DairyNZ and Beef+Lamb NZ, who are equal shareholders in DataLinker Ltd, an independent company operating and servicing the website. The portal is a fee-for-service model that allows secure data uploads and standardised data sharing, subject to the data custodian's rules.

Other examples abound, but are generally variations of Platform as a Service (PaaS) models, such as AgX (www.agxplatform.com), that provide the platform for users of different agricultural applications and software packages to seamlessly share data across their disparate software tools.

7.4 Data governance frameworks

Although the interoperability technologies and standards can be established, as demonstrated by the SoilML IE for example, there are some considerable challenges in brokering the arrangements for data supplies, establishing the metadata (especially in relation to data quality), mapping those data to current standards, and drafting new standards where required. This need to develop social architectures (cf: system architectures) has, to some extent, also been confirmed in the recommendations of the P2D project.

The publication and global adoption of the FAIR principles: Findable, Accessible, Interoperable and Reusable, for scientific data (Wilkinson et al., 2016) created the potential to develop data stewardship and governance frameworks for soils data. The FAIR principles are:

- *Findable*: Data and metadata are easy to find by both humans and computers. Machine readable metadata is essential for automatic discovery of relevant datasets and services.
- *Accessible*: Limitations on the use of data, and protocols for querying or copying data are made explicit for both humans and machines.
- *Interoperable*: The computer can interpret the data, so that they can be automatically combined with other data.
- *Reusable*: Data and metadata are sufficiently well described for both humans and computers, so that they can be replicated or combined in future research.

Other components of a governance framework may include the Open Archival Information System (OAIS) reference model that identifies mandatory requirements (CCSDS, 2012); the ICSU World Data System “Core Trustworthy Data Repositories Requirements” (ICSU, 2016); and the Creative Commons licensing system (creativecommons.org).

Some examples of agricultural data stewardship models exist, such as the New Zealand Farm Data Code of Practice (Farm Data Accreditation Ltd, 2015) that was established to support the DataLinker program and covers the rights to data, data security and access, and data sovereignty. However, there are very few (if any) existing agricultural data stewardship and governance models that are comprehensive (in that they cover data contributions from any source), and none specifically focused on soil data.

7.5 Conclusions

From the above review, the following conclusions can be drawn:

1. There is more soils data being collected that at any previous time in history, much of it through the adoption of precision agriculture (e.g. grid sampling), sensor technologies (e.g. soil moisture sensors, spectroscopy) and digital agriculture in general (e.g. machinery performance). The soils data is stored in a variety of databases on disparate computer systems, in both the private and public sectors, with an increasing volume in the private sector.
2. It is recognised at all levels, from international to individual farms, that there would be benefits in bringing these data together in a seamless and standardised way for improved decision support. The technological systems architecture to do this has been proven at the international level, but the social architecture is still lacking.
3. There are initiatives at all scales, from the international to the regional, that have developed soils data interoperability and standards, but a globally unified standard is yet to emerge.

Almost all the current developments have been in either the public sector, or the private sector, but not across both.

4. Having many disparate data systems does not present a barrier to interoperable soil data federation, provided that the data custodians agree to provision their data. Therefore an agreed data stewardship and governance model would be required to make data FAIR: findable, accessible, interoperable and reusable.
5. There are numerous published models that can be adapted and adopted to interoperably federate soils data. These include three key components: a) the public-private data model conceptualised by Antle et al. (2017b), b) the systems architecture options by Box et al. (2015), and c) the FAIR Principles for scientific data Wilkinson et al. (2016). By adopting these conceptual models, a soil data federation could be achieved.

7.5.1 Opportunities for the Soil CRC

Being an independent entity, the Soil CRC is in a unique position to establish an Australian soil data portal that would interoperably federate data from both public and private sources. In that respect it could occupy a role in the 'pre competitive space' of the model conceptualised by Antle et al. (2017b), and supply federated, harmonised and standardised soil data and modelled data to the 'competitive space' to greatly improve Australia's agricultural profitability.

The federated data could include data from research programs funded by the Soil CRC, open data (typically government and research data), data contributed by the Soil CRC members (e.g. grower groups, farmer data co-operatives, research organisations), and industry contributed data. Access to these data would greatly benefit both the research and industry partners of the Soil CRC by ensuring that all research would be built on the best available and most current data sets available.

An initial step in establishing such a data federation would require agreement on a data stewardship and governance model that would allow FAIR access to the data, within the rules agreed by the data custodians. Once that had been established, developing the systems and technologies would follow the international models, built on open source software and open standards. The collection and input of data would need to be made as seamless as possible for the contributors, who would remain custodians and curators of their own data sets.

A data portal is the logical initial step in supporting many of the other Soil CRC programs, such as Program 1 (sub program 2), Program 2 (sub program 4) and Program 4 (sub program 3).

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8 DISCUSSION

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8.1 Soil Performance

Throughout this review the terms “soil health”, “soil quality”, “soil function” and “soil performance” have been used somewhat synonymously. While these terms are not strictly equivalent, the review has not suggested a clear view on how to determine if a soil is performing well or not, or indeed, where on the continuum of performance a particular soil type might sit against another soil type, perhaps of completely different origin and geochemistry. The debate between the exact meaning of the terms ‘soil health’ and ‘soil quality’ is one that continues to occur (Doran and Parkin 1994; Bennett and Cattle 2013, 2014), but a more important point is that it is possible for a given soil type to be of good health, but actually poor quality soil under the various definitions of these terms. Consider a soil type that has relatively poor capability for contributing to productivity e.g., a leached posodol or a sodic soil, but is currently in its natural condition without human influence. Under soil health we would categorise this as a healthy, in reference to itself and other soils of that type, and under soil quality we may consider it to be of poor quality as its production level is low. In essence, it is both the condition and the capability of the soil that defines its contribution.

In determining soil performance, it has been suggested that this is indeed a function of a soils capability and its condition (McBratney et al. 2014), whereby:

$$performance = capability + condition$$

where capability and condition are defined as (McBratney et al. 2014):

Capability: The capability of any given soil refers to its potential functionality, and historically came out of work on agricultural development and land use, but it can be applied more widely. The question that capability can answer is, ‘What functions can this soil be expected to perform, and in doing so what can it produce?’ To answer this question it is equally important to understand the soil's capability in the context of its own reference state.

Condition: The condition of the soil is concerned with the current state of the soil and refers to the shift in capability compared to the reference state. The concept of soil condition strengthened in the 1990s and the current vernacular would refer to soil condition as ‘soil health’ (Karlen et al., 1997). However there is little value in talking about the health of any given soil, unless there is an understanding of how ‘healthy’ it can actually be. Unlike capability, the condition of a soil is contemporary and is measured on a short-term management time scale.

The use of this definition of performance goes beyond a discussion of semantics between soil health, discussion or function, and adds a further dimension of land suitability to the definition. If we consider the issue of urban encroachment on agricultural land. Focusing on just soil health or soil quality and their indicators does not directly address the problem of urban encroachment into primary production land. If a soil is healthy/high quality, or the reverse, does not affect the ability to build an urban precinct on it. On the other hand, if this urban precinct is built, it will have some effect on the rest of land that is still in production. The question then is, if the precinct had been built on poorer health/lower quality land would this have had a different effect than if it were built on the healthy/high quality land? On this basis, soil performance as a function of soil condition and soil capability transcends a simple measure, and provides a means with which to make these decisions well informed, not just on the productive land in the region, but on a larger scale and across mores aspects (e.g. ecosystem services).

The Soil CRC needs an agreed basis on which to define performance, irrespective of the terminology used. It will be important to note that some soils have low capability to produce e.g. Western Australian sands, but may already be performing in an optimised fashion, or still have capability to be optimised. Therefore, in considering the various indicators, as has been recommended earlier in the review, it is likely that different soil types will have different indicator requirements for the measurement/assessment of soil condition and soil capability, or some other variant of these terms. For this reason, it is recommended that the soil performance metric be based on both soil condition and soil capability.

8.2 Combined indicators of soil performance

From this Scoping Study there are several clear points that emerge. The first and most obvious is that although it may be convenient to categorise soil indicators into physical, chemical and biological, their separation is not holistic and since they are part of a holistic system in which the farmer or scientist operates we cannot consider one without the other.

The use of soil indicators is based on the scientific method of observation and gathering empirical and measurable evidence to hypothesise soil performance. By its nature, the scientific method of observation and experimentation is reductionist in both its subject and scale. However, the limits to reductionism are met within complex systems that are inherently irreducible and require holistic thinking to understand them. Measuring and monitoring soil performance is challenging due to the inherent temporal and spatial variability of soil and the variety of functions it delivers (Gregorich & Carter 1997; Kibblewhite et al. 2008). In any landscape, the variability and variety of soil properties means that there are numerous potential measures that can be used to indicate soil performance, but the selection of indicators is specific to the needs of the individual end-users and the context of the systems (natural or anthropogenic) in which they are applied.

Soil indicator research is more suited to systems thinking, which is founded in the belief that the components of a system can be best understood in the context of the whole, rather than in isolation (Checkland 1981; Skyttner 2006). In other words, the only means to understand why particular soil properties would indicate systematic processes is to understand their relationship to the entirety of the system, including the components outside of the domain of science. In its application to dynamic systems (like agriculture), Mella (2008) applies five 'rules' to systems thinking: 1) the necessity to observe both the whole and its interdependent parts (seeing both the forest and the trees); 2) the necessity to see the variables beyond those considered significant, as well as their temporal variations; 3) understanding the causes of the variation in all the observed variables; 4) connecting the variables in a chain of causal relations that loops the variations into an interacting system; and 5) specifying the boundaries (both external and internal) of the system under study.

In the context of the above, it is apparent that current soil indicators are:

- System specific. Soil performance indicators are specific to types of agricultural systems, such as irrigated horticulture, dryland broad acre cropping systems, and dairying. At a regional scale, soil health indicators are also specific to natural systems, such as forests, ephemeral wetlands and coastal mangrove systems.

- Time specific. Indicator values can vary on daily scales (e.g. soil moisture), seasonal scales (e.g. soil biology), annual scales (e.g. soil carbon), decadal scales (e.g. soil structure) and beyond (e.g. soil profiles).
- Landscape specific. Soil performance is spatially variable from the paddock scale to the continental scale. A high performing soil in the sand belt of Western Australian might be considers a low performing soil in comparison with a degraded volcanic plains soil of south west Victoria.
- History specific. In a single soil-landscape unit, the environmental history of one paddock or land parcel to another determines the comparative soil indicator value. Hence the antecedent land use and land management determines the current value of the soil indicator.
- Purpose specific. Indicators are used to assess the value of soil in: agriculture, natural resource management, catchment management, environmental protection, real estate, banking and finance, product marketing and branding, and social licence perception.

To reinforce the need for a systems thinking approach to research the most appropriate soil performance indicators, the results of the survey questionnaire shows different viewpoints depending on the perspective of the end-user. The implication for future research is that there is a need to gather data from beyond the normal soil science domain, such as the evidence from farmers, agricultural practitioners, indigenous land managers, historical observations and social policies. Much of this evidence is not easily quantified and therefore the research relies on both qualitative and quantitative data to understand why particular indicators or suites of indicators would make the most appropriate and pragmatic measure of soil performance. This holistic approach may challenge the conventional scientific method traditionally used to understand soil performance, but adopting this approach allows new insights and thinking required to evaluate, revise and question the current soil indicators used for soil management.

The review questions the relevancy of our current indicators, many of which are direct descendants of research undertaken many decades ago and do not fully exploit the potential of technology and data of the new digital age, changes in farming systems such as precision agriculture, and changed practices such as no till farming. This notion questions whether the current indicators will remain relevant as farming systems become more spatially heterogeneous in the future. Similarly, sensor technologies may raise the importance of plant-based sensors, and therefore the relevance of plant-based indicators, cf, soil-based indicators.

Besides the complexity of indicator selection, the interpretation of the indicator value also remains problematic. Threshold values are as varied as the soils in a landscape and their use, so the definition of thresholds is equally challenging. Many soil indicator thresholds are also historic, represented as maximum and minimum critical values that can affect say, agricultural production. However, the acceptable range for one purpose, like agricultural production, needs to be balanced against the environmental and ecological thresholds, which are often represented as critical points that lead to transition to other states, or tipping points for system or species collapse. The emergence of combined thresholds considering both production and ecosystems services is new and deserving of more research.

Combining indicators, when we are aggregating data from different soil properties, remains a challenge. The development of a universal framework or index that uses combined physical, chemical, biological indicators is yet to emerge, although is proposed in the context of soil security (McBratney et al 2014; Field et al. 2016). Irrespective of the framework chosen, the common element should be a focus on soil performance, whereby performance outcomes serve both the longevity of agricultural production and ecosystem services simultaneously, or the increase in both, but not at the detrimental expense of either. For example, in relation to soil carbon, the service is carbon sequestration but the performance is carbon cycling capability. In other words, indicators could be measured by products from a farming system, other than the produce.

8.3 Determining indicator usefulness

Building on soil performance and the requirement for combined indicators defining a whole land system, is a persistent question underpinning any management, be it agricultural or otherwise: “How do I make a decision?” This is the question we are trying to answer from the perspective of an end user.

In terms of determining soil condition, and soil capability, within the context of seeking to optimize soil performance, we need to start with the following assertion: “We can measure anything and everything if we try and given unlimited resources.” While we understand unlimited resources are not available, we must appreciate the sentiment. Thinking of this notion in terms of mathematical limits, then, the number of things we could measure (x) approaches infinity ($x \to \infty$), meaning the number of combinations with tools of measurement (t_n) would trend similarly, even though the physics describing measurement are finite:

$$\lim_{x \to \infty} (t_n x) = \infty$$

On this basis, simply asking “what do you measure?”, or “what tools do you use to measure?” never answers the underpinning question of how one might make a management decision, as even where the tools are limited the indicators (x) are not. Given unlimited resources we answer this by measuring everything, but we know this is not the way the real-world works. Thus, we need to identify means to determine which indicators are useful within a defined decision construct, then allowing us to determine the sensors of potential use, should the exist or can be developed. Hence, defining the decision construct and diagnosing the existing on-farm soil constraints provides an extremely useful framework of approach.

The issue with indicators is that they are the things we measure and we have described these as approaching an infinite number So, how then do we determine usefulness without solely relying on the question “Which indicators do you find important?” While such information is a very useful starting point, this question assumes that all indicators being used by end users and defined as important, are in fact actually important. The underlying issue being that we do not know the level of understanding of each indicator, and thus whether it is falsely or truly important. Additionally, as described by Bennett (2015) where an end-user does not know they have an issue, then they cannot suggest the corresponding indicators to be important, or where a certain issue is known, indicators that at first consideration are abstract to the end-user might be considered as less important. A better focus is one that asks an end-user to discuss their business within a number of integrated sub-systems.

Management sub-systems will be distinctly finite and an end user will have an acute understanding of the importance of these systems to their operation. We should not seek to define the subsystems as a list initially, but lead the end users to discuss the management systems defining their business, which will construct the list of subsystems as multiple users are engaged. This approach is using a constructivist learning (Tobin and Tippins 1993) approach to extracting the information we seek to learn. The group discussion might be contextualised by asking each end-user to consider their business operation, and then asking them to reflect on the critical decision points within that operation. Reflection with context leads to deeper learning and richer data extraction. Using such an approach the end-users reflect on and define their subsystems, providing us with a highly meaningful list. Something like this could be used to define the nuances and commonalities both within and between agricultural industries.

The next step would be to unpack the important management decisions, drivers, and/foci within each subsystem. Let the subsystem be set as the context and this inform the discussion on what management typically needs to address within this context, recording these foci. Once this is complete for each subsystem, the process would be repeated, discussing how these decisions are made and what information they use to support these. This is now identifying the indicators within the context of:

$$Usefulness = business\ operation \times management\ subsytem\ \times management\ decision$$

Meaning that indicator usefulness will be a function of the business operation and its management subsystems, as influenced by the impact/ importance of the inherent management decisions.

The recommendation here is that we augment direct survey information with a method that allows us to triangulate what is 'needed' through a constructivist-reflective paradigm. The boundaries of this exploration include what we as researchers know and what exists in literature and under development. Doing this, the characteristics of end-user 'needs' are defined and usefulness is identified by inference. While we should value end-user responses from the survey data, and we do not suggest otherwise, a sole focus on asking anyone what they want is inherently biased. The real question is what do you 'need', but it is more often than not biased by what one 'wants' and the answer restricted to the boundaries of an end-users mental construct of 'what exists'. The information not yet known to an end-user is not included (unknown, unknowns) and information perceived as abstract is discarded. Within this information great discoveries and potential to excel will exist. Excluding it though bias is a disservice to the entire point of our work being to benefit end-users. Such an approach would link an enormous wealth of metadata to each indicator and allows us to infer which indicators are common across operations and subsystems, which are industry specific, which have the greatest cost-benefit, and those that are aspirational because they don't exist in measurable terms yet, but are needed.

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9 CONCLUSIONS

The main conclusions drawn from this Scoping Study are:

9.1 The need for soil indicators

Key messages:

- Indicators are useful to measure soil health, soil function and soil performance.
- There are many different types of soil indicators we already use for different purposes.
- It is important to know what we measure and for what purpose.

Soil properties have been regularly used for centuries to indicate soil condition for farmers, whether it is quality, health, function or performance. In more recent times soil indicators are also used to evaluate soil performance for non-agricultural purposes, such as natural resource management, catchment management, environmental protection, real estate, banking and finance, product marketing and branding.

9.2 Indicators must be fit-for-purpose (useful)

Key messages:

- We farm in different systems, locations, landscapes, soils climates and markets.
- Each of these variations has a different baseline, threshold, and critical point for soil health, soil function and soil performance.
- Soil indicators must be matched to their purpose and desired outcome that the land manager is seeking.
- A framework for determining the usefulness of an indicator is required.

No individual soil property or group of properties can universally indicate soil performance across the variety of global farming systems, ecosystems, geographies, seasons and markets. Therefore, indicators must be matched to their purpose, in the context of when and where they are measured and how the indicator value relates to a baseline and the upper and lower boundaries of the measure for that purpose. However, the usefulness of any indicator, or suite of indicators, can only be truly evaluated within the context of the business operation, its management subsystems, and the impacts of management decisions.

9.3 A suite of indicators may be a better measure

Key messages:

- The measure of one indicator varies a great deal, according to the type of test, the time it is measured and condition of the soil.
- Indicators can influence each other and careful and skilled interpretation of soil tests or measurements is required to understand their meaning.
- Sensors are increasingly used to measure soil indicators and new sensors are continuously being developed.

Soil performance may be evaluated as the sum of soil capability and soil condition, where capability indicates potential and the condition indicates actual state. Since the indicator values vary in the spatiotemporal landscape, and in relation to each other, a collection of indicators may be a more realistic measure of soil performance. It is possible that these may be measured more widely (in the spatiotemporal sense) using new sensor technologies.

9.4 The research journey to find appropriate and pragmatic indicators

Key messages:

- The Soil CRC has embarked on a decade long journey to explore the suite of soil health, soil function and soil performance indicators that are best suited to different purposes.
- This may include sensors, big data analytics, machine learning and artificial intelligence to find the suite of indicators to best measure the different needs.

Since an overarching aim of the Soil CRC is to make Australasian farmers more profitable and better stewards of their soils, capturing farmers' data and knowledge of soil performance and condition will help in deriving a suite of useful indicators as a measure of agricultural profitability. But since we do not know what we do not know (unknown, unknowns) there remains the opportunity for new discoveries to benefit end users. It is likely that more sophisticated suites of soil performance indicators will emerge over time that will be rapidly and repeatedly measured through the use of sensors, providing spatiotemporal maps to allow both proactive and reactive management to improve soil performance.

10 RECOMMENDATIONS

From the review and analysis undertaken through this Scoping Study, seven research projects are proposed to fill the gaps relating to soil performance indicators while meeting the Soil CRC Milestones. The projects are designed to adopt a systems thinking approach to derive the most appropriate soil health/quality/function/performance indicators that will link to agricultural yield, productivity and profitability, as well as public good outcomes.

10.1 Proposed research projects

Project 1 (soil performance indicators). Building resilient and productive farming systems through linking sensitive indicators, soil functionality and plant performance. ***Project submitted in 2018 first round call***.

This project will address specific industry problems; 1) lack of measurable definitions of high performance soils; 2) limited use of soil testing and poor comparability of temporal and spatial results; and 3) slow and expensive testing and monitoring of soil performance.

This project will deliver higher and consistent yields in high rainfall grazing, dryland grains and subtropical sugarcane production systems. The approach will be based on: 1) accelerating understanding of soil:plant functional relationships through the validation and application of novel sensing, chemical and genomic technologies and data analytics and informatics; 2) identifying appropriate spatial and temporal soil indicators and performance metrics that improve soil management for productivity and resilience; and 3) delivering practices to producers that improve plant nutrient use and turnover, water availability and use, soil structure and ecosystem resilience.

<u>Program 2 Milestones:</u>

- 2.1.3 From existing soil metrics develop management target values for key soil indicators (physical, chemical, and biological) for economically important high performing soils.
- 2.1.4 Explore relationships and interdependencies between key indicators for high performing soils.
- 2.1.5 Explore, and develop novel methods or metrics for assessing soil chemical, physical and microbial function / activity for guiding management practice.
- 2.2.1 Establish steering committee of farmers, scientists and industry representatives

<u>Program 4 Milestones:</u>

- 4.1.2 Test methods for indicators of high performance soils (including biological, chemical and physical methods) evaluated and validated for the assessment of novel plant and system based re-engineering
- 4.1.3 Soil rhizosphere re-engineering technologies developed and assessed at glasshouse and small field plot scale
- 4.1.4 Five medium/long term field sites across three regions will deliver data to evaluate novel plant and system based soil reengineering methods
- 4.2.1 Glasshouse/ mechanistic studies addressing multiple soil chemical and physical constraints deliver data used to inform field studies

Project 2 (soil data accessibility): Visualising Australasia's Soils: A Soil CRC interoperable spatial knowledge system. ***Project submitted in 2018 first round call***.

The Visualising Australasia's Soils interoperable spatial knowledge system provides the Soil CRC participants, and the broader agricultural industry in general, access to data, information and knowledge on Australasian soils. The project leverages established technologies developed by the lead researchers to federate data from private and public sources to make agriculture data more Findable, Accessible, Interoperable and Reusable (FAIR - Wilkinson et al. 2016). It includes a data stewardship and governance model for custodians to clearly set the rules under which access to their data, or parts of their data, is possible. The soil research data cloud will address limitations for next generation data models and knowledge products by increasing access to multidisciplinary data through seamless automated data presentation. The Visualising Australasia's Soils project will support data discovery and innovation with research, industry, government and on-farm data shared to enhance decision making and generate new insights into the productivity, profitability and resilience of Australasian agriculture.

Program 2 Milestones:

- 2.1.3 From existing soil metrics develop management target values for key soil indicators (physical, chemical, and biological) for economically important high performing soils.
- 2.1.4 Explore relationships and interdependencies between key indicators for high performing soils.
- 2.3.2 Run a workshop to engage key researchers, stakeholders to identify limitations and options for server based storage, analysis and retrieval of soil sensory data.
- 2.3.3 Develop capacity, procedures and common protocols for communication, storage and access of sensed data for all sub- projects.
- 2.3.4 Explore and develop new approaches for server based analysis of sensed data (including machine learning).
- 2.3.5 Report on soil quality, function, targets of high performing soils based on analytics of server based HPS project data, and 3rd party soil data.
- 2.3.6 Development of front-end apps and software to allow access and visualisation of soil metric data and soil performance by 3rd parties.

Education Milestones:

- Training Courses and Workshops provided in various locations across the nation for: farmers, farmer groups, extension officers and consultants, agronomists and soil scientists.
- Production of online information sheets and course materials for on- farm implementation of new practices and of integrated technologies.

Project 3 (indigenous land management focus): Healthy soils, healthy country: exploring a framework for indigenous indicators of soil health.

A scoping study to explore the potential to exchange learnings between the indigenous peoples of New Zealand and Australia on the development of methods, tools and frameworks for assessing soils and soil health. This may result in the selection of a suitable framework, or modification of a framework, for adaption and application by Indigenous Australians to manage and monitor soil health and support decision-making. Ultimately, an indigenous indicators framework of soil health developed by traditional land owner groups that sits alongside traditional science-based methods serves a two-fold purpose:

- Incorporating indigenous values and traditional science-based measures into a framework specifically to strengthen the management of indigenous lands, and
- By building two-way capacity, traditional science-based approaches can be strengthened by indigenous knowledge and worldviews.

Alignment with Soil CRC Outputs:

- Output 1.4 Partnership model and resources to support innovative companies. Design and development of new partnership model and set of resources focused on soil management and improvement technologies to help innovate and entrepreneurial companies to take new projects and services to market.
- Output 2.1 Key indicators of high performance soils. Identification of data and thresholds defining a high performance soil and determine key indicators of high performance soils.

Program 2 Milestones:

- 2.1.5 Explore and develop novel methods or metrics for assessing soil chemical, physical and microbial function / activity for guiding management practice.

Project 4 (public good/natural capital focus): Developing a framework for soil security and natural capital using a suite of indicators, and guidelines for assessment.

Sustaining soil security, soil ecosystem services and the natural capital of our landscapes is of growing importance in many public and private sector services. These include catchment managers, municipal planners, environment protection agents, produce marketers, brand marketers, realtors, and bankers and financiers to name a few. A project to research and develop or adapt a framework for informative indicators (both on-farm and off-farm) and thresholds for soil security and social licence to develop various soil types for different soil uses is required. Ideally, the framework would consider baselines, capability, condition, capital, codification, connectivity and market encouragement.

In addition to the framework, the project aims to develop a holistic package which includes risk assessment tools, risk management options and guidelines for use. This would include research in how best to proactively respond to emerging indicators, baseline changes, and changing market drivers to inform public land managers and planners, produce marketers and agribusiness. The intention is to derive an alert system for both private and public land managers to identify emerging trends in soil health/quality/function/performance indicators and include guidance on appropriate responses to those trends.

Alignment with Soil CRC Outputs:

- Output 1.1 User manual for the creation of market based instruments. Development of a manual that will guide governments, financial institutions and value chain participants in developing and implementing market-based instruments to capture and distribute financial returns from good soil stewardship.
- Output 1.3 Cost-benefit assessment of alternative soil management interventions. This output will support decision-making by enabling farmers to economically assess alternative soil management options. The analysis will occur across a diverse range of regions and livestock and cropping enterprises. The accuracy and utility of existing decision support systems will be improved by linking biological predictive tools to economic risk analysis.
- Output 2.1 Key indicators of high performance soils. Identification of data and thresholds defining a high performance soil and determine key indicators of high performance soils, including microbial functionality across key soil types.

Program 2 Milestones:

- 2.1.2 Review information on soil health nationally and internationally to identify and develop indicators of soil health and function for economically important high performance soils.
- 2.1.4 Explore relationships and interdependencies between key indicators for high performing soils.
- 2.1.5 Explore and develop novel methods or metrics for assessing soil chemical, physical and microbial function / activity for guiding management practice.
- 2.1.7 Develop guidelines and targets for key indicators, deliver information to industry, and develop a framework for their utilisation.

Project 5 (farming/production focus): Quantitative links between 'tactical' and 'strategic' indicators: building a better suite of soil function indicators for decisions on the farm.

Farmers make management decisions monthly – seasonally – annually based on readily measured parameters, whereas more inter-annual – decadal farm sustainability are reflected in less sensitive parameters like soil carbon. The question is how can simple and frequent tests be used to predict long-term soil health?

The intention is to undertake research on the relationship or response that one indicator has on another, especially applied to the benefits of rotation in timeframes suited to strategic decision making. This is particularly important for the rise in prominence of biological indicators of soil performance and farm productivity, and the response that soil biology might have to chemical and physical conditions. For tactical decision making, including early warning, crop selection, and monitoring short-term soil change frequency and amplitude, research what indicators would be best suited to different farming systems in different locations. Emphasis may be given to sensors, mapping and visualisation of nitrogen, compaction, yield, lime (acidity) and moisture.

Spatial and temporal variability needs to be considered in developing indicators and associated sampling strategies. Hence an objective is to identify and calibrate (within boundaries of soil types, farming systems and ecoclimatic regions) indicators that are better suited at quantifying fluxes of resources – i.e. fluxes of carbon, nitrogen, water, phosphorus. While biological indicators would probably be the best candidates for this, as they are both responsive and drivers, consideration of surrogates for other soil functions may also provide more versatility in assessments. Identifying and calibrating indicators of stress tolerance, stress resistance, plasticity and/or resilience is a secondary aim.

Alignment with Soil CRC Outputs:

- Output 1.3 Cost-benefit assessment of alternative soil management interventions. This output will support decision-making by enabling farmers to economically assess alternative soil management options. The analysis will occur across a diverse range of regions and livestock and cropping enterprises. The accuracy and utility of existing decision support systems will be improved by linking biological predictive tools to economic risk analysis.
- Output 2.1 Key indicators of high performance soils. Identification of data and thresholds defining a high performance soil and determine key indicators of high performance soils, including microbial functionality across key soil types.

Program 2 Milestones:

- 2.1.4 Explore relationships and interdependencies between key indicators for high performing soils.
- 2.1.5 Explore and develop novel methods or metrics for assessing soil chemical, physical and microbial function / activity for guiding management practice.
- 2.1.7 Develop guidelines and targets for key indicators, deliver information to industry, and develop a framework for their utilisation.

Project 6 (farming/production focus): ‘Horses for courses’: matching indicators to their purpose and standardising their measurement and interpretation.

Analysis of (big) data combined with a deeper social science survey (i.e. questionnaires, interviews, focus groups – perhaps in collaboration with Program 1 researchers) to determine which indicators are best suited to which farming systems over what timeframes in which geographies, and what are the thresholds for those indicators. The intention here was to fully explore what farmers are already using and why they have chosen those particular indicators. In other words, to learn from the experience of farmers, consultants and advisers who have generally played an insignificant role in development of soil quality assessment schemes – despite being important end users.

A component of this project is to explore the historical context for the current soil indicators, i.e. the environmental, temporal, scientific and technological limitations under which they were developed and whether it needs revision to bring them up to current day knowledge. The aims are to understand the limitations of the current indicators (and the inherent liability of that, in using indicators that are not fit for purpose), and to understand the standard operating procedures for common indications (when, why and how they should be used).

Similarly, the exploration of a qualitative and/or quantitative indicators framework that enables conversions between “intuitive” indicators and western-science-based indicators is required. Commonly-used “intuitive” indicators include those used by farmers applying biodynamic / biological / holistic principles. Some of these indicators have been cross-validated (e.g. Emmett-booth et al. 2016) but not many biological indicators have been cross-validated, despite wide usage by farmers (e.g. BRIX test).

Once the indicators are identified, determine what protocols and farm-specific and robust tools can be used to measure the indicators, that are also cost effective, pragmatic and accurate to the level required. However, <u>context is critical</u> and future Soil CRC work should maintain focus on contexting measurement of soil properties according to soil type, landscape, agricultural industry, agro-ecological zone etc.

<u>Alignment with Soil CRC Outputs:</u>

- Output 2.1 Key indicators of high performance soils. Identification of data and thresholds defining a high performance soil and determine key indicators of high performance soils, including microbial functionality across key soil types.
- Output 2.3 Intelligent analytics of big data. Development of back-end capability to analyse raw soil data and assess the interactions within it and provide the results to farmers and agronomists. The analytics will be driven by intelligent and machine learning algorithms to process a continuous multi-source data stream.

<u>Program 2 Milestones:</u>

- 2.1.3 From existing soil metrics develop management target values for key soil indicators (physical, chemical, and biological) for economically important high performing soils.
- 2.1.5 Explore and develop novel methods or metrics for assessing soil chemical, physical and microbial function / activity for guiding management practice.
- 2.1.7 Develop guidelines and targets for key indicators, deliver information to industry, and develop a framework for their utilisation.

Project 7 (farming/production focus): Benchmarking soil compaction: severity, extent, variability.

Soil compaction has been identified as a serious issue in a variety of farming systems, as confirmed in the Soil CRC Program 2 workshop. The ultimate intention of this project is to map variation in compaction at the paddock scale, and investigate the relationships between compaction and soil chemical and biological indicators and soil function (including a PhD project perhaps?).

The project should address soil compaction as a key soil constraint and provide a framework for the identification, assessment, benchmarking and monitoring of soil compaction for key cropping soils for different agricultural industries. Such a project could develop the concept of identifying and measuring where a soil is on the 'compaction continuum' for a range of key soil types. Techniques could be developed for farmers and advisers to understand where they are on the compaction continuum and better understand and manage variability. This work would then provide Programs 3 and 4 with more robust methods for measuring changes in compaction due to amelioration interventions.

Existing sensing techniques, such as constant velocity penetrometers, along with proximal sensing could be utilised to determine the best indicators to map and measure compaction at the paddock scale (linking to Program 3 on mapping soil constraints). Novel imaging techniques could also utilised to visualise compaction and effects on plant roots and soil pore architecture (which affects water and air movement through the soil). Assessments for CTF and non-CTF systems and for key industries such as Grains, Sugar and Horticulture. Confounding variables such as soil moisture, clay content and soil structure need to be factored in to assessments. Interactions between other relevant constraints (e.g. sodicity) could be assessed and consideration given to determining how some biological and chemical properties 'shift' along the 'compaction continuum' (relating to amelioration and degradation).

Alignment with Soil CRC Outputs:

- Output 2.1 Key indicators of high performance soils. Identification of data and thresholds defining a high performance soil and determine key indicators of high performance soils, including microbial functionality across key soil types.
- Output 2.2 Sensor networks for on-demand assessment of key soil indicators. Development of 'use appropriate' sensors to provide actionable information on soil water, nutrients and microbial function. This may include the novel re-configuration of existing sensors or the creation of new sensors to fill any identified technology gaps.

Program 2 Milestones:

- 2.1.4 Explore relationships and interdependencies between key indicators for high performing soils.
- 2.1.5 Explore and develop novel methods or metrics for assessing soil chemical, physical and microbial function / activity for guiding management practice.
- 2.1.7 Develop guidelines and targets for key indicators, deliver information to industry, and develop a framework for their utilisation.

ACKNOWLEDGEMENTS

This research is funded by the CRC for High Performance Soils and supported by the Cooperative Research Centres program, an Australian Government initiative. In-kind support was provided by: Federation University Australia, Agriculture Victoria Research, Manaaki Whenua Landcare Research, Southern Cross University, University of Southern Queensland, University of Tasmania, NSW Dept of Primary Industries, University of Newcastle, Griffith University, Southern Farming Systems, Riverine Plains Inc., WA No Tillage Farmers Association, Society of Precision Agriculture Aust., Liebe Group and Mallee Sustainable Farming. The authors also acknowledge the time given by the workshop attendees, those who contributed to the online questionnaire, and colleagues who contributed time and ideas to this project.

APPENDICES

APPENDIX 1: COMPACTION AND SOIL STRUCTURAL CHANGES RESULTING FROM TILLAGE, HEAVY MACHINERY AND GRAZING

Radford et al (2000), suggested that soil compaction has been recognized as the greatest problem in terms of damage to Australia's soil resource. Subsoil compaction adversely affects soil physical properties, and has been shown to decrease yields as well as water and nutrient use efficiencies by wheat and sorghum (Ishaq et al 2001). Soil bulk density and penetration resistance were increased, and soil total porosity and air-filled porosity were decreased in a sandy clay loam (fine-loamy, mixed, hyperthermic Typic Haplargids, USDA; Luvic Yermosol, FAO). The increase in soil strength due to compaction decreased yields of wheat by 12–38% and of sorghum fodder by 14–22%. Similarly, Drewry et al. 2008, In a review of cattle treading in pasture, showed that decreases in macroporosity result in decrease pasture yield. For instance, Van der Weerden et al. (2010) also showed that decreases in macroporosity also increase greenhouse gas (e.g. N_2O) production.

Bingham et al (2010) investigated the interactions between soil compaction and N availability on the growth and root tissue composition of young barley plants in a controlled environment study. Compaction and low N supply increased C:N by a factor of 1.3 and 1.8 respectively, whilst the lignin:N ratio was increased by 1.7 and 2.1 respectively. Hence, both compaction and low N supply independently and in combination, altered composition of root tissue in a way that might reduce the rate of root degradation by soil microbes. The impact of soil compaction on the fate of root tissue in the field is likely to depend on the extent to which compaction restricts N availability to the plant. It may be necessary to consider the effects of soil structural conditions and N availability on tissue quality in models of nutrient cycling.

There are differences in the extent of compaction from different sources. Improvement in cultivation systems may help alleviate the effects of compaction as Bell (2011) performed a simulation study using APSIM (Agricultural Production Systems Simulator) to investigate the sensitivity of wheat crop growth and yield to reductions in root growth and water conductivity in the surface soil (0-10 cm). Mild surface soil compaction from livestock was found to reduce grain yield by less than 10%. This implies that, in most cases, the impacts of compaction by livestock on crop performance are small, which is supported by the few studies that have investigated this experimentally. In more severe cases, crop losses could be up to 30%, especially if surface conductivity was greatly reduced and ground cover levels were low. Crop growth and yield were more sensitive to reduced surface conductivity and rainfall infiltration than to reduced root growth in surface layers. But it needs to be emphasised that impacts from compaction can be very soil and circumstance dependent, as both the resilience of the soil and specific soil moisture content will determine the longer-term outcome.

Impacts of Wheeling and Heavy Traffic:

The trafficking of a moist–wet Vertisol by a laden harvester gave a significantly poorer structural state to a maximum depth of 0.4 m. Soil porosity derived from soil clod shrinkage data provided the greatest depth of effect *(Radford et al 2000)*.

Subsoil compaction adversely affected soil physical properties, and has been shown to decrease yields as well as water and nutrient use efficiencies by wheat and sorghum (*Ishaq et al 2001).* Soil bulk density and penetration resistance were increased, and soil total porosity and air-filled porosity were decreased in a sandy clay loam (fine-loamy, mixed, hyperthermic Typic Haplargids, USDA; Luvic Yermosol, FAO). The increase in soil strength due to compaction decreased yields of wheat by 12–38% and of sorghum fodder by 14–22%. There occurred a reduction in soil bulk density and penetration resistance after three crops. For wheat, both the water and nutrient use efficiencies significantly decreased by up to 38 and 8%, respectively, while for sorghum the reduction was 22 and 14%.

Lozano et al (2013) found that the maximum stresses transmitted to the soil surface by sugarcane transport vehicles are higher than tyre inflation pressures when they analyzed the compaction process of an Ultisols in the costal table of Pernambuco, Brazil, subjected to vehicle traffic during sugarcane harvest. The pseudo-analytical model SoilFlex was used for modeling bulk density and soil moisture scenarios based on undisturbed soil samples taken at different depths. It was concluded that the topsoil (0–20 cm) was in a high risk of soil compaction during sugarcane harvest due to field vehicle traffic. However, there is lower risk of soil compaction in dry soil or soil with bulk densities above 1.5 g cm^{-3}. Traffic with the haulout truck or the tractor–trailer set is inconvenient when bulk density is lower than 1.4 g cm^{-3} and moisture content higher than 16%. Risk of soil compaction can be reduced if new strategies of on field traffic be developed for sugarcane transport with haul-out trucks and trailers as well as experiments with different wheel settings and tyre types, such as single super tyres instead of dual regular road tyres.

Radford et al (2001) also suggested that compaction can be avoided completely by using a controlled traffic farming system. Trafficking the soil at low soil water contents minimizes yield decline. Tillage operations to control weeds can be delayed by using herbicides until the surface soil dries. Soil compaction caused by axle loads of 6–10 Mg on a wet Vertisol (25–32% soil water) reduced grain yields (wheat and maize) by reducing soil water storage and/or crop water use efficiency (WUE). Annual applications of an axle load of 6 Mg on dry soil (<22% soil water) had little effect on crop performance. Crop and pasture roots ameliorated the initial compaction damage by creating wet–dry cycles. Such biological amelioration was as effective as mechanical amelioration by tillage. After a 3-year pasture ley, grain yield exceeded control in subsequent wheat and maize crops. However, pasture production is generally less profitable than cropping, and a commercial pasture would include further compaction by animal hooves.

Heavy wheel traffic causes soil compaction, which adversely affects crop production. The adverse effects of compaction of a wet Vertisol (Vertosol, ASC) with a 10 Mg axle load can persist for up to 5 years. This result is attributed to insufficient wet–dry cycles to swell and shrink the entire compacted layer, a no-tillage regime during the amelioration process, and low earthworm numbers in the compacted soil. Compaction of dry soil with a 6 Mg axle load had little effect, indicating that problems can be avoided by using wheel traffic only when the soil is dry. Since this is not always possible, a better way to avoid problems is to permanently separate wheel zones and crop zones in the field (controlled traffic farming). When a clay soil is already compacted, management options to hasten repair should be considered. These include tillage, deep ripping, sowing a ley pasture or sowing crops that repair compacted soil *(Radford et al 2007).*

Patel & Mani (2011) determined the compaction of sub-soil layers due to different passes of a test tractor with varying normal loads in a field experiment conducted on alluvial soil with sandy loam texture, in a complete randomized design. The bulk density and penetration resistance in 0–15 cm depth zone continuously increased up to 16 passes of the test tractor, and more at higher normal loads confirming the dynamic nature of compaction process. The compaction effect decreased in the sub-soil layers when the load was not in higher range. At depths below 30 cm, the combination of only higher load and higher passes was effective. The compaction process due to increased load and multiple passes, considered in the study, almost terminated in the depth below 45 cm. The increase in bulk density and penetration resistance due to increased loads and passes was significant in the soil depth range of 0–45 cm at 1% level of significance. However, beyond 45 cm soil depth, the influence was not significant. The R^2 calculated from observed and predicted values with respect to regression equations for bulk density and penetration resistance were 0.7038 and 0.76, respectively.

Botta et al (2008) quantified soil compaction induced by tractor traffic on two tillage regimes: conventional tillage and direct drilling in Argentina. In both soil conditions, there was a direct relation between tractor weight and subsoil compaction which does not depend on vehicle ground pressure. Axle weights lower than 40 kN caused subsoil compaction in conventional tillage. Topsoil compaction is directly related to ground pressure and will not depend on total axle load if correct matched conventional and radial tyres are used. Radial tyres reduced topsoil compaction and rut depth compared to cross-ply tyres. Moreover, the magnitude of change in bulk density and cone index values are reduced by lowering inflation pressure and increasing tyre size

Impacts of Tillage:

The dramatic effect of soil compaction and structural degradation on a commercial cotton crop grown on a Vertisol near Dalby, Queensland was confirmed by *McGarry (1990).* Differences in growth, yield and root systems of the two adjoining crops, were explained in terms of soil profile morphology and soil shrinkage indices. The compaction did not directly cause the yield difference; rather its presence severely limited the owner's range of management options normally used to obtain a satisfactory crop. The owner faced an unexpected and inexplicable crop failure which in terms of his whole-farm management gave only one option, i.e. to stop all inputs into this field. This soil structure degradation was caused by seedbed preparation of wet soil, prior to sowing the cotton crop.

Fernández-Ugalde et al (2009) determined effects of conventional- and no-tillage practices on soil physical quality indicators and water availability in an on-farm study in the semiarid Mediterranean Ebro Valley. The suppression of tillage resulted in increased penetration resistance of the tilled layer (0–15 cm) in the studied carbonate-rich degradation-prone soil, with natural low organic matter content, silty texture, and weak structure. However, other physical quality indicators, such as aggregate-size distribution, water stability and water retention characteristics were significantly improved after 7 years of continuous no-tillage (NT). Throughout the 2007–2008 growing season field water content and its availability for plants under NT were greater, especially for the driest months. This greater field water content also improved water uptake by the crop, resulting in greater barley yield under NT than conventional tillage (CT) in the driest year. The increased plant-available water content under NT, due to the improvement of soil structural properties (i.e. aggregate stability, pore-size distribution), helped thus to overcome the most limiting factor for crop production, and it seems to compensate for the greater penetration resistance in the studied soil.

de Oliveira Ferreira (2013) carried out a study in the State of Rio Grande do Sul, Brazil to assess the effect of soil order and climate type on carbon stratification ratio (CSR), with soil tillage and different cropping systems taken as treatments. CSR was assessed in the 19th and 22nd experimental years for Oxisol and in the 10th and 17th years for Alfisol. This index was calculated through the ratio of SOC stocks in the 0–0.05 and 0.05–0.15 m soil layers. The carbon pool index (CPI) was determined through the ratio of SOC stocks in the 0–0.15 m soil layer in a given treatment compared with native vegetation. Regardless of the soil order, SOC was influenced by C input and the tillage system; there was a positive linear relationship between CSR and CPI. In more oxidative environments, such as tropical and subtropical climates, the critical CSR value is lower than previously proposed for temperate soils. In Brazilian agriculture because of the highly oxidative SOC environment, the improvement in quality of soil management is captured by CSR index. Higher SOC, CSR and CPI values were found when soil was minimally disturbed and crop rotation was intensified. Low indices were found under tilled soils that were associated with short fallow periods and lower crop diversity.

Nunes et al (2015) aimed to evaluate the effect of seeder equipped with fixed shanks openers, working at three depths, in a Ferralic Nitisol (Rhodic), under no tillage (NT) on the mitigation of soil compaction and corn (*Zea mays* L.) plant development. The use of the seeder improved macroporosity, total porosity and availability of water to the plants and reduced penetration resistance, bulk density, and degree of compactness in the 0.07–0.17 m layer as well as promoted development of corn plants with greater stalk diameter, greater root dry mater mass, and greater root length; and also improved the development of corn plant root system in 0.05–0.17 m layer of a soil under NT. Hence, this kind of seeder presents high potential to improve soil physical root growth conditions on clay soils under NT as it can break the compacted soil layer and keeps the crop residues on the top soil.

In a study in Spain, *López-Garrido et al (2014)* found that in the same soil, cropped with the same crop rotation, two techniques of conservation agriculture, reduced tillage (RT) and no tillage (NT) (five years of establishment) yielded very different results. Although both treatments, NT in particular, improved soil quality in relation to chemical and biochemical properties, their impact on the soil physical properties was completely different, penetration resistance reaching prohibitive values for root growth under NT. Consequently, the crop performance and seed quality were greatly and negatively affected. On the contrary, the crop response under RT was very positive. Seed quality was even slightly, but significantly, better than under traditional tillage (TT) with soil inversion. It is therefore desirable to encourage farmers to use less invasive techniques in the environment, by introducing a judicious and flexible land management.

Ten years of finger millet/horsegram/pigeonpea cultivation, reducing the tillage intensity to the bare minimum and application of recommended quantities of fertilizers favorably influenced soil physical, biological properties and also contributed to the buildup of SOC but only modestly. N fertilization was able to increase, or at least maintain SOC even under conventional tillage (CT) systems and substitution of inorganics with organics increased the carbon buildup and labile C pools. On the other hand, no addition of inputs severely affected the crop production and caused reduction in SOC content and unfavorable changes in soil chemical and biological properties. Hence application of recommended dose of fertilizers is absolutely essential for not only realizing the optimum yields but also for SOC maintenance or build up. Utilization of crop residues as animal feed and application of farm yard manure is one of the possible alternatives for crops whose residues have fodder value under small holder situations of India. Reducing the tillage intensity had significant negative effect on crop yields and there is a need to minimize the yield reduction for making the practice acceptable to the farming community. One of the approaches is to enhance the surface cover with either residues or organic matter for greater rainfall infiltration and moisture conservation and the other is to control weeds effectively *(Prasad et al 2016)*.

Franchini et al (2007) identified soil parameters potentially useful to monitor soil quality under different soil management and crop rotation systems in a field experiment in the State of Paraná, southern Brazil. Greater MB-C and MB-N, lower CO_2-emission rates, lower qCO_2, lower ratios of soluble-C/MB-C and soluble-N/MB-N and higher microbial quotients-C and -N emphasize the importance both of NT and of inclusion of legumes in crop rotations as efficient means of conserving SOM in the tropics. Such patterns of enhancement in C and N stocks in the soil after only 5 years are suggestive of achievement of agricultural sustainability. Furthermore, the parameters associated with microbiological activity were sensitive and rapid indicators of effects of soil management, demonstrating their usefulness as indicators of soil quality in the tropics.

Hamza & Anderson (2002) established that ameliorating the negative effect of soil compaction, through a package of ripping and gypsum application, with stubble retention and in the absence of nutrient deficiencies, would significantly increase wheat/legume yields in both sandy loam and sandy clay loam soils of Western Australia. On the other hand, the improvements in soil physical properties such as porosity, soil stored water, water infiltration rate, cation exchange capacity, and water-stable aggregates were higher in the sandy clay loam than in the sandy loam soil. The major difference between the soils prior to treatment was in the strength of the topsoil in particular and the root-zone in general.

Annualized crop yield, soil nutrients, and chemical properties varied among treatments due to variations in tillage intensity and cropping sequences after 30 years. At the surface layer, soil Olsen-P, K, Zn, and Na concentrations and CEC were greater, but pH, buffer pH, and Ca concentration were lower in NTCW, STCW, and FSTCW than STW-F. At the subsurface layers, EC, Na, and SO_4–S concentrations were greater in FSTW–B/P and FSTCW than the other treatments. Olsen-P, K, and Zn concentrations decreased, but Ca, Mg, Na, and SO_4–S concentrations, pH, buffer pH, EC, and CEC increased with soil depth. Annualized crop yield was lower in STW-F than the other treatments. Long-term reduced tillage with continuous cropping increased P, K, and Zn concentrations and CEC by reducing soil disturbance and increasing crop residue returned to the soil and annualized crop yield, but reduced pH and basic cations at the surface layer due to increased N fertilizer application compared with the traditional system of conventional tillage with spring wheat-fallow. Reduced tillage with continuous cropping may be adopted for maintaining long-term soil fertility and crop yields compared with the traditional system *Sainju et al (2015).*

No-tillage system associated with crop rotation increases the amount of crop residues left as mulch on the topsoil, and can be an important and sustainable alternative for soil management in tropical and subtropical conditions. The objective of this work was to evaluate the soil physical properties affected by cover crop, rotation and soil management in a long-term experiment in South Brazil. The high amount of crop residues added to the soil during the years improved the soil aggregations parameters, and NT not promoted soil compaction, and the fallow treatment presented the lowest values for mean weight diameter, geometric mean diameter GMD and also for aggregate stability index. Furthermore, under conventional system, the soil disturbance by plough every season, enhanced the macroporosity and diminished the microporosity on conventional system comparatively to no-tillage, and promoted the formation of smaller diameter classes *(Calegari et al 2010).*

Continuous intensive monocultures of rice can lead to subsoil compaction, reduced topsoil quality and decline in rice yield. *Linh et al (2015)* evaluated the effect of rotating rice with upland crops on properties of an alluvial paddy clay soil, rice yield components, and economic profitability by establishing a field experiment in the Vietnamese Mekong Delta for 10 years with a randomized complete block design including four rice crop rotations with upland crops and four replications. Rotation with deeper tillage improved SOC quality, physical quality of soil in terms of bulk density, soil porosity, soil aggregate stability, and soil penetration resistance compared to the traditional rice monoculture practice, especially in the 10-20 and 20-30 cm depth layers. As a consequence, also rice rooting depth and root mass density was strongly increased in all three rice upland crop rotations. This resulted in improvements of rice growth, yield that was 32-36% higher compared to the control, and farmer's profitability even increased 2.5-2.9 times. Rotation with upland crop can be solution to avoid further degradation of paddy soil.

Bingham et al (2010) investigated the interactions between soil compaction and N availability on the growth and root tissue composition of young barley plants in a controlled environment study. Compaction and low N supply increased C:N by a factor of 1.3 and 1.8 respectively, whilst the lignin:N ratio was increased by 1.7 and 2.1 respectively. Hence, both compaction and low N supply independently and in combination, altered composition of root tissue in a way that might reduce the rate of root degradation by soil microbes. The impact of soil compaction on the fate of root tissue in the field is likely to depend on the extent to which compaction restricts N availability to the plant. It may be necessary to consider the effects of soil structural conditions and N availability on tissue quality in models of nutrient cycling.

Defossez & Richard (2002) reviewed soil compaction models and also discussed their evaluation under laboratory or field conditions. The development of a compaction model includes: (i) modelling the propagation of the loading forces within the soil resulting from forces applied at the soil surface from farm vehicles; (ii) modelling soil stress–strain behavior. Models predict stress distribution in the soil induced by farm vehicle and change in soil structure: increase in dry bulk density and rut depth formation. The models based on Boussinesq equations for stress propagation were considered useful since they use a small number of parameters. They have been successfully assessed in field conditions for homogeneous soil under a wide range of soil and water conditions. The difference between simulations and observations becomes more apparent when dealing with heterogeneous structures (clods, firm subsoil). The models based on the finite element method (FEM) have been shown to be more adequate for modelling the 3D distribution of stress within the soil induced by wheeling and the complex stress–strain behavior of soil. Nevertheless, these models require more mechanical parameters and have been evaluated under limited conditions in laboratory bins or in the field with low compaction intensities.

Impacts of Grazing:

Grazing animals provide a livelihood for farmers, but they may also produce adverse environmental effects. Soil under pasture can be compacted as a result of grazing animals exerting pressure on the ground comparable to that of agricultural machinery. In grazing systems based on permanent pastures or rangelands, there is little opportunity to ameliorate poor soil physical conditions through tillage. Hence, it is important to understand the effects of grazing on soil physical properties and the consequent effects of these properties on pasture growth and composition. Compaction to greater depth and other changes in soil physical properties are more likely in recently tilled or wet soils. The response of pasture to the poorer soil conditions caused by grazing is difficult to determine, but it is likely to be small compared with the defoliation effects of grazing. Maintenance of a vigorous pasture should be a major aim of grazing management and would also achieve the secondary aim of maintaining acceptable soil physical conditions *(Greenwood & McKenzie 2001)*.

Grazing and trampling by livestock appear to cause deterioration of soil physical properties and to increase soil erodibility. *Zhou et al (2010)* investigated these impacts in soils sampled from an ungrazed grassland, a continuously grazed grassland, and a track trampled by stock in the northern Loess Plateau of China. The soil in the ungrazed area had a significantly lower bulk density and significantly higher water content, proportion of stable aggregates, and infiltration rate than that in the grazed area or beneath the track. Soil resistance to scouring was lower in the grazed area and the trampled track, compared with the ungrazed plot, probably due to the effects of livestock trampling that compacted the soil and destroyed plant roots.

In China, a significant deterioration of physical and chemical topsoil parameters as a consequence of sheep grazing in a *Leymus chinensis/Stipa grandis* dominated semiarid steppe was revealed (*Steffens et al 2008).* There were significantly higher bulk densities and lower OC, total N and total S concentrations in grazed areas compared to ungrazed areas, which can be attributed to the combined effect of animal trampling, reduced above- and belowground organic matter input and root growth and erosion as a consequence of grazing. Elemental stocks, calculated using bulk densities as well as an equivalent mass to take into account changing bulk densities following grazing, showed a significant decrease for OC, total N and total S in grazed areas. Highest losses were calculated for heavily grazed areas. Whereas C/N remained constant in all analyzed plots, C/S and N/S ratios showed narrower values in heavily grazed areas. This points towards a selective mineralization of S-depleted organic matter and lower organic matter inputs in grazed areas. Despite low minimum detectable difference (MDD) values resulting from the large number of samples and low variances, no ameliorating effects of reduced or excluded grazing could be verified five years after land use change.

Livestock grazing with good management and manure recycling to the grazed plots could not degrade soil physical and hydrological properties. Hereafter, over utilization of the available grass herbage by livestock and removing manure from grazed plots is responsible for soil degradation *(Taddese et al 2007*). The impact of grazing on soil physical properties in the east African highland, Ethiopia was studied from 1996 to 1998 at two sites with 0-4% and 4-8% slopes at the International Livestock Research Institute (ILRI) Debre Ziet Research Station. The grazing had no significant impact on total nitrogen, soil bulk density and total porosity of the soil, but improved the plant available-P compared to non- grazed plots at both slopes in all soil depths. Since manure is not collected from grazing plots the soil organic matter content did not decline, it was rather stable and slightly increasing. At both sites the soil water content was high in heavily grazed plots as compared to the rest of the treatments. The steady state infiltration rate was significantly different only in light grazing treatment at 4-8% slope.

However, an even minimal grazing activity caused a significant deterioration of the soil properties in the loess steppe vegetation systems in China *(Xie & Wittig et al 2004).* A continual decrease in organic matter in the surface soil was correlated directly to soil compaction. The organic matter content in soil of over-grazed areas was only a third of the organic matter found in non-grazed areas. This decrease can be attributed partly to the poor living conditions for soil organisms in compacted soils, but also to a significant reduction in litter. Thus in intensively grazed areas hardly any plant litter remained to be incorporated into the soil as humus. Likewise root density also suffered its largest decrease in these areas. Nitrogen and phosphorous (total and available) content was not significantly different in non-grazed and slightly grazed areas, but a noticeable decrease was apparent between the latter and moderately grazed areas. Available Potassium was similar for all grazing levels. Grazing had no significant effect on the pH of soil solution.

Higher stocking rate over the short term increased soil compaction and bulk density in Nama Karoo subshrub/grass rangeland of South Africa, significantly decreasing the infiltration rate *(Du Toit et al 2009)*. Considering all aspects, it seems that a light stocking rate (4 SSU ha^{-1}) has least influence on the soil parameters whereas even no grazing increased bulk density and soil compaction and lowered infiltration rate. From a hydrologic point of view, grazing levels and rotation schemes need to be tailored for sustainable utilization of arid subshrub/grass vegetation by livestock.

The effects of high grazing intensity on physical, chemical and biological properties of soil in a semi-steppe rangeland in the Sahand Mountains (Iran) were a higher soil bulk density, lower extractable base cations and P, and higher soil pH at both depths (0–10 and 10–20 cm). The highest values of microbial biomass carbon, total fungi and bacteria were observed on the light treatment. Grazing significantly affected soil properties unfavorably and reduced vegetation vigor and composition, jeopardizing the sustainability of the ecosystem *(Mofidi et al 2012).*

Bella et al (2015) suggested that continuous grazing management in the temperate salt marshes of Samborombón Bay (Argentina) might have negative consequences for animal production and ecosystem conservation. Soil salinity was greater on the grazed than on the ungrazed sites, especially those in the medium (ME) and lower (LE) elevation levels, which in turn changed the plant community structure through the increase of salt-tolerant and non-palatable species and the decrease of palatable species. Soil physical variables (soil bulk density and soil bearing capacity) were also higher on the grazed than on the ungrazed sites, which can be related to the decrease in soil organic matter (SOM), and suggest an incipient compaction process; however, magnitude of the impact was small, as soil bulk density values were still lower than those values considered critical for plants growth in clay soils.

The impacts of long-term grazing on compaction were assessed in mixed prairie and fescue grassland ecosystems of Alberta. Solonetzic soils were less sensitive to compaction under grazing than Chernozemic soils. Heavy intensity and/or early season grazing had greater impacts on compaction than light intensity and/or late season grazing increasing bulk densities and penetration resistances. Compaction occurred at greater depths under heavy intensity grazing than under light intensity grazing *(Naeth et al 1990).*

Donker et al (2002) compared the effects of high intensity [4.16 animal unit month (AUM) ha^{-1}] short-duration grazing (SDG) versus moderate intensity (2.08 AUM ha^{-1}) continuous grazing (CG) by wapiti (*Cervus elaphus canadensis*) on soil compaction as measured by bulk density at field moist condition (Db_f) and penetration resistance (PR) in Edmonton, Alberta, on a Dark Gray Luvisolic soil of loam texture. The Db_f and PR of the top 10-cm of soil were significantly ($P \leq 0.05$) greater by 15 and 17% under SDG than CG, respectively, by wapiti. Generally, Db_f in both grazing treatments decreased over winter at the 0-7.5 cm and 12.5-15 cm depths, suggesting that freeze-thaw cycles over the winter alleviated compaction. Soil water content under SDG was significantly ($P < 0.05$) lower than CG. Total standing crop and fallen litter were significantly ($P \leq 0.05$) greater in CG treatment than the SDG. The SDG treatment had significantly ($P \leq 0.05$) less pasture herbage than CG areas in the spring (16%) and fall (26%) of 1997, and in the spring (22%) and fall (24%) of 1998, respectively. The SDG did not show any advantage over CG in improving soil physical characteristics and herbage production.

The impact of integrating cattle into a sod-based crop rotation has been evaluated in Florida, to understand the short and long-term effects of winter grazing on soil properties and productivity in terms of cotton yield *(George et al 2013).* The effects of grazing were more pronounced under non-irrigated conditions which could explain significant cotton yield differences between non-irrigated grazed and non-grazed plots. Greater microbial biomass C and nutrient cycling indicated by greater N, P, and K levels in the top 0–30 cm of soil depth in the grazed (especially non-irrigated) plots could further explain the greater cotton yield in those plots. This indicates that integrating winter grazing into a sod-based rotation could be a feasible management option under water-limited situations. The slight increase in soil bulk density at shallower depths did not seem to be detrimental to crop productivity or root growth at deeper depths and soil quality.

In northern Colorado, the effects of seasonal grazing treatments (early spring and late summer) on soil physical properties in a montane riparian ecosystem were evaluated *(Wheeler et al 2002)*. Infiltration rates and bulk density were used as primary indicators of responses to a 1-time heavy grazing event on previously protected paddocks. The impact of soil bulk density, porosity, gravimetric water content, organic carbon concentration and texture on infiltration rates were measured at varying depths. Few differences between spring and late summer grazing periods on soil physical properties were found. A stepwise multiple regression model for infiltration rate based on soil physical properties yielded a low R^2 (0.31), which indicated much unexplained variability in infiltration. However, infiltration rates declined significantly and bulk density increased at the 5-10 cm depth and 10-15 cm depth in grazed plots immediately following grazing, but the highly organic surface layer (0-5 cm) had no significant compaction.

Infiltration rates and soil bulk densities returned to pre-disturbed values within I year after grazing events, suggesting full hydrologic recovery. This recovery may be related to frequent freeze-thaw events and high organic matter in sons.

The new system of "cell grazing" or "time control grazing", involving short intensive grazing followed by a long period of rest, has become popular amongst graziers of Australia. *Sanjari et al (2008)* carried out a study on a large grazing property in the Traprock region of Queensland where the two grazing systems, conventional and cell grazing were compared and the influence of the two systems on soil properties and grass production was studied. Total soil organic carbon and nitrogen levels increased and concentrations of soluble phosphorus and nitrogen in runoff and soil extracts were reduced under cell grazing compared to conventional grazing system, possibly due to the increased plant growth and higher rate of uptake of soluble nutrients under cell grazing. The long rest period provided by cell grazing system together with a more uniform animal distribution over the confined cells appears to have positively contributed to both physical and chemical recovery of the soil after each round of grazing. Such a recovery under cell grazing contributed to increased herbage mass and higher productivity of the grazing lands. The presence of a higher quantities of litter and above ground organic materials on lands under cell grazing reduced hoof pressure on the soil underneath and reduced compaction. The smaller size of the paddocks in cell grazing also contributed to a more even distribution of animals in the cell, a lower overall trampling opportunity and a reduced rate of soil damage by compaction.

Cattle grazing of corn residues in an irrigated no-till corn–soybean system in eastern Nebraska for 16 years had little or no effects on soil properties (such as bulk density, wet soil aggregate stability, particulate organic matter, soil organic C, and nutrients except Ca and S) on a Tomek silt loam in eastern Nebraska *(Rakkar et al. 2017)*. Spring grazing increased the cone index (soil compaction parameter) by 1.3 to 3.4 times relative to the control, but fall grazing had no effect. However, the level of compaction was small and below the critical level (cone index <2 MPa) that causes crop yield losses. Indeed, the increased cone index values were not significantly correlated with crop yields. Residue removal by grazing did not reduce soil C stocks and soil fertility but had some positive impacts on some microbial communities (actinomycetes).

Northup et al. (2010) examined the impacts of additional grazing during summer on soil compaction within paddocks of grazed wheat in central Oklahoma. Both agricultural practice and grazing applied to conservation-tilled wheat paddocks increased compaction of near-surface soils within two years, although within different sections of the profile. Conservation tillage, with or without inclusion of a summer legume in a dual-crop system, did not limit compaction in the short term, and may result in higher bulk density of soils for several years before soil improvement occurs. The results therefore suggest that combining grazing of wheat with grazing legumes during the summer, under conservation tillage, may not represent sustainable management in the short term.

Bell et al (2011) found no effect of sheep grazing on subsequent crop growth or yield in southern Australia, despite evidence of surface compaction and reduced infiltration rate. Consistent with previous findings, predicted average grain yield was reduced by <10% under mild and moderate scenarios typical of those reported experimentally. Crop yields were reduced by lower rainfall infiltration and fallow efficiency in locations with summer-dominant-rainfall, and by reduced root exploration at locations with winter-dominant-rainfall. Lower residue cover levels amplified reductions in rainfall infiltration, especially reducing the accumulation of soil water during summer fallow. Long-term simulations suggested that soil impacts generating large reductions in root growth and infiltration rate are required to considerably reduce subsequent crop yields. Such impacts are unlikely where current best-practice grazing management occurs, but would be possible on structurally degraded soils where surface cover is allowed to fall below critical levels. Thomas et al. (2010) found that grazing stubbles was worth $15–20/ha/year on average, which equates to approximately 100 kg of wheat grain. Hence, where livestock enterprises obtain only small benefits from grazing crop stubbles, it may be sensible to avoid the risks of soil damage by livestock. However, the potential risk and cost would be offset when greater benefits can be obtained by the integration of livestock in cropping systems via grazing dual-purpose crops or ley pastures.

Long-term grazing effects on grassland soil properties in southern British Columbia in spring versus fall season grazing as well as grazing [at a moderate rate of 0.6 animal unit months (AUM) ha^{-1}] versus non-grazing by beef cattle on selected soil properties 20 and 30 year after the establishment of the field experiment were studied by *Evans et al. (2012).* Spring grazing had greater soil bulk density, greater mechanical resistance within the top 15 cm of the soil profile, higher pH, and lower polysaccharides as compared to fall grazing for both treatment years. Greater soil bulk density, mechanical resistance, and pH were observed under the grazed treatment relative to the control without grazing. Since a moderate stocking rate was used in this study unlike previous studies, long-term grazing did not have critical detrimental effects on soil properties.

In Atlantic agroecosystem land use, progressive decrease in livestock is one of the most expected changes *(Rounsevell et al. 2006),* especially in mountain areas affected by the removal of the European Union subsidies for marginal grazing land (*Strijker 2005; Taylor 2006)*. Soil microbial community function is very sensitive to the impacts of livestock grazing exclusion. *Aldezabal et al. (2015)* evaluated the effect of grazing abandonment on microbial function and diversity through changes promoted in aboveground vegetation and soil properties. Grazing abandonment for 5 years induced shifts in floristic composition, decreased soil compaction at 0–10 cm soil depth, and reduced soil temperature in the summer due to a thicker plant layer. Subsequently, soil enzymatic activities and microbial biomass were reduced, and CO_2 emissions and metabolic quotient were increased, indicating a lower metabolic efficiency of soil processes in excluded plots. The bacterial community was more diverse compared to the fungal community, but no significant difference in bacterial species richness was found between excluded and grazed plots. Microbial genetic diversity was not directly correlated with aboveground vegetation diversity and no clear pattern emerged as a response to grazing abandonment, probably because soil microbial diversity depends on site attributes that operate at a very fine spatial scale.

The long-term (25-75 yr) elimination of grazing on semi-arid rough fescue grasslands in the southern interior British Columbia and the associated greater above-ground biomass and canopy cover of rough fescue measured in 2007 on ungrazed plots were not associated with differences in soil total C and N between pastures with and without grazing. However, long-term elimination of grazing had increased the labile pool of soil organic matter as reflected by greater soil polysaccharides. Soil compaction (as characterized by bulk density and mechanical resistance) was greater on plots with long-term grazing relative to those without grazing. *Krzic et al. (2014*) advised that soils in these grazing-sensitive grasslands need more than 75 years to fully recover from the impacts of overgrazing.

Concentrations of SOM, Total nitrogen, Ca^{2+} and K^{+} in soils, as well as, water infiltration rate and basal soil respiration improved progressively following 6- and 12-year exclusion of livestock in a degraded *Stipa tenacissima* steppe in South Tunisia (*Jeddi & Chaieb 2010)*. The results suggested that excluding grazing livestock on the arid degraded steppes had a great potential to restore vegetation and soil. Exclosures enhanced the total plant cover, the dry matter yield, the number of species per unit area and the Shannon–Wiener diversity.

Production systems based on single crops and grazing of crop leftovers have produced grave soil degradation problems in soils of Venezuelan savannas. *Lozano et al. (2010)* proposed some conservation management systems as alternatives to prevent degradation and improve the quality of these soils. The introduction of cover crops (*C. macrocarpum* and *B. dictyoneura*) produced significant changes in the superficial horizon (0 to 5 cm), in most of the physical properties of the Typic Plinthustults soil evaluated (bulk density; saturated hydraulic conductivity; porosity; and resistance to penetration), as compared to the plant cover in natural savanna. Besides, grazing activity did not have a negative effect on the physical properties evaluated, since in spite of there being variation due to grazing in some properties, values are far from the critical levels that affect plant growth.

In Finland, compaction of a heavy clay soil (Vertic Cambisol) to a depth of 0.4-0.5 m owing to high axle load traffic tended to reduce yields and nitrogen uptake of crops for several years, even though the soil froze at least to the depth of soil compaction in most years. Yield losses were most pronounced in the first 3 years and the rainy sixth year after the compaction. The heavy clay soil of this study, with a good natural structure, appeared to be able to maintain moderate fertility despite the compaction. Compaction of a well-decomposed peat had a clear effect on the growing of barley and spring oilseed rape. Nitrogen yield was found to be more sensitive measurement of the influence of soil compaction than seed yield. The bulk weight or the thousand-kernel weight of yields was not notably affected by the compaction *(Alakukku & Elonen 1995)*.

APPENDIX 2: WET-SIEVING METHODOLOGY COMPARISONS

The review of wet-sieving technologies by Imhof (1986) provides a detailed listing of the use of wet-sieving methods in agricultural studies. Some additional studies are listed here as well as details on field-based wet-sieving kits.

Beare and Bruce (1993) describe the effects of different pre-treatment conditions and wet-sieving procedures on water-stable aggregate distributions of sandy and clayey textured soils in Georgia, USA. Four soil pre-treatment procedures were compared: (1) air-dried, capillary wetted (AD-CW), (2) air-dried, tension wetted (AD-TW), (3) air-dried, slaked (AD-SL), and (4) field-moist, capillary wetted (FM-CW). Air-drying soils resulted in a greater quantity of aggregates in the coarser fractions (> 250 *μ*m), as compared to field-moist soils, with a consequent reduction in the finer fractions (<250 *μ*m). Differences between methods of wetting air-dried soils were more pronounced for the clayey soils where both AD-CW and AD-SL resulted in a greater proportion (22–24%) of the soil mass in the finer fractions (<250 *μ*m), as compared with AD-TW (4.5%). The FM-CW procedure had the lowest coefficients of variation (2-8%) for repeated measurements.

The AD-CW and FM-CW procedures were also used to compare the effects of cropping systems [conventional tillage (CT) (soybean/fallow), CT (sorghum/fallow), and no-tillage (NT) (sorghum/clover)], erosion classes (slight, moderate, and severe) and irrigation (drip-irrigated or non-irrigated) on water-stable aggregates (>250 *μ*m). In general, water-stable aggregates increased with decreasing intensity of cultivation, increasing severity of erosion and irrigation. Air-drying soils resulted in less differences in water-stable aggregates between treatments, but provided more detailed information on the interactive effects of cropping system and irrigation as compared with the field-moist condition. Similar differences were observed in aggregate disruption rates that were calculated from the aggregates recovered after wet-sieving for intervals of 1–32 min. Although water-stable aggregates were lower by FM-CW, this procedure showed greater separation of treatment means (e.g. erosion classes) than the AD-CW procedure.

Also compared single versus multiple-sieve techniques for describing the effects of pre-treatment conditions on aggregate distributions. For the clayey soil, a fine fractionation into eleven aggregate size classes revealed the greatest differences (P<0.05) between the FM-CW and AD-CW procedures, while a coarse fractionation into macro- (> 250 μm) and micro- (< 250 μm) aggregates showed no differences. However, for the sandy soil, differences in aggregate distributions between the FM-CW and AD-CW procedures were found at most levels of fractionation, but were not detected by comparing the calculated mean weighted diameters. In general, findings emphasise the value of comparing soil-specific responses to different pre-treatment conditions, particularly those that compare the distributions of aggregates among size classes, as a means for describing environmental influences on soil structure.

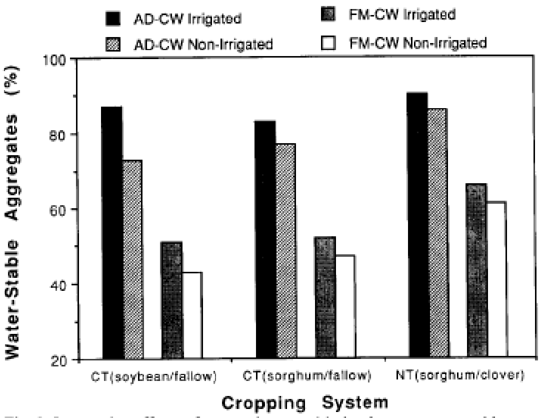
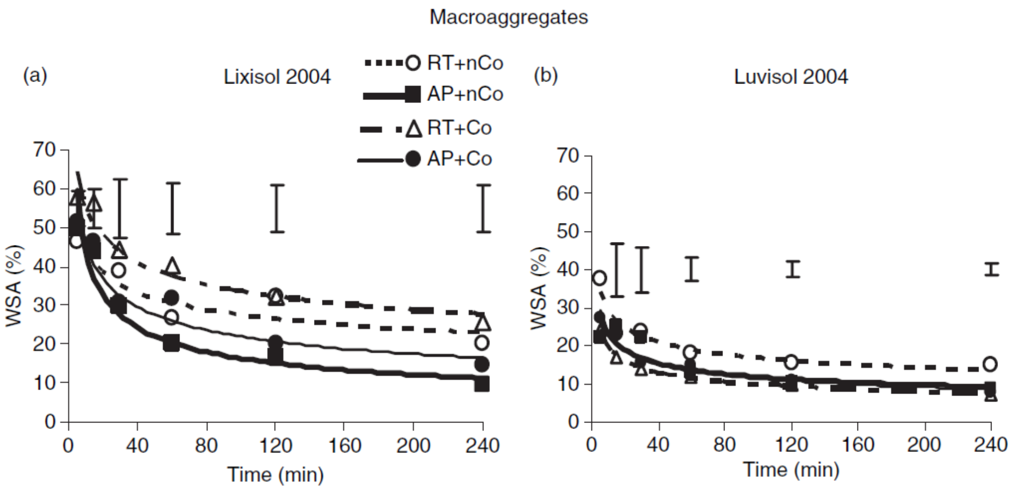


Fig. 3. Interactive effects of crop culture and irrigation on water-stable aggregates (> 250 μm) recovered following AD–CW and FM–CW pretreatment of soils from site 4. Values are adjusted treatment means ($n = 3$) from the ANOVA across erosion classes.

Outtara et al 2016 Effects of ploughing frequency and compost application in cotton-maize rotation in Burkina Faso



Aparicio and Costa 2007

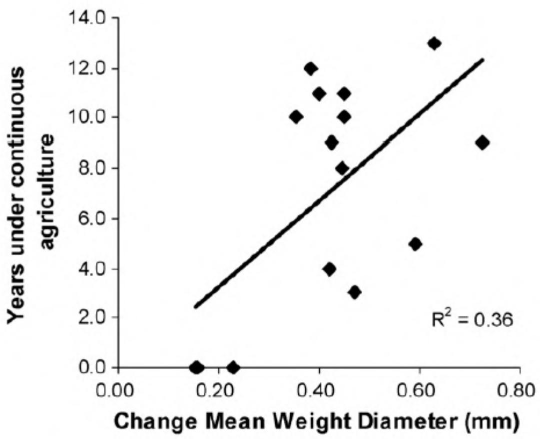
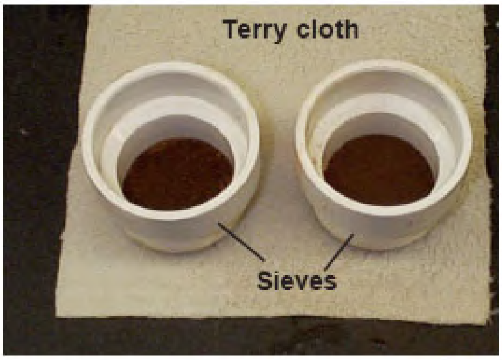


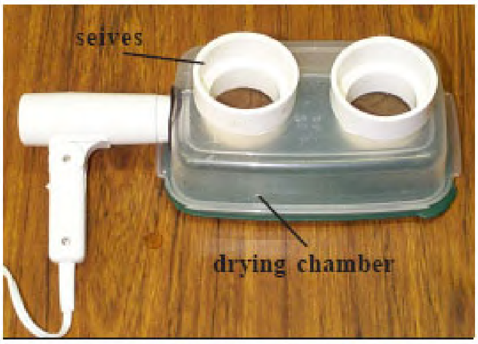
Fig. 6. Change in the average diameter weighed based on the years under continuous cropping for the three studied establishments.

A recent study by Sarker et al. (2018) assessed the effect of different long-term farming systems/practices and site-specific conditions (such as soil type, soil texture and SOC content) across Australia on soil aggregate stability using dry and wet aggregate separation techniques (Devine *et al*. 2014; Six et al. 1998). The Mean Weight-Diameter (MWD) of soil aggregates separated by dry and wet sieving approaches was calculated by multiplying the proportion of soil in each aggregate-size class by the mid-point of the size class and then summing those values (Devine et al., 2014). High values of dry (Dry MWD) and wet MWD (Wet MWD) indicate a more cohesive soil condition, with less susceptibility to tillage, wind or water erosion (Gajić *et al*., 2013). The Aggregate Stability Index (ASI) was calculated by dividing the WMWD by the DMWD; an index of 1 represents completely stable structure (Devine et al., 2014). In the Luvisol at Condobolin (Central West Farming System trial), the perennial pasture and no-till farming systems had higher soil aggregate stability than the conventional tillage and reduced tillage systems, with no impacts of management on SOC and total N, S and P stocks at all depths. The tillage and stubble management practices in the Luvisol at Merredin and Vertisol at Hermitage had no impact on soil aggregate stability.

A study by Pulido Moncada *et al.* (2013) compared aggregate stability tests for soil physical quality indicators. Although there is not a sole satisfactory methodology that applies universally up to now, aggregate stability has been proposed as an indicator of soil physical quality (SPQ). Difficulties persist when comparison of aggregate stability from different procedures are performed. The objective of this study was to evaluate appropriate aggregate stability methods that enable to distinguish the SPQ condition of both temperate and tropical medium-textured soils. Among different methods tested, results show that wet-sieving using the well-known rapid wetting methods of Kemper & Rosenau (1986) and of Le Bissonnais (1996) rendered similar results in both environments. The mean weight-diameter value of both methods for assessing aggregate stability can be considered as a dependable indicator of soil structure status for comparing soils. These aggregate stability methods are in correspondence with only one out of the eight SPQ indicators when entirely soils were used. It was concluded that the aggregate stability should be used judiciously, and in concert with other indicators, for an overall assessing of SPQ condition.

Field wet-sieving techniques





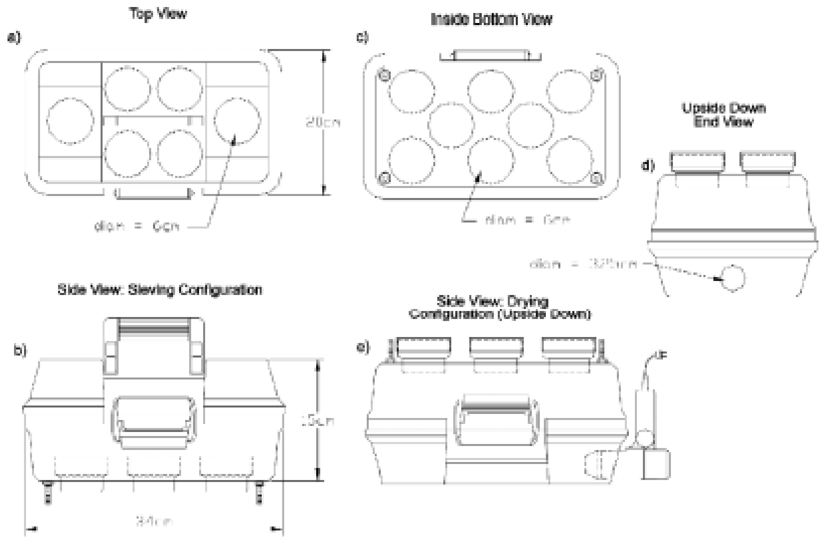
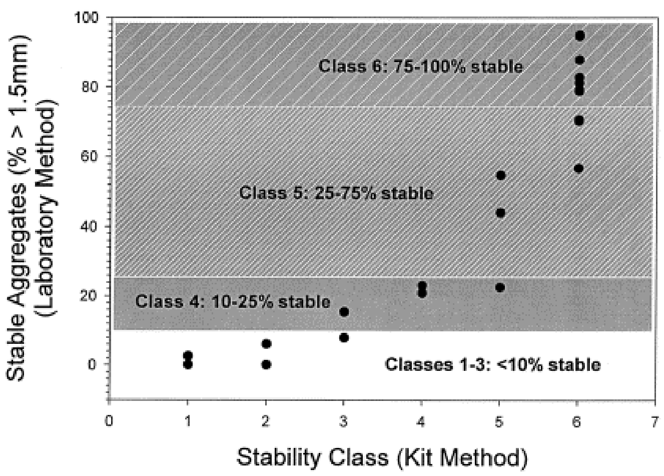


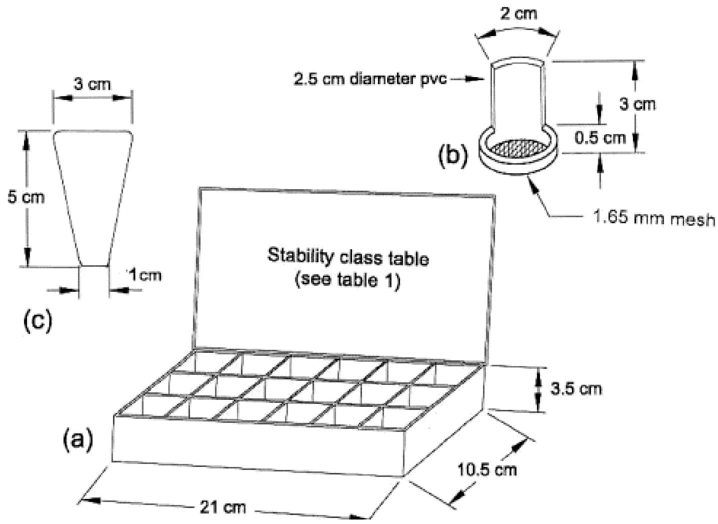
Fig. 2. Diagram of constructed combination sieving and drying apparatus: (a) six 6-cm viewing holes in top of trunk-style tackle box; (b) side view of sieving configuration with sieves; (c) inside bottom view of tackle box showing eight 6-cm sieve holders; (d) upside-down end view of tackle box showing insertion hole for hair-dryer; (e) side view of tackle box showing drying configuration with sieves and hair dryer.

The USDA developed field kits using 0.25 mm aperture sieves.

Field kit (Herrick *et al.* 2001).

Herrick *et al*. (2001) developed a field-based soil stability kit that is inexpensive and easily assembled and permits many samples to be evaluated quickly. Soil samples are rated on a 1-6 scale based on combination of observations of slaking during the first 5 minutes following immersion in distilled water, and % remaining on a 1.5 mm sieve after five dipping cycles at end of 5-minute period. Permits up to 18 samples to be evaluated in less than 10 minutes and eliminates need for transportation, minimising damage o soil structure. The kit has been adapted for use in citizen-soil quality monitoring program in Illinois (USA) and has been found to be highly sensitive to differences in management and plant community composition in rangelands.




2 cm
2.5 cm diameter pvc
3 cm
0.5 cm
(b)
1.65 mm mesh
3 cm
5 cm
1cm
(c)
Stability class table
(see table 1)
3.5 cm
(a)
10.5 cm
21 cm

APPENDIX 3: WORKSHOP AGENDA AND ATTENDENCE LIST

Program 2: Soil Performance Metrics

Workshop for Scoping Studies 2.1 and 2.2

March 26th to March 28th 2018

AgriBio Centre, Melbourne

Victoria Room A – AgriBio Centre

Agriculture Victoria Research, 5 Ring Road, La Trobe University, Bundoora, Victoria 3086

Map: https://www.google.com.au/maps/@-37.7240167,145.0526348,17z?hl=en

AGENDA

Monday 26th March

Victoria Room A will be available from 9am for team meetings, etc.

Lunch at 12 noon

Workshop commences 12:30 pm (Facilitated by ***Pete Dahlhaus***)

Welcome and recap of Scoping Project 2.2

End-User focus:

- What are end-users' expectations from this workshop?
- Why are end-users interested in this workshop?

Researchers and developers focus:

- Physical indicators: report from the review team
- Chemical indicators: report from the review team
- Biological indicators: report from the review team
- Results of online questionnaire to date

Discussion: thoughts on indicator needs, integration, scale, precision, proxies, etc.

Workshop dinner: at The Stolberg, 197 Plenty Rd, Preston

Finger food at 6:30pm, Dinner at 7:00pm (Drinks at your own cost)

Tuesday 27th March

Workshop commences 8:30am (Facilitated by ***Marcus Hardie / John Bennett***)

Welcome and recap of Scoping Project 2.1

Possible solutions – who is doing what?

- Existing sensors for indicators: reports from review team
- Proposed analytical methods: reports from review team

What else is doable in the sensor space?

- Workstation discussions: physical, chemical, biological, contact / aerial / remote etc
- Reporting back

Lunch - 12 noon

Small group discussions: concurrent sessions for indicators & sensors

Sensors (Review 2.1) *(Marcus & John)*

- Recommendations from Scoping Review
- Scope, context, purpose, engagement and focus
- Future research emphasis on: measurements?, technologies?, standards? data? prototypes? fully-developed? applicability?
- Draft proposals: sensors, analytics, methods, etc.
- Final consensus?

Indicators (Review 2.2) *(Mark, Bryan, Doug, Pauline, Gwen)*

Research design for project(s) to explore pragmatic and practical indicators for:

- On-farm use for decision making
- Immediate performance / Long-term sustainability (tactical and strategic decisions)
- Farmer values / Indigenous values (NZ + Australia)
- Social licence – Agro-ecosystems as clean providers of ecosystem services
- Natural capital accounting (local / national scale, contaminant legacy, fertility, etc.)
- Green labelling / consumer demands
- Food safety / biosecurity / animal health / human health

Discussion: which indicators could be / should be "sensed"?

- Best indicator(s) for each valued purpose
- Best indicators for overall assessment of soil health / high performance
- Which indicator(s) has potential to meet all required criteria (reproducibility, low analytical cost, amenable to sensor technology, clearly interpretable, quick to measure

Wednesday 28th March

Workshop commences 8:30am (Facilitated by ***Richard Doyle***)

Welcome and recap of Program 2

Brief presentation of immediate funding mechanisms (Michael Crawford)

- Upcoming CRC investment rounds, potential projects, estimated project sizes and investment, guidelines, etc.

Future projects, research and development investment

- What should the research focus be?
- Scale of the project(s) and timing?
- Partnerships and skill sets?
- Risk profile
- Measurement, technologies, standards, prototype sensors
- Sensors, proposals, analytics, methods and final consensus

End-User view

- what are you thinking now,
- what is the future looking like for you.

12:30 pm **Lunch**

Additional time for discussions on future projects, networking, establishing collaborations, etc.

Room will be available until 4:30pm

Participant list

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Jodi McLean	Soil CRC Operations Manager	jodi.mclean@soilcrc.com.au
Moragh Mackay	Federation of Victorian Traditional Owner Corporations (Guest)	moragh.mackay@fvtoc.com.au

APPENDIX 4: SURVEY QUESTIONNAIRE RESULTS AND DATA

The survey questionnaire report is available for download from:

http://data2.cerdi.edu.au/dataset/soilcrc-a-review-of-indicators-of-soil-health-and-function

The report title is:

A review of indicators of soil health and function: Farmers' needs and data management. Survey results.

The Report contains the following information:

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SOIL CRC
Performance through collaboration

Australian Government
Department of Industry, Innovation and Science

Business
Cooperative Research Centres Program