Hort Innovation

Final Report

Navigating the Wealth of Soil Health Information & Identification of Opportunities

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PT16003

Project:

Navigating the Wealth of Soul Health Information & Identification of Opportunities – PT16003

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Content

Summary

Soil health is a substantial and broad field that covers the physical, chemical and biological components of soil and their interactions. The objectives of this research project were to (a) critically review the relevant soil health literature, (b) identify critical knowledge gaps and provide direction for research priorities in soil health improvement for the potato industry, and (c) identify industry-ready information and create extension materials for delivery to potato levy payers and the industry to enable them to improve soil health, and hence productivity and long-term sustainability.

A review of the scientific literature was carried out to determine the state of knowledge of soil health, defined as the ability of soil to support agricultural productivity in the long-term, in potato production systems. The review considered the different aspects of soil health (physical, chemical and biological, how to measure them and how they can be influenced by management practices. The review used over 220 references from relevant Australian and international sources with a focus on peer-reviewed journal articles.

A draft review and a preliminary plan for future investment formed the basis of the collaborative scientific workshop held on November 16 and 17, 2017 in Melbourne, Victoria with 18 national and international delegates. The workshop identified critical industry priorities, existing knowledge and tools, what soil health tools the industry would like and how soil health practices should be communicated to growers followed by thinking into the future and scoping potential prospective R&D areas. Interviews with other industry personnel throughout the year ensured that outcomes have industry relevance.

Other key outputs included communication and extension materials for delivery to potato industry stakeholders. Key points disseminated through multi-media videos, fact sheets and oral presentations included:

- The use of tools and practices to encourage sustainable practices including those outside the potato crop (e.g. cover crops/pasture),
- Reducing tillage and traffic, particularly when soils are wet,
- The use of strategic grazing to remove potato volunteers and reduce soilborne pathogen levels,
- Organic matter content as a useful surrogate measure of soil health

The project also identified skepticism about soil health practices and potential barriers to adoption. Demonstrating benefits (including financial) of healthy soil is essential. If the soil is more robust and resilient it may allow for shorter rotation times between potato crops, reduced powered implement demands, provide a greater return as a leased paddock and provide a better image of a sustainable end-product.

Eight potential soil health projects were identified including:

a) Identifying regional soil health drivers of yield gaps/yield decline
b) The potato soil microbiome and productivity
c) Understanding the potato soil microbiome and its link to soil health under different management strategies
d) Mycorrhiza for enhancing potato production and disease suppression?
e) Healthy soils for shorter rotations
f) Improving soil structure and reducing compaction
g) Volunteer and weed management in potato systems
h) Better predictive systems using local soil factors

It was also recommended that future research relating to soil health should encompass a number of basic principles including the use of multiple locations, production systems and discipline areas, and projects that enable field testing over a minimum of five consecutive years.

In summary, the key messages from this project will encourage the uptake of sustainable and profitable potato practices, while the recommendations will provide additional areas of focus to gain the most benefit from better understanding soil health.

Keywords
Soil health; potato; sustainability; productivity; literature review; grower extension videos; investment plan

Introduction

Maintaining, and improving, soil health is of vital importance across the agricultural sector. Understanding the physical, chemical and biological processes and interactions underpinning healthy soils is vital to managing soils for long-term productivity. There have been several major research programs in soil function and soil health in Australia over the last ten years, including those funded by Hort Innovation (previously HAL) and other industry bodies including the Grains Research and Development Corporation (GRDC).

The structure of soil, its formation, resilience and recovery after disturbance is key to understanding what constitutes a healthy soil and how to protect it. It is well recognised that elements of soil physical structure, such as aggregation, porosity, and pore continuity and size distribution, have an important influence on internal drainage and aeration, and hence the ability of the soil to provide an environment that enhances beneficial soil biology. Collectively, these factors are important foundations of soil health. In mechanised cropping systems which are highly disruptive, soil management approaches which minimise repetitive destruction and reformation of soil structure are an important part of achieving healthy soils.

A diverse community of living organisms is considered one of the components of a healthy soil. These organisms include earthworms, arthropods, nematodes, fungi, protozoa and bacteria. Whilst some of the larger organisms can be collected and, to some extent, identified visually, the range of microorganisms and the functions they perform in the soil is much more difficult to determine. Recently, powerful DNA based tools that provide 'fingerprints' of the overall structure of microbial communities have become more affordable and, for example, formed the basis of data generation in the GRDC Soil Biology Initiative "Harnessing the biological potential of our soils" project led by Dr Paulene Mele.

Understanding the interactions between the soil environment and the organisms living within it is important for understanding and controlling soil borne plant diseases. The complexity of the soil ecosystem means that physical and biological factors that promote (or reduce) the growth of disease causing organisms interact with factors that promote (or inhibit) the growth and resistance of plants. Climate, soil conditions, competing organisms and plant host genetics all have a role in determining the severity of any disease in a particular crop in a particular season.

The wealth of knowledge on these topics can be overwhelming. The objective of this work was to enable potato growers to increase productivity by providing them with the knowledge of what constitutes a healthy and productive soil and what the current best practices are for improving soil health. **The project provided an independent and comprehensive review of the current state of knowledge of factors influencing agricultural soil health, a plan for future investment and a package of communication and extension materials.**

Methodology

The project methodology involved four key activities:

1) Extensive review of relevant literature pertaining to soil health. This substantial review focused on the potato industry but drew on relevant literature from other crops where related work provided cross-commodity benefit. The review encompassed all aspects of soil health (i.e. physical, chemical and biological components) that are required for resilient and healthy cropping soils. *There was a distinct focus on practical aspects that could be related to crop productivity and profitability*. Over 220 journal articles, books and industry reports from both Australian and International sources were utilized and cited in the review, with a focus on material that had already been peer reviewed. An initial draft review was prepared in the first six months of the project and this was provided to Hort innovation and workshop participants as background to inform the collaborative workshop. Feedback received by the research team during and after the workshop was utilised to finalise the literature review of soil health R & D for the potato industry. In addition to collation for reporting to Hort Innovation and industry, the review will be published in a peer-reviewed scientific journal to authenticate the high level of independent scientific expertise used in its production.

2) Scientific workshop review and planning session. In consultation with Hort Innovation and industry bodies (PPAA) we identified experts from the broad fields of potato/vegetable pathology, soil science, cropping systems, diagnostics, soil biota community analyses, physical and chemical soil assessment, and soil nutrition, to invite to the 2-day workshop. Additionally, growers and industry representatives were also invited. In total, there were 18 attendees over the 2-day workshop which ran as facilitated round-table discussions. On day 1 the key topics included identifying the critical industry priorities and existing knowledge and tools that industry can use, what soil health tools the industry would like and how soil health practices should be best communicated to growers. Day 2 focused on thinking into the future and identifying tools and technologies that might most benefit industry, followed by a scoping of potential prospective R&D areas.

Approximately 1 month after the workshop a summary of the key outcomes was provided to workshop attendees to seek participation feedback and input into the workshop outputs.

3) Soil health project outputs for industry. Further interviews and discussion with other industry personnel and a range of growers (fresh, processing and seed) throughout the year consolidated many of the findings and ideas of the workshop and ensured that outcomes would have grower and industry relevance.

For grower benefit we prepared the following extension and communication tools: a 1 page snapshot of key soil health concepts, including practices, tools and technologies that will aid growers in improving soil health. We have also provided links to key soil health websites that promote sustainable practices on the back page of this document. We have also prepared four 5-minute multi-media videos of potato growers discussing key soil health issues and how they can be applied. All these communication tools will be made freely available on the internet (Youtube for videos, Ausveg newsletter for articles) and also supplied to Hort Innovation for their usage in other communication (PT15007) and extension programs. Some key outcomes for growers will also be communicated in the July/August 2018 Potatoes Australia issue.

For industry benefit, we have also prepared a catalogue of the most significant soil health issues/challenges facing or likely to impact the industry, and a listing of research priorities to address these knowledge gaps for the benefit of growers.

4) Final Report. This will document all phases of the project and will outline the project background, methodology, outputs and outcomes, monitoring and evaluation, and project recommendations. The appendix in the final report will include detailed outcomes from the scientific workshop and a copy of the literature review.

Outputs

The main outputs from this project were:

1. Literature Review. An extensive review of the literature on soil health pertaining to the potato industry was produced. This was provided to expert workshop participants and formed part of the basis for the investment plan. This review is provided as an appendix in this report (Appendix 1).

This review will also be published as a peer-reviewed scientific paper and we are shortly to submit this paper to the International journal, 'Agriculture Ecosystems and Environment'. The journal publication process is useful for validating the scientific merit of the review.

2. Workshop. A workshop with national and international experts in soil health was held on November 16 and 17, 2017 in Melbourne, Victoria, to gather feedback on the draft review and develop priorities and recommendations for future investment in soil health by the potato industry. The invited workshop included:

- 18 participants over 2 days
- 5 round table discussion sessions

A summary of workshop attendees and key points from each session are included in Appendix 2.

3. Soil health outputs for industry. A summary of the key outputs for industry has been developed and these have been, and will continue to be, disseminated to the potato industry and growers at appropriate forums.

We have provided the following materials to aid in the communication of the project objectives and outcomes:

Industry magazine, newspaper articles, media

- ABC radio interview 3rd July (ABC Hobart Drive Program) promoting project and objectives (attached as audio file)
- Potatoes Australia Aug/Sept 2017 providing project objectives and asking for industry feedback - https://ausveg.com.au/app/uploads/publications/Potatoes-Australia_August-September-2017_V11_Web.pdf (page 8)
- Tas Country (13 April 2018) promoting the project and providing key grower messages (Appendix 3)
- Potatoes Australia June/July 2018 summarizing the key project outcomes for grower benefit - https://ausveg.com.au/app/uploads/publications/Potatoes-Australia_June-July_Web.pdf (page 9)

Multi-media format videos (Appendix 4) and fact sheet (Appendix 5)

- 5 multi-format 4-7 minute videos of growers discussing soil health have been provided to Hort Innovation for their use. This material will also be available free through Youtube with links provided in the AusVeg Weekly updates.
- A fact sheet will be provided to Hort Innovations for their use. It provides the key grower messages for implementing sustainable soil health practices and useful Web resources for growers who want additional information on soil health.

Project summary presentation

- A powerpoint presentation of the key outcomes and specifically key project recommendations has been provided to Hort Innovation.
- This presentation was also provided to the SIAP on June 26, 2018 at Melbourne Airport.
- A presentation to growers on key project outputs was made at the 2018 Potato Industry Conference (August 12-14, Melbourne, VIC).

4. Final Report. This final report is a key output but within it we would like to highlight the following outputs:
Future proposed areas for research investment

We have proposed eight separate project topics that we consider worthy of future investment:

a) Identifying regional soil health drivers of yield gaps/yield decline

b) The potato soil microbiome and productivity

c) Understanding the potato soil microbiome and its link to soil health under different management strategies

d) Mycorrhiza for enhancing potato production and disease suppression?

e) Healthy soils for shorter rotations

f) Improving soil structure and reducing compaction

g) Volunteer and weed management in potato systems

h) Better predictive systems using local soil factors

These projects were derived based on knowledge gaps identified in the literature review and feedback from workshop and industry interviews. The projects include basic science (e.g. b, c) which have the potential to unlock and discover largely new areas – such projects provide greater risk but the long term benefits are substantial. Most of the other projects are largely applied in nature and are likely to provide substantial insight and incremental improvement into strategies for improving soil health management.

It was also recommended that future research relating to soil health should encompass a number of basic principles including the use of multiple locations, production systems and discipline areas, and projects that allow field testing over a minimum of five consecutive years.

Outcomes

The key outcomes of this 1-year-project are two-fold:

<u>Literature review and investment plan for future</u>

The specific target audience for these scientific findings will be research communities, and funding and industry bodies interested in soil health within the potato sector.

The Literature review has been completed as a part of this project and appears in Appendix 1.

The recommendations of this project have been provided in this Final Report so are also available. This provides a plan for future potential research activities that the project team believe will provide maximum benefit to the potato industry in the soil health field. The outcomes of these recommendations will be post-project completion (medium to long-term) and dependent on SIAP priorities and the level of funding and resources to support the recommended research projects.

Notwithstanding, Hort Innovation and the SIAP will have reasoned and informed recommendations for decisions on future investment by levy payers into improving soil health across the industry.

<u>Soil health project outputs for industry</u>

The specific target audience for these more applied findings are the growers and associated industry bodies.

Recommendations that improve practical crop management, with an emphasis on soil health, have been made available through videos (Appendix 3), fact sheets (Appendix 4) and oral presentations to the SIAP panel and at the 2018 Potato Industry Conference. This is the most productive way of targeting a large proportion of potato growers.

Potato growers, and researchers, will be able to access user-ready information for improving productive soil health. We expect that growers will use this information, where possible, to improve the productivity and long-term term sustainability of their business. The uptake and adoption change of these communication/extension outputs is not able to be assessed in this project as most of these materials will be made available after project completion.

Monitoring and evaluation

Overall, the project has delivered on the key criteria established during the planning stage of this project. A range of outputs and outcomes have been met as described above. Other outputs/outcomes will occur after project completion, including some communication/extension activities and most importantly the potential development of new projects, as provided in the recommendations section below.

Key Evaluation questions (KEQ's) for the project are provided below with an indication of whether project expectations were met:

<u>What has been the impact and/or outcome of the project?</u>

- What are the immediate outcomes as measured by improved awareness of the available extension materials
- To what extent has the project contributed to increased knowledge
- To what extent has the project contributed to the goals of the stakeholders and Hort Innovation

The extension materials (videos, fact sheets) will be available soon after project completion, so it is impossible to comment on their potential outcomes at this time. While some extension activities were planned as part of the project, the cessation of the potato extension program (PT15002) did not enable dissemination of our material at those seminar days planned. Key outcomes of the project have been provided in a recent June/July2018 Potatoes Australia article and this should encourage discussion and knowledge transfer between growers. There will also be an opportunity to provide growers and the potato industry with key project outcomes through a formal presentation at the 2018 Potato Industry Conference (12-14th August, Melbourne, Victoria); an event that attracts over 200 grower and industry representatives.

The project has contributed significantly to the stakeholders and Hort Innovation by providing a reasoned and independent review of soil health material and the identification of potential future projects that will aid the sustainability and productivity of the potato industry. The impact of these recommendations can only be determined by the SIAP, and progression of any of the recommended projects would indicate that this project met expectations.

<u>To what extent has the project met participation objectives?</u>

- How effectively has the project shared its findings with stakeholders and the broader agricultural community?
- Did the project achieve its outcomes measured or otherwise?

As stated above, apart from a recent Potatoes Australia article, most communication and extension to growers and the industry will be after project completion through fact sheets, videos and a conference presentation.

Communication with key stakeholders has been effective with industry representatives involved through attendance at the workshop, formal and informal interviews, and/or through e-mail feedback on project recommendations. Additionally, a summary presentation to members of the SIAP on June 26 2018 enabled further communication and feedback on project outcomes and recommendations.

As stated above, this project met the two key outcomes as described above.

How effectively was the project delivered?

- Timeliness, within budget
- What impacted on these?

The project has been undertaken on budget. The timeline for this project has been pushed out by 2 months and this has been mainly been due to unavailability of growers to do the soil health videos, which are an essential component for extending the project findings. This has resulted in this minor delay. It is also worth noting that the cessation of PT15002 has meant that we will now deliver the key communication/extension activity at the Potato Industry Conference post-project completion.

How appropriate was the design of the project in order to meet the outcomes?

- To what extent were the project methodologies and approaches appropriate for meeting project outcomes

Our interactive workshop, which brought together industry and academic experts, was a key component of the project that has enabled the key outcomes and recommendations to have academic and industry rigor. The funding of this workshop was a critical component of the project which enabled us to meet project outcomes (described above).

What resources have been used to run the project?

- How could the project have been run more efficiently
- What other resources, in-kind or otherwise were used to meet the project outcomes

The one-year project used a diverse range of expertise, with some of the input from TIA and from industry being in-kind, which aided in achieving project outcomes. A successful extension program (PT15002) would have aided dissemination of material to industry through oral presentations, but the opportunity to present at the 2018 Potato industry Conference should provide a superior alternative for reaching more growers and industry.

Recommendations

1. Grower tools

A major recommendation from this project is that key issues relating to soil health and their important link to 'productivity and profitability' are promoted and extended to potato growers and the industry.

As such, we have provided some initial extension material that summarises key principles that growers can implement, if they are not already doing so. We also provide links to other soil health material that may benefit potato growers.

Additionally, we present four grower snapshot multi-media videos which cover the soil health practices they are using in their potato growing operation. The growers come from major Australian production regions.

We recommend that these materials be extended to potato growers wherever possible.

2. Principles of future projects relating to soil health

Soil health is something that needs to be considered from a long term perspective and from a range of discipline areas, cropping systems and environmental regions. A solution to a problem in one area may not be applicable to another. If projects are to provide benefits to all potato growers they should aim to test hypotheses that encompass:

- Multiple locations covering a diverse range of environmental and agro-ecological differences.
- Multiple potato production systems e.g. (potato – long term pasture rotations vs continuous vegetable cropping rotations) and also market requirements (fresh, processing (French fries, crisping), seed)
- Five consecutive years (soil health benefits are rarely demonstrated in the first few years of a project).
- All components of soil health (biological, chemical, physical) and use expertise from a range of disciplines (microbiology, soil science, pathology, agronomy, engineering).

3. Future proposed areas for research investment

Below are recommendations for potential future research projects based on the knowledge gaps identified through this project.

Soil health in different agro-ecological zones

a) Identifying regional soil health drivers of yield gaps/yield decline

Given the diversity of production regions and soil types (e.g. heavy textured soils of Tasmania to the light sands of the Mallee region) in the Australian potato industry, it is likely the physical, chemical and biological health of soil, and how management practices affect these, will vary considerably.

A research project will:

Characterise the locally relevant soil management systems used by growers in the major production regions to help identify the particular strengths and weaknesses of various production systems and environments and the regional soil health drivers of yield gaps/yield decline.

Expected outcome: Scientifically justified reasoning as to what soil management traits of a potato growing operation provide it with a distinct advantage (and increased profitability) in a distinct production region – these beneficial characteristics/traits would be encouraged and promoted. Likewise, the negatives associated with yield decline can be identified – and if important – prioritized as a research objective.

Soil biology and healthy soil communities

b) The potato soil microbiome and productivity

Soil community analysis is a new technology that allows a greater understanding of complex microbiological processes that occur in the soil. Changes in communities may be a result of practice and/or cultural change but it is likely that there will also be community properties or markers that are associated with highly productive potato soils. Linking the soil microbiome to known function is an evolving research area that has significant potential for knowledge gain and benefit to potato growers.

A research project will identify:

- Whether soil community analysis can be used as a surrogate or an indirect measure of soil health.
- Whether potato crop productivity can be interpreted through soil community analysis.
- Specific soil community markers that are indicative of productivity.

Expected outcome: Scientific findings at both a basic and applied level that provide greater knowledge of this evolving technology with benefits to the research community and the potato industry. Long-term benefits include a potential new soil health test for growers.

c) Understanding the potato soil microbiome and its link to soil health under different management strategies

Changes in soil communities, measured by soil community analysis, may provide a measure of improvement or decline in soil health.

A research project will identify:

- How soil communities change with potato production practices: detailed comparative analyses of native soils vs potato cropped soils vs cropping soils not used for potatoes
- How potato rotation length (continuous, 3 year, >6 years) impacts soil communities
- How soil conditioning treatments (tillage, cover crops, pastures) impact soil communities.

Expected outcome: Scientific findings that link changes in soil communities with different management practices. This project has the opportunity to identify what communities are more robust and resilient to change and what community populations are more transient in response to varying practices.

d) Mycorrhiza for enhancing potato production and disease suppression?

Mycorrhizal fungi have the potential to improve the growth and performance of potato crops by improving the interface between the soil environment and the potato root itself; however sound scientific research is a pre-requisite for identifying the potential in this area. Productivity gains and increased capacity to suppress pathogen attack are key outcomes attributed to the use of mycorrhiza.

A research project will provide:

- Evaluation of the benefits for potato yield and soil-borne disease suppression of mycorrhizal fungi across different Australian potato production systems
- Methods to efficiently establish mycorrhizal associations through application of inoculants and/or encourage naturally occurring potato-associated mycorrhizal fungi in intensive potato production systems.
- Economic analysis of the cost:benefit of promoting mycorrhizal associations in potato.

Expected outcome: **Independent scientifically** justified findings into mycorrhizal usage in potato production systems.

Resilient and robust soils

e) Healthy soils for shorter rotations

The time between consecutive potato crops varies with the farming system, the cultivar and purpose of the crop (processing, fresh, etc.) amongst a range of other factors. Australian potato rotations are generally fairly long (about five years) compared to rotations in other countries (USA – typically a 2-3 year rotation). Given that potatoes would often be the most valuable crop in the rotation, there may be scope to shorten the rotation in some cases, particularly where strong soil health practices have created a more robust soil.

Through regionally focused data gathering, a research project will identify:

- Soil management practices used by growers in relation to their rotation length.
- The impacts of rotation length on a standard suite of soil health measures; including pathogens.
- The impact of rotation length and other management practices on profitability and long-term productivity.

Expected outcome: Rotation length should be chosen based on the ability of a soil to produce a high quality profitable crop, sometimes little scientific evidence is utilized in determining rotation length, rather a standard length is used. Scientific measurements (pathogen, disease, marketable yield) generated under a number of rotation/management strategies will provide industry with more information into identifying opportunities for altering (shortening) rotation length - this may lead to greater flexibility in paddock usage.

f) Improving soil structure and reducing compaction

Organic carbon (OC) is a key measure that many growers will use to gain an insight into how their cropping ground is performing. Without close attention to soil management practices and deliberate organic matter return to the soil, OC will decline over time with continual cropping

A project will:

- Conduct long-term studies of soil health changes associated with lower disturbance soil management practices, such as reduced traffic and tillage.
- Study the impact of regular single species and diverse cover crops on soil OC in a range of different potato production systems (Note that this work may be partially covered in current Vegetable levy projects).

Expected outcome: Better knowledge of the timeframes required to improve physical soil health (compaction problems) and build organic matter. Can change occur in one year or five years and how long does the residual benefit of increased organic matter and reduced compaction damage last?

Integrated disease management

g) Volunteer and weed management in potato systems

The presence of potato volunteers and key weed species that host potato pathogens through a rotation break reduces the benefit of that rotation break. Volunteer tubers can be difficult to control and control strategies will vary based on the farming system used e.g. grazing vs non-grazing option. Likewise *Solanaceous* weeds e.g. blackberry nightshade, present a challenge that can also cause increases in soil borne pathogen levels.

A research project will:

- Quantify the impact of potato volunteers and weed alternative hosts on soil-borne pathogen populations through typical rotations.
- Determine strategies (grazing, chemicals, cover crops, etc.) that are most effective for removing volunteers and weeds and reducing soil borne pathogen levels and subsequent potato disease.

- Research would need to be tested across a range of agro/environmental conditions and farming systems.

Expected outcome: Quantified measurements (including pathogen levels, volunteer numbers) that demonstrate impact of weeds/volunteers and the best strategy to reduce their impact.

h) Better predictive systems utilizing local soil factors

Across one farm there can be immense variation in soil properties (soil depth, moisture holding capacities) and general topography which can ultimately impact overall soil health and the subsequent quality of the potato crop grown. Predicta Pt and the associated training manual is a tool that can provide a guide of potential disease risk for three soil borne pathogens across a given paddock region – however other parameters can heavily influence disease progress as exemplified by the disease triangle which incorporates environmental parameters. With integrated use of soil and environmental information and mapping (EM, etc.) it is may be possible for farmers to not only more accurately identify whether disease, waterlogging, etc. may occur, but exactly where in the paddock it is most likely. This may enable better targeted management options within a paddock.

A research project will identify:

- Whether a range of integrated soil and environmental monitoring tools and data (at a farm level) can better predict crop outcomes including productivity (yield) and crop health (soil borne disease).
- What specific tools may complement Predicta Pt: soil and moisture variability, environmental monitoring data and other tools.
- Whether problem areas in a paddock be identified and strategically treated e.g. short term: chemical treatment to high risk areas of a paddock, variable rate irrigation; longer term: drainage, organic matter addition.

Expected outcome: Better predictive systems will provide greater grower knowledge on the possible constraints and limitations of a given paddock and a better decision making tool.

****Specific disease control***

This project did not have the aim to identify or prioritize specific potato soil borne disease research priorities as the key diseases have been identified in a recent report (PT13013).

Most of the recommended projects above will enable better understanding and/or controls of certain soil borne diseases. If there is a requirement to re-prioritise the importance of soil borne diseases and potential controls, a separate workshop bringing together growers, industry, service providers and researchers would be necessary.

Intellectual property, commercialisation and confidentiality

‘No project IP, project outputs, commercialisation or confidentiality issues to report’

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Appendices

Appendix 1 – Literature review

Soil Health for the Australian Potato Industry

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This project has been funded by Hort Innovation, using the Potato industry Grower and Processors research and development levy and contributions from the Australian Government. Hort Innovation is the grower-owned, not-for-profit research and development corporation for Australian horticulture.

Contents

Summary

Maintaining the health, and therefore productivity, of agricultural soils is vital for continued sustainable agricultural production to support the world's growing population. Potatoes are one of the most important food crops worldwide, including in Australia, where they are grown in a variety of agro-ecological systems. Potato crops are demanding on the soil and therefore maintaining or improving soil health can be challenging for growers. This review considers the different aspects of soil health in a potato production context, how to measure them and how they can be influenced by management practices. Soil health is a complex concept encompassing the physical, chemical and biological properties of the soil in combination with ecosystem services and below and aboveground growth of plants. Although our understanding of soil health and its impact on crop productivity has improved in the last thirty years, knowledge gaps in this area still remain, especially for potato productivity. There is a paucity of long-term studies for Australian soils and climatic

regions and, given the range of conditions in which potatoes are grown, regional guidelines on the effects of management strategies for Australian growers are needed.

Introduction

The importance of soil health to agricultural productivity and sustainability, ecosystem function and indeed human health, has been recognised for some time. Soil health has been defined in many ways; definitions often include the idea of “the capacity of soil to function as a vital living system” which acknowledges the dynamic nature of soil (Doran & Zeiss, 2000; Karlen et al., 1997; Larkin, 2015). Soil health definitions generally encompass the ability of soil to support environmental quality and the growth of plants and animals, sometimes with specific reference to “long-term sustainable agricultural productivity” (Arias et al., 2005). Kibblewhite et al. (2008) suggested that a more realistic view of soil health is to consider soil as a living system in which the functions of the soil (carbon transformations, nutrient cycling, provision of habitats through maintenance of aggregates and pore networks, and regulation of pests and diseases) are connected. There has been some debate regarding the difference between the terms soil health and soil quality but it is now generally accepted that soil quality refers to “fitness for a specific use” (Doran & Zeiss, 2000; Larkin, 2015). Here we use the term soil health because the focus of this review is on the factors that will influence the soil system, and hence the long-term productivity of the potato industry.

The potato industry and its soil health challenges

Potato (*Solanum tuberosum* L.) is the world’s third most important food crop for human consumption after rice and wheat, with an estimated global annual production in 2014 exceeding 381 million tonnes, grown on more than 19 million hectares (Food and Agriculture Organisation of the United Nations, 2017). The major global production regions include China (25%), India (8%), Russia (6%), the Ukraine (6%) and the USA (5%) (Food and Agriculture Organisation of the United Nations, 2017). Since 2005, production from developing nations has exceeded that from developed nations (Food and Agriculture Organisation of the United Nations, 2008), and it is estimated that potato provides nutrition for over a billion people.

The potato industry in Australia produces 0.35% of the world’s supply (Food and Agriculture Organisation of the United Nations, 2017). In 2014/15, the Australian industry was worth approximately AUD$660m with 1.33 million tonnes produced annually (Horticulture Innovation Australia, 2016). The major potato growing regions in Australia are shown schematically below (Figure 1).

Figure 1: Major potato growing areas of Australia (source: (Horticulture Innovation Australia, 2017))

Australia does not import fresh potatoes. Potatoes grown for processing in Australia account for about 64% of all potatoes grown for consumption, 34% are grown for the domestic fresh market while the remaining 2% is exported for fresh consumption (Horticulture Innovation Australia, 2016). Of the processing crop, the three major states by area are Tasmania (31%), Victoria (26%) and South Australia (21%). The fresh market is dominated by SA (40%), followed by Victoria (19%) and NSW (16%) (Australian Bureau of Statistics, 2016). Approximately 8% of all potatoes are grown for seed (123 000 tonnes) with 40% of these estimated to be certified (Horticulture Innovation Australia, 2016)

In Australia, potatoes are grown on a wide variety of soil types ranging from light textured sands to heavier textured loam, clay loam and clay soils. On the more productive soils, potatoes are grown in rotation with other vegetable crops (including carrots, onions, beans, peas) usually on a three – five year rotation. On the less fertile sandy soils, potatoes may be the sole intensive vegetable crop grown on a at least 5-6 year rotation with grazed pasture or cereal crops. A potato crop generally requires high inputs of fertiliser, pesticides and water along with significant tillage and traffic. Whilst these inputs are intended to increase yield, they can sometimes have the reverse effect. Pesticides are used to control disease but some negatively impact other parts of the food web (Howell et al., 2014) although these impacts are often inconsistent (Tarrant et al., 1997). Irrigation can increase yield, but some studies have also shown that at times it increases disease incidence (Larkin et al., 2011), particularly if used in excess. Traffic is particularly heavy at harvest time and the impacts of traffic can be exacerbated due to moist or wet soil conditions at harvest. Soil compaction caused by harvest traffic requires intensive post-harvest tillage for remediation. Such intense management practices can affect soil health by changing the physical, chemical and biological properties of the soil. The result can be static or decreasing potato yield and quality, or the need to increase inputs to maintain production.

Overall, the Australian potato industry faces many challenges including biosecurity threats (tomato potato psyllid), global dumping of processed products, cheaper imports and increased costs of labour: these are predominantly external challenges which are not directly controllable by growers (Horticulture Innovation Australia, 2016). One important factor that growers can manage to ensure the long-term productivity and sustainability of the industry is the continued health of the soil. The main threats to continued soil health in potato growing regions are soil disturbances and carbon loss from tillage, compaction, erosion and disease. Improving soil health will require better understanding of the complex factors that constitute soil health and the availability of suitable indicators and tools with which to measure soil health. While Australia's potato industry is relatively small by world standards, it is of sufficient scale and diversity to encounter, in some form, most of the soil health challenges found globally and for locally developed strategies for improved soil health to have relevance elsewhere.

This review is concerned with soil health in the potato industry with a particular emphasis on recent research that has investigated the link between soil health and productivity. Relevant findings from research on crops other than potatoes have also been included where required. We examine three factors related to healthy soils: the physical and chemical characteristics and biological communities of soils with a focus on potato growing areas; management practices that have been shown to have an effect on soil health and productivity; and, practical ways to measure soil health.

What constitutes healthy soil?

Soil is a complex and dynamic system. Determining what constitutes healthy soil has been the subject of many studies and reviews (Karlen et al., 1997; Lehman et al., 2015; Porter et al., 2011). The physical, chemical and biological characteristics of soil are closely intertwined: the physical structure and chemical constituents influence which organisms live in a particular soil, and soil biota can change the structure of the soil and transform its organic and chemical constituents. These interactions are important for crop growth because they can affect root penetration, water infiltration and nutrient availability in addition to the beneficial (plant growth promoting) and harmful (disease) effects of the resident soil organisms. Soil stability (resistance to, and the capacity to recover from, perturbation) is related to many soil properties, including organic matter, aggregation, the quantity and quality of carbon inputs, soil texture and pH (Griffiths & Philippot, 2013).

Soil structure is a dynamic property influenced by a large number of variables that broadly fall into three categories (Bottinelli et al., 2015): environment (parent material, topography, climate); anthropic (land use management, tillage, traffic) and biological (macrofauna, plant roots, microbial activities). Ecological functions regulated by soil structure include infiltration, percolation and storage of water; gas exchange, dynamics of soil organic matter (SOM) and nutrients; the diversity and activity of soil microbial biomass; and, susceptibility to erosion (Bottinelli et al., 2015).

The interplay between soil structure and soil biology is close. Some soil macrofauna influence soil structure through the incorporation of organic matter and the construction of galleries and burrows (e.g. earthworms and burrowing social insects such as ants). Such structures can have a significant influence on water infiltration, gas exchange and the distribution of plant roots (Bottinelli et al., 2015). Abdollahi and Munkholm (2014) showed that increased macroporosity, which may be caused by fauna or plant roots, resulted in lower mean weight diameter, and hence more friable soil. Other soil macro fauna influence soil at the aggregate level through grinding and ingestion, and the resultant addition of secretions to the soil matrix (Bottinelli et al., 2015). Where some soil fauna influence soil structure, for others, the influence is reversed. Many soil organisms (e.g. mites, which may number in the millions per m^3) have no capacity to burrow or dig through the soil. They rely on interconnected soil pores for their physical habitat (Gupta, 1994; Lee & Foster, 1991). Soil compaction (from machinery traffic) and disruption (from tillage) has negative impacts on these soil organisms (Beylich et al. 2010; Brussaard & van Faassen, 1994; Pangnakorn et al., 2003; Whalley, Dumitru, & Dexter, 1995), partly as a consequence of the reduced volume and connectivity of soil pores. Soil compaction, which has been reported in potato producing areas in Australia (Cotching & Sparrow, 2012), represents a loss of habitat for these organisms. For those soil invertebrates that are capable of actively burrowing (e.g. earthworms, ants, beetles and some insect larvae), compacted soils may be habitable, but are a less desirable habitat than uncompacted soils (Beylich et al., 2010).

The functioning of soil depends on the decomposition of complex organic carbon as an energy source (Kibblewhite, Ritz, & Swift, 2008). Soil organic matter is an important component of soil, and influences a substantial part of the physical, chemical and biological activity needed in soils for productivity (Murphy, 2015). Soil organic matter is the source material for sequestered soil organic carbon (SOC) which is composed of different fractions: particulate OC (turnover time <1-2 years); humus OC (HOC, 5-25 years); and, resistant OC (250-2500 years). Particulate OC is a very significant food and energy source for the soil microbial population, while HOC ranks as a moderate to high energy source (Murphy, 2015). The biomass of soil organisms nominally accounts for 2% of the SOC, but it contributes to a much larger proportion of the actively cycled carbon fraction (Lehman, et al., 2015). Soil biology is central to the development and maintenance of soil structure, it recycles and influences nutrient bioavailability and can suppress plant diseases (Murphy, 2015). Therefore the amount and complexity of available organic matter is one of the most commonly used measures of soil health (MacEwan et al., 2009).

What represents ideal nutrient status in relation to soil health very much depends on the plants to be grown in the soil. Compared to many other crops, potatoes have a high nutrient requirement and many growers apply excess amounts of NPK fertiliser to their crops rather than risk reduced yields (Sparrow, 2012). The risks of excess nutrients can include reduced plant growth, excessive non-productive plant growth, increased susceptibility to pests and disease, plant toxicity, with associated risks to consumers, and loss of nutrients to the broader environment through run off (phosphorus) or leaching (nitrogen).

The term soil biota covers a diverse range of organisms from the very small bacteria and viruses to the quite large macrofauna such as annelids (earthworms). Soil biology has an influence on soil stability, not simply in relation to the absolute number of species present, but importantly, because of the way these organisms function in the soil. The roles of different types of invertebrate fauna in the soil, including their contribution to soil structure, nutrient cycling and plant health, are described in excellent reviews by (Lee & Foster, 1991) and (Lee & Pankhurst, 1992). The soil macrofauna have two major effects in the soil ecosystem: first, the cycling of nutrients, especially carbon through complex food webs and secondly, effects on soil structure (Bottinelli et al., 2015) mainly as result of the action of macroarthropods and annelids (earthworms). Microfauna play an important role in the release of nutrients immobilized by microorganisms and are therefore an important part of the detritus foodweb in agroecosystems (Gupta, 1994). The importance of soil organisms was demonstrated by Bender and van der Heijden (2015) in an artificial lysimeter system with initially sterile soil. They inoculated the soil with either organisms less than 11 µm in size – mostly bacteria – or organisms, including arbuscular mycorrhizal fungi, up to 2 mm in size and found increased nutrient use efficiency, reduced nutrient leaching and higher crop yields (first year 22%, second year 17%) in the latter treatment.

There is a significant amount of information available (Table 1) regarding the effects of different agricultural and land management practices on the abundance and diversity of different types of soil fauna (Leslie et al., 2017; Pangnakorn et al., 2003; Rieff et al., 2016). The importance of a diverse population of soil biota was emphasised by Coleman and Whitman (2005) who re-iterated the idea that functional redundancy (many organisms with the same function but a range of tolerances to environmental conditions) may be essential to ensure that soil can provide ecosystem services and remain productive under changing conditions. A large study across soil types and land management practices in Europe found that the abundance of soil macrofauna was able to distinguish between agricultural practices such as fertilisation regimes (Cluzeau et al., 2012). Similarly, the presence of particular genera of nematodes has been correlated with particular land management practices (Malherbe & Marais, 2015) or particular disturbances (Zhao & Neher, 2013) although neither of these studies were carried out in potato systems. Few recent studies have investigated the effects of management practices on both soil fauna and crop yield simultaneously. However, one study on the effects of cover crops and the use of vermicompost tea in zucchini found a correlation between the crop yield and the abundance of specific types of nematodes at particular times in the crop cycle (Wang et al., 2014).

Table 1: Examples of studies on effects of land management practices on soil fauna

Land management practice	**Effects observed**	**Crop**	**Reference**
Cover crops	Increase in soil food web complexity	Soybean	Leslie et al. (2017)
Cover crops	Increased abundance of bacterial feeding nematodes after cover crops compared to fallow	Tomato and corn	Dupont et al. (2009)
Cover crops	Increase in earthworm population under cover crops compared to bare fallow	Barley	Roarty, Hackett, and Schmidt (2017)
Reduced tillage	Increase in soil fauna abundance compared to conventional	Sugarcane	Braunack and McGarry (2006)
Reduced tillage	Zero till not significantly different faunal abundance compared to reduced till	Soybean and corn	Domingues and Bedano (2016)
Tillage & traffic	Increased earthworm incidence under zero tillage compared to conventional tillage	Wheat	Pangnakorn et al (2003)
Strip tillage & organic inputs	Increased nematode and earthworm abundance compared to conventional tillage with synthetic fertiliser & pesticide	Continuous tomato or diverse vegetables	Overstreet, Hoyt, and Imbriani (2010)
Amendment - manure	Increase in earthworm abundance and diversity compared to fallow	Maize	Ayuke et al., (2011)

Amendment – manure	Increases in microbial biomass and soil enzyme activity compared to non-amended	Potato	Ninh et al. (2014)
Amendment – manure	Increased yield and improved soil biological properties (earthworm abundance) compared to non-amended control	Potato	Rees et al. (2014)
Amendment – compost	Changes in soil microbial characteristics compared to non-amended	Potato	Larkin et al. (2017)
Amendment – compost	Increases in soil microbial population and changes in characteristics compared to non-amended	Potato	Bernard et al. (2012)
Conservation system	Increase in macrofaunal abundance compared to conventional system (tillage, pesticide and mineral fertiliser application)	Various	Henneron et al. (2015)
Good agricultural practices & no till	Increased abundance of ants, collembolans, mites & earthworms when GAP applied	Various	Bedano et al. (2016)
Controlled traffic	Increased abundance and diversity of soil arthropods	Vegetables	Rodgers et al. (2018)

Arbuscular mycorrhizal fungi (AMF) are fungi that live in association with many plants. The fungal hyphae penetrate plant cells to form structures called arbuscules. These fungi belong to the phylum Glomeromycota and associate with a large variety of plants including potatoes as well as many other vegetable crops (Rouphael et al., 2015). The main benefit of AMF to plants is that they improve nutrient uptake (Rouphael et al., 2015; Smith & Read, 2008) primarily because the fungal hyphae increase the volume of soil available to the plant roots. AMF have also been shown to affect phytohormone balance in plants which affects both the development of the plants and their tolerance to stresses including sub-optimal pH, salinity and drought (Rouphael et al., 2015). AMF not only improve the growth of individual plants but can benefit the ecosystem through promoting soil stability and, in agricultural ecosystems, reducing the requirement for inorganic phosphate fertilisers (Gianinazzi et al., 2010). AMF are undoubtedly an important part of healthy soil, but the significance of their role depends on the physical and chemical characteristics of the soil. In some soils with high levels of available phosphate they play very little role in improving plant growth (M. H. Ryan & Graham, 2002). However, in other situations they have been shown to improve plant health and yield (Buysens et al., 2016; Douds et al., 2007; Imperiali et al., 2017).

Bacteria (including both the bacterial and archeal domains of life) are the smallest of the cellular soil biota but are both abundant and diverse within the soil. They have important roles in biogeochemical cycling of both major and minor nutrients and are providers of ecosystem services (Hermans et al., 2017; Lee & Pankhurst, 1992). The plant growth promoting rhizobacteria directly affect growth and lessen the impact of diseases (Hayat et al., 2010). Some studies have shown links between soil properties, such as water content, nitrous oxide emissions and the abundance of particular groups of bacteria (e.g. ammonium oxidising bacteria) in microcosms (Wang et al., 2017) and in the field (Lin et al., 2017). It is also worth noting that bacteria can influence the physical structure of soil through the production of extracellular polysaccharides which bind particles together to form aggregates (Stevens et al., 2014). The importance of aggregate formation, stability and resilience has been known for a long time but the role of bacteria (and other soil biota) in promoting aggregate formation is not well understood (Deng et al., 2015; Stevens et al. 2014).

Soil health & disease

Part of soil health, although not always explicitly included in the definition, is the expectation that plants grown in healthy soil will have a lower incidence of disease from soil borne pathogens. However, the situation is more complex than just presence or abundance of soil pathogen inoculum, with the soil environment and host susceptibility playing critical roles in disease risk, as exemplified by the classic disease triangle principle (Agrios, 2005). In general however, lower soil pathogen inoculum levels are usually associated with reduced disease risk (Brierley et al., 2013; Hay et al., 2016). Molecular tests have been recently developed that can detect and quantify major pathogens in potato cropping soils and provide an assessment of disease potential in fields prior to planting (Brierley et al., 2016; Brierley et al., 2013; Hay et al., 2016; Lees et al., 2010b; Sparrow et al., 2015). Infested potato seed tubers can also provide important sources of pathogen inoculum within potato cropping systems that can increase disease risk and contaminate cropping soils (Andrade et al., 2008; Tegg et al., 2015)

The soil environment is equally critical for disease expression with soil physical, chemical and biological characteristics all influencing disease risk. For example, changes in soil compaction, moisture (De Boer et al., 1985; Lapwood et al., 1973), temperature (De Boer et al., 1985; Merz et al., 2012), pH (Lambert & Manzer, 1991) and microbial suppression (Exposito et al., 2017; Ninh et al., 2015) have been shown to alter disease in potato crops. Indeed, in some circumstances these factors may be of greater importance than pathogen inoculum levels, as evidenced by lack of disease in microbially suppressive soils where pathogen content can be high. Host genetic resistance will also be of importance in determining disease risk (Falloon et al., 2003; Merz et al., 2012; Wilson et al., 2010).

Manipulation of cultivar choice, agronomic practices, and the soil environment can be used to reduce pathogen levels and manage soil-borne disease (Fiers et al., 2012). Such practices, including planting resistant cultivars (Falloon et al., 2003; Merz, et al., 2012; Wilson, et al., 2010), maintaining seed health (Lees et al., 2010a; Tegg & Wilson, 2015), crop rotation (Larkin et al., 2011; Sparrow et al., 2015), soil and seed pesticide treatments (Brierley et al., 2015; Errampalli & Johnston, 2001; Falloon et al., 1996), irrigation practices (De Boer et al., 1985; Lapwood et al., 1973; Wilson et al., 2001), and soil pH and nutrition (Dees & Wanner, 2012; Lambert & Manzer, 1991), not only impact disease expression but will also influence soil health more widely. The effect of management practices designed to improve soil health on disease incidence has recently been reviewed by Larkin (2015). Larkin concluded that management practices that improve soil health generally increase soil biota abundance, diversity and activity which, over time, reduces disease incidence even if these practices do not remove pathogens from the soil. The mechanisms involved in this resilience against disease are not entirely understood.

The common soil-borne diseases of importance to the Australian potato industry (Table 2) have been discussed elsewhere (Clayton-Greene, 2015; Stagnitti, 2015). Estimation of the costs associated with major diseases is often difficult to obtain (Table 3). A number of studies from the UK, USA, Canada and Australia have attributed costs and/or yield reductions specific to some soil borne pathogens and diseases (Wilson, 2016), noting that there are both direct and indirect costs.

Table 2: Major common soil-borne pathogens and pests of significance to the Australian industry

Pest or disease organism	**Disease**
Bacteria	
Streptomyces spp.	Common scab
Pectobacterium spp.	Blackleg, soft rot
Fungi and Oomycetes	
Spongospora subterranea	Powdery scab
Rhizoctonia solani	Black scurf, stem cankers

Colletotrichum coccodes	Black dot
Fusarium spp.	Fusarium dry rots
Helminthosporium solani	Silver scurf
Phoma spp.	Gangrene
Phytophthora erythroseptica	Pink rot
Pythium ultimum var. *ultimum*	Leak
Verticillium spp.	Verticillium wilt
Nematodes and insects	
Meloidogyne spp.	Root-knot nematode
Pratylenchus spp.	Root-lesion nematode
Naupactus leucoloma	White-fringed weevil
Significant pests and diseases not detected within potato crops in Australia	
Clavibacter michiganensis subsp. *sepedonicus*	Bacterial ring rot
Synchytium endobioticum	Potato wart
Leptinotarsa decemlineata	Colorado potato beetle
Potato mop-top virus	Mop top
Tobacco rattle virus	Spraing
Globodera pallida	White potato cyst nematode

Table 3: Estimated annual costs (AUD$1000's) associated with three soil borne diseases for the Australian processed potato industry (A Ramsay pers. comm.)

	Common Scab	**Powdery Scab**	***Rhizoctonia* stem and stolon canker**
Processing crops			
Labour for on-farm discards	48	88	62

On-farm discards	1173	2722	2124
Pesticides	76	0	1238
Yield loss	0	9043	1648
Factory grade out	110	119	0
Processing seed crops			
Certification failure, grade out & value downgrade	206	877	285
Yield loss	35	519	71
Total loss	1648	13367	5428

Effect of land management practices on soil health

Cover crops

Cover crops, grown instead of seasonal fallow, provide a wide range of benefits which vary depending on the local soil and climatic conditions (Lehman, et al., 2015) and the nature of the farming system. The variety of crops, including cover crops, in the rotation, has a significant influence on soil biology by increasing the quantity and variety of carbon entering the soil through plant biomass, exudates, and residues. Additionally, cover crops that include a leguminous component increase N in the soil by stimulating the free-living N fixing bacteria and symbiotic N fixers (Lehman, et al., 2015). As an example of direct benefit from cover crops, nitrogen use efficiency in a subsequent potato crop was improved with cover crops of either forage radish or winter pea (Jahanzad et al., 2017). This reduced the amount of nitrogen fertiliser required representing a reduction in production costs. Additionally, these two cover crops were also shown to increase the mineral content of the potato tubers (Jahanzad et al., 2017). Abdollahi et al. (2014) showed that the use of cover crops created continuous macropores, which improved water and gas transport within the soil, and also root growth of subsequent crops. Cover crops play an important role in providing ground cover to reduce or prevent erosion by wind and water, as well as being a source of carbon inputs for maintenance or enhancement of soil quality (Reicosky & Forcella, 1998). Frequency of cover cropping has been shown to have a significant impact on soil biology as measured by differences in microbial biomass C and N, with annual cover crops making a significantly larger contribution than less frequent crops (Brennan & Acosta-Martinez, 2017). This study determined that while additions of compost were able to increase SOC over the 6-year period of investigation, cover crops had a far more significant effect on the soil food web, with the proposition that it was the below-ground C inputs (i.e. roots and root exudates) that were the primary driver of increases in microbial biomass.

Cover crops have been shown to increase yields in vegetable rotations including potato (Jahanzad et al., 2017; Neeteson, 1989; Snapp et al., 2005). A recent cover crop study (Belfry et al., 2017) which included a biofumigant, *Raphanus sativus*, compared the quality, marketable yield and profitability of processing tomatoes in Canada over a three year period. The quality was not affected by the use of any particular type of cover crop although the marketable yield was either significantly greater than, or not different to, the fallow control depending on the treatment. The profit margin was higher for the oat plus *Raphanus sativus* and the authors concluded that cover crops have no negative impacts and, if carefully chosen, have the potential to increase profits. Jahanzad et al. (2017) found that winter cover crops improved both the yield and nutritional quality of potatoes. They observed that some cover crops increased the tuber yield when a reduced amount of mineral nitrogen fertilisers were applied, and forage radish was shown to increase the mineral content of tubers. A review of cover crops used in the potato industry in the USA (Snapp, et al., 2005) concluded that they were useful, but the specific cover crop used needed to be matched to the problems experienced by individual growers as different cover crops had different benefits and costs associated with them. Compared to higher latitude areas in Europe and North America, in Australia cover crops can be grown in two to four months between cash crops rather than instead of cash crops. This makes cover crops attractive to Australian potato growers because their inclusion does not interfere with their cash crop regime.

Biofumigant cover crops

Biofumigant crops, which are most commonly from the Brassicaceae family, produce glucosinolates (GSL) that break-down when the plant tissue is damaged to form isothiocyantes (ITC), compounds that can have toxic effects on some soil biota including many crop pests and disease-causing organisms (Matthiessen & Kirkegaard, 2006). Biofumigation has been developed as an alternative to chemical fumigation of soil with materials such as metham sodium and methyl bromide which are generally highly toxic and can have negative environmental impacts which in some areas has led to their withdrawal from use (Noling & Becker, 1994). Biofumigants are most often grown in a crop rotation as cover crops which are subsequently incorporated into the soil, however, they can also be applied to the soil as seed meals or oils (Matthiessen & Kirkegaard, 2006).

Biofumigants provide the same general benefits to soil health as other cover crops. For example, several studies have shown that biofumigant crops have reduced the incidence of nematode infections in comparison to control plots (Fatemy & Sepideh, 2016; Lord et al., 2011; Ngala et al., 2015) and of fungal diseases including *Verticillium* (Larkin et al., 2011), *Rhizoctonia*, *Phytophthora* and *Sclerotinia* (Ji et al., 2012; Larkin & Griffin, 2007). However, biofumigants are not always successful at reducing disease (Bensen et al., 2009; Hartz et al., 2005; Larkin et al., 2011; Sexton et al., 2007; Vervoort et al., 2014). Hartz et al. (2005) reported no reduction in the populations of *Fusarium* spp. or *Verticillium dahlia* in spring after winter crops of *Brassica napus*, *B. juncea* or *Sinapis alba*.

Such variable, although generally positive, effects of biofumigant crops on disease incidence and crop yields are commonly reported in the literature although reasons for the variability are rarely explored. A yield benefit is usually noted where disease incidence is reduced (Bensen et al., 2009; Ji et al., 2012; Wang et al., 2010). In some instances, yield increases (in potato, lily and carrot) were observed without apparent reduction in disease (Korthals et al., 2014), and the incidence of *Pratylenchus* nematodes and *Verticillium* fungal infections were not as well controlled by biofumigants as they were by chemical fumigants. However, the yield of crops following biofumigants increased, which the authors concluded was due to effects on soil biota rather than soil chemistry. Larkin et al., (2011) observed improved potato yields in all years where the chemical fumigants were applied, but in comparison, results with the biofumigant cover crops were variable, only providing yield increases in some years. Many other studies have also reported inconsistent effects with increases in some years or crops and not in others (Hartz et al., 2005; Monfort et al., 2007; Wang et al., 2010; Yim et al., 2016). It is often suggested that inconsistent results with biofumigant crops are due to the difficulties of ensuring that a consistent and effective concentration of the biofumigant chemicals are retained and distributed throughout the soil during the active phase of release, although other, often unnamed, influences are also cited as critical factors (Hartz et al., 2005; Larkin & Griffin, 2007). Studies that have measured the levels of either the GSL precursors or toxic ITC compounds report that their concentration is much less than the concentration resulting from applications of fumigants such as metham sodium (Bensen et al., 2009; Mattner et al., 2008). Vervoort et al. (2014) were unable to correlate changes in nematode communities to ITC concentrations and concluded that other factors including the mechanical disturbance to the soil, absence of host plants and the effect of adding organic matter to the soil were most likely responsible for the decline in nematode populations.

Crop Rotation

Potato are generally grown in a rotation with a mixture of other crops which may include other vegetables, cover crops (including biofumigants), grains and pastures. Both time between potato crops and the number and diversity of crops in the rotation affect the yield of the subsequent potato crop and overall soil health. In most studies (see Table 4), longer time intervals between potato crops resulted in increased yield and reduced disease. The downside of this is that it also reduces the long term profitability of the potato crops because a cash return is realised less often**.** However, this is not always the case. For example, Dung et al. (2015) noted that where “best practices” are routine, the effect of increased time between potato crops is not significant. This provides some evidence that it may be possible to reduce rotation times if the soil health is maintained and the production system is optimised for local conditions.

Table 4: Examples of effects of rotation duration on potato crops

Rotation sequence	Rotation durations tested	Results	Reference
Potato – barley Potato – barley - clover	3 year and 2 year	Results inconsistent Disease generally lower in 3 year	Peters et al. (2004)
Potato only OR Potato – potato- onion – onion OR Potato – onion – oat - broccoli	4 and 2 year	Increased yield, decreased disease in 4 year	Wright et al. (2017)
Potato – barley – oat Or Potato – barley – oat – onion – poppy – broccoli Cover crops between each cash crop	6 and 3 year	Increased yield, decreased disease in 6 year	Sparrow (2015)
Potato-dry bean-wheat OR Potato-wheat-sugar beet-drybean OR Potato-wheat-sugar beet-wheat-dry bean	3, 4 and 5 year	Increased yield, decreased disease in 5 year. No significant effects observed first 5 years	Larney et al. (2016)
Various - data from 336 crops analysed	Various – data from 336 crops analysed	Other factors – field characteristics, cultivar more important Number of years since last potato crop only sig effect for some cultivars	Dung et al. (2015)
Potato – barley OR Potato – barley/timothy – timothy Plus other systems	2 and 3 year compared to continuous potato	Disease reduced , yield increased by all rotation compared to continuous Effects not consistent	Larkin et al. (2017)

Tillage and traffic

Research into the impacts of machinery traffic on soil structure and crop performance is as old as mechanised agriculture with many publications spanning the decades (Allmaras et al., 1983; Blunden et al., 1994; Defossez & Richard, 2002; Flocker et al., 1960; Hamza & Anderson, 2005; Hubbell & Gardner, 1948; McDole, 1975; Weaver & Jamison, 1951). The practical and economic consequences of machinery traffic vary with numerous factors including soil type, moisture, soil tilth, vehicle load, cropping system and environment. However, the weight of evidence indicates that mechanised traffic on fields results in soil compaction, and increasingly so as agricultural machinery has increased in size and weight, with consequent negative effects on a range of soil physical parameters, such as bulk density, infiltration, hydraulic conductivity, plant available water and pore size, structure, connectivity and distribution (Destain et al., 2016; Soracco et al., 2015; Stenitzer & Murer, 2003; van Dijck & van Asch, 2002). The most effective solution to compaction-related soil damage under mechanised agriculture is to limit field traffic movements to permanent traffic lanes and hence remediate or avoid most of these problems (Alvarez & Steinbach, 2009; Bai et al., 2009; Chamen & Longstaff, 1995; Li et al., 2007; McHugh et al., 2009; Tullberg, 2010; Unger, 1996).

Most research and practical application of controlled traffic has been conducted in dryland grain production in situations that combine both traffic control and no-till management. However, improvements have been measured in soil structural conditions under controlled traffic, even in the presence of conventional tillage operations, in intensive vegetable production (Lamers et al., 1986; McPhee et al., 2015). The most important application of tillage in vegetable cropping systems is to alleviate harvest-induced soil compaction and prepare a seedbed for the next crop (McPhee et al., 2015). Other purposes of tillage include management of crop residues, and in some cases, weed control. Tillage can have both positive and negative impacts on soil structure, depending on the initial physical state of the soil prior to tillage (Bangita & Rao, 2012; Jabro et al., 2011; Nunes et al., 2015; Salem et al., 2015). If the soil is in a compacted state, tillage will help remediate the soil and create a more friable and porous structure, although it is arguable that appropriately selected and managed cover crops may provide a more effective form of remediation through root penetration (Calonego et al., 2017; Chen et al., 2014; Nguyen et al., 2011; Rosolem & Pivetta, 2017; Stirzaker & White, 1995; Williams & Weil, 2004). Conservation tillage practices can also improve soil health by increasing organic carbon, as observed in three-year rotations in a potato crop in Canada (Adams & Hide, 1981).

The literature is relatively sparse on the impact of tillage on soil biology, particularly in potato or other vegetable cropping systems. In the Australian dry land grain industry, biological activity of cropped soils was shown to be low compared to other land uses, such as native, undisturbed pastures and woodlands, and long term pastures (Bell et al., 2006). There was relatively little benefit from stubble retention and zero-till, but consistent benefits from pasture break crops, implying that a living cover crop is needed to enhance soil biology (Brennan & Acosta-Martinez, 2017). The dry land grain environment is one of infrequent cropping, with often not more than one crop per year, with the fallow period used to accumulate soil moisture.

The difference in microbial biomass between cultivated and uncultivated soil was demonstrated in a study of a strip-till vegetable production system, with the inter-row region being representative of uncultivated soil (Overstreet & Hoyt, 2008). This study showed a negative impact of tillage disturbance on soil microbial biomass, compared to no disturbance. There was also evidence that synthetic fertiliser inputs accentuated the negative impact, an effect also reported by Diosma et al. (2006) in wheat. In further findings, long-term strip-till management showed a 31-fold increase in earthworms compared to ploughing (Overstreet et al., 2010). A meta-analysis based on 139 observations from 62 studies from around the world showed that overall, microbial biomass and activity was greater under no-till compared to tillage (Zuber & Villamil, 2016).

Similarly, studies on the effects of agricultural machinery traffic are extremely rare. A study of biology in dry land grain growing vertosols, (Pangnakorn et al., 2003) showed that the combination of controlled traffic and no-till gave a higher incidence of earthworms than any other cultivation and traffic combination. Absence of tillage appeared to have a larger effect than absence of traffic. The negative impact of traffic was judged to be caused by soil compaction, resulting in restricted movement and reduced oxygen intake on the part of the worms, rather than physical crushing. In a major study of sugar cane yield decline, significant yield and sustainability advantages were found through adoption of a new production system based on controlled traffic, minimum tillage and the use of leguminous break crops (Bell et al., 2003; Braunack & McGarry, 2006; Garside et al., 2004; Stirling et al., 2010). The response of the soil macrofauna (particularly earthworms) to the use of minimal-disturbance planting technologies for both the legume break crop and the following sugarcane crop was significant. Nine months after planting sugarcane, earthworm densities were over 5 times higher in direct drilled beds compared to conventionally tilled soil (Bell et al., 2003). The earthworm response was reflected in the abundance and diversity of other macrofauna, and the resultant increase in soil macroporosity produced large increases in water infiltration (Stirling, 2008). It was concluded that improved capture of water during periods of low rainfall was probably a key reason that crop yields increased in response to direct drilling (Bell et al., 2003). Monitoring of soil arthropod populations in a vegetable cropping rotation showed that the use of controlled traffic, even in conjunction with relatively high tillage disturbance, gave significant increases in arthropod populations and species diversity in spring, although similar results were not observed from winter sampling (Rodgers et al, 2018).

Organic soil amendments

Organic amendments (OAs) are derived from material of plant or animal origin and include manure, compost, crop residues, biochar and green and industrial wastes (Halloran et al., 2013; Larkin, 2015) and are primarily intended to add carbon and nutrients to the soil and improve crop yield. The addition of OAs can also alter environmental conditions in the root zone including soil pH, structure and water-holding capacity, all of which can directly or indirectly affect plant health, susceptibility to disease and crop yield.

A number of studies, some in potato rotations, have reported large increases in soil carbon (Carter et al., 2004; Grandy et al., 2002; Mallory & Porter, 2007; Moulin et al., 2011; Ros et al., 2006) and in particular more labile carbon (Carter et al., 2004; Grandy et al., 2002) although this is a long-term process that may take much longer than one year to become apparent (Grandy et al., 2002). There have also been large increases in cation exchange capacity (Mallory & Porter, 2007). OAs can also enhance soil physical properties including improved soil aggregation(Grandy et al., 2002; Mallory & Porter, 2007; Moulin et al., 2011) and reduced bulk density (Larkin et al., 2011b). One of the benefits of higher SOC is enhanced soil water holding capacity and it has been suggested (Carter et al., 2004; Halloran et al., 2013; Larkin et al., 2017) that the yield benefits of OAs arise from this. Where soil moisture is limiting, particularly in lighter soils, application of OAs have frequently increased soil moisture retention (Bernard et al., 2014; Carter et al., 2004; Larkin et al., 2011b; Larkin et al., 2017; Ninh et al., 2015) and this practice has been discussed as a means of reducing irrigation in North America (Halloran et al., 2013; Paulin, 2005).

Many studies have demonstrated increased potato yields with application of compost (Bernard et al., 2014; Carter et al., 2004; Kimpinski et al., 2003; Larkin et al., 2011b; Larkin et al., 2017; Larkin & Tavantzis, 2013) or manure (Kimpinski et al., 2003; Ninh et al., 2015; Rees et al., 2013). Usually, OAs do not fully replace mineral fertiliser; fertiliser rates are commonly scaled back to adjust for expected nutrient supply from the amendments. Ros et al. (2006) reported a decrease in yield when using only compost compared with application of mineral fertiliser. In several studies yield increases in potatoes have been attributed to the additional nutrients made available through mineralisation of the OA (Ninh et al., 2015; Ros et al., 2006). Increases in soil N, P, K, Ca and some trace elements have been reported (Grandy et al., 2002; Mallory & Porter, 2007; Moulin et al., 2011; Ninh et al., 2015; Rees, et al., 2013; Ros et al., 2006). However in most of these studies the fertiliser applied in conjunction with compost has been at non-limiting rates, and yields have been higher compared with the mineral fertiliser treatment (Bernard et al., 2014; Carter et al., 2004; Larkin et al., 2017; Larkin & Tavantzis, 2013) suggesting a non-fertiliser response to the amendment. Mallory and Porter (2007) also reported that levels of foliar macro-elements were lower or at best equal to the non-amended treatments and suggested that increased yield in amended plots was probably not related to the supply of these nutrients.

The responsiveness of crop yields to OA will also depend on the soil type and cropping history. The majority of studies in potato crops have been conducted on light to medium textured soils with organic carbon levels less than 2% (Ninh et al., 2015), often at sites with a history of long term potato production and low organic matter inputs. Bernard et al. (2014) conducted trials on two soil types and there was a consistently greater yield response on the soil with total carbon levels less than 2%. In Western Australia, Paulin (2005) also recorded significant improvements in SOC with application of compost, particularly on sandy soils with OC levels less than 1%. In contrast, soils of higher clay content will likely be far less responsive to OA application. For example, in Tasmania, potatoes are predominantly grown on ferrosols and dermosols (L. Sparrow pers. comm.) with mean OC levels of 4.0 and 2.7% respectively (Cotching et al., 2004).

Most studies have evaluated effects over short term periods (2 - 3 years) but there have also been long term studies with compost applied over 7 years or longer (Kimpinski et al., 2003; Larkin et al., 2017; Mallory & Porter, 2007; Ros et al., 2006). Effects were both cumulative and residual with yield benefits reported by Larkin et al. (2017) continuing for the two years of measurements after applications were discontinued.

Addition of OAs also results in significant modifications to soil biota. In many studies (Bernard et al., 2012; Larkin et al., 2011b; Larkin et al., 2017; Ninh et al., 2015; Ros et al., 2006) there have been large increases in microbial populations and activity resulting in substantial shifts in soil microbial community structure and profiles. However, few studies have been carried out to directly correlate the presence or abundance of particular bacteria with plant yield although there are some studies into the effect of soil amendments on both bacterial communities and plant growth or yield. Rames et al. (2013) examined changes in bacterial and fungal community structures under different management strategies (use of rotations, minimum tillage and OAs) and showed a correlation between the abundance of particular groups with management practices as well as yield and disease incidence. Wang et al. (2017) noted that compared to both no fertiliser and inorganic chemical fertiliser, the addition of a fermented bioorganic fertiliser to apples increased yield and changed the bacterial community structure. In a potato system, Larkin et al. (2011b) observed a significant increase in yield when composted manure was used as an OA and significantly different microbial communities were present in this soil compared to the same system without compost. Studies in other crops and pasture have also shown the effects of OA applications on soil macrofauna (Bünemann et al., 2006). However, apart from a study by Rees, et al. (2013) which showed increased earthworm numbers after application of poultry manure, there has been limited investigation on the effects of OA application on these species in potato crops.

In addition to increasing beneficial organisms, the addition of OAs have been shown to suppress a number of plant pathogens and pests. Application of compost has been associated with suppression of some soil borne diseases including *Rhizoctonia solani, Phytophthora* spp., *Streptomyces scabies* and *Fusarium and Verticillium* wilts (Bailey & Lazarovits, 2003; Bonanomi et al., 2010; Conn & Lazarovits, 1999; Termorshuizen et al., 2006). However, other studies have reported increased incidence of soil borne disease and pests relative to unamended soils (Bernard et al., 2014; Conn & Lazarovits, 1999; Kimpinski et al., 2003; Larkin et al., 2017; Larkin & Tavantzis, 2013). It appears that the effects of OA on disease incidence are very dependent on amendment properties (Bailey & Lazarovits, 2003; Bonanomi et al., 2010; Conn & Lazarovits, 1999; Larkin et al., 2017; Termorshuizen, et al., 2006) and soils involved (Conn & Lazarovits, 1999) as well as the specific disease or pest organism (Bonanomi et al., 2010; Conn & Lazarovits, 1999; Noble & Coventry, 2005; Termorshuizen, et al., 2006). This may be due to OA altering the chemical and physical characteristics of the soil which in turn influences plant resistance to disease rather than the OA directly impacting disease organisms. Sterilisation of the amendments or soil decreased disease suppression in some studies, supporting the role of soil organisms in disease suppression (Bonilla et al., 2012; Noble & Coventry, 2005). The most likely explanation is that disease suppression is usually biologically mediated with the physical and chemical parameters of the OA affecting growth and activities of soil microbiota, including pathogens, thereby modifying disease suppression (Bonilla et al., 2012). There is also opportunity to combine effects from different management strategies. For example, OAs can increase tuber yield but also disease. Bernard et al. (2014) showed the inclusion of a rapeseed rotation crop mitigated the negative effect of a compost amendment on diseases.

A significant constraint to adoption of OA is the cost of the OA and its transport and application (Halloran et al., 2014; Paulin, 2005). However, there are also other economic benefits with application of OA through reduction in fertiliser costs. Paulin (2005) calculated that half of the cost of applying compost in Australia could be covered by decreased fertiliser costs and the overall gross margin analysis suggested that the use of compost in vegetable production can increase grower returns. Another significant benefit noted by Halloran et al. (2013) is improved risk management through greater yield stability with the amendment providing additional buffering, particularly in seasons with low rainfall (Mallory & Porter, 2007) or minimising stress events such as irrigation failure (Paulin, 2005).

Management of arbuscular mycorrhizal fungi

Increasing the abundance of AMF prior to the planting of cash crops to increase plant growth has been suggested for over twenty years (Dodd et al., 1990). The inoculation of a cover crop with AMF (*Rhizophagus irregularis*) and *Trichoderma harzanum* was recently shown to increase subsequent potato yield more than inoculation of the potato crop itself (Buysens et al., 2016). There is evidence that manipulation of AMF in potato crops can affect the productivity of the potato although results have been variable with increased, decreased and no effect on yield reported (Buysens et al., 2017; Douds et al., 2007; Duffy & Cassells, 2000; Loján et al., 2017). The reasons for variable yield results are not known but many potato soils have high concentrations of available phosphorus, which may help to explain the lack of response. It may also be that the AMF used as inoculants have to compete with naturally occurring AMF (Buysens et al., 2017; Loján et al., 2017). Both field studies showed the abundance of the inoculated *Rhizophagus irregularis* strain was very small compared to the abundance of native AMF, however it should be noted that potato yield was comparable between inoculated and non-inoculated plants. In comparison, Douds et al., (2007) found significant increases of 33–45% in potato yield in inoculated plants compared to controls in the first year, though increases were less (20%) although still significant in the second year and these responses were unaffected by the source of inoculum (commercial or on-farm). The most extensive analysis of a particular strain (*Rhizophagus irregularis* DAOM 19798) in 231 field trials carried out by farmers in their usual commercial conditions ran over a four-year period throughout North America and Europe. This analysis showed an average highly significant increase in potato yield of 9.5% (Hijri, 2016) although 14% of the trials resulted in a decreased yield. The study hypothesized that poor application of the inoculant was the cause of the yield decreases, although other factors including differences in soils, particularly P availability and competition with native AMF, should also be considered.

Some studies have reported that greater diversity in crop rotations is associated with more diverse AMF populations compared to continuous cropping of the same crop (Jansa et al., 2006). Another six-year study reported no differences in AMF diversity between different crop rotations including potato and a mixed oat and pea crop (Vestberg et al., 2011). However, the importance of AMF biodiversity, as opposed to abundance, has not been clearly elucidated although its importance has been implied because different AMF species respond differently to environmental conditions (Jeffries et al., 2003).

AMF are also used in potato crops to reduce the incidence of root nematodes. A pot trial found that some species of AMF were effective in reducing nematode infection with a concurrent increase in yield (Deliopoulos et al., 2008) but the commercial inoculant that contained a mix of AMF species was not as effective as the single strain inoculants. Another study, also using a mixed inoculant, reported an increase in the number of nematode cysts compared to the control, but also an increase in the yield of tubers (Ryan et al., 2003).

It has been noted that inoculants only provide a benefit to crops under specific circumstances: when the plants are subject to some kind of stress; when the inoculant is adapted to the local conditions and when the organism is already present in the area (Imperiali, et al., 2017; Ryan & Graham, 2002). It is more likely that land management practices that promote the growth of indigenous AMF able to colonise the cash crop (e.g. reduced tillage or the use of AMF host cover crops) will have longer lasting effects on productivity. These effects may not be measurable in good years but will provide benefits to the crop when plants are under stress (either biotic or abiotic) or by allowing a reduction in fertiliser application.

Measures or indicators of healthy soil

There is a myriad of characteristics of soils that contribute to soil health that can be measured and described. Larkin (2015) lists nine attributes of a healthy soil: high levels of organic matter; friable structure; high water-holding capacity and drainage; adequate nutrients and balanced nutrient cycling; sufficient depth for root growth; large and diverse populations of soil biota; low populations of pathogens; resistance to degradation and resilience to stress. The diversity of soil, climates and agro-ecosystems means that there is unlikely to be a standard range of values for any particular characteristic that definitively describes healthy soil (Kibblewhite et al., 2008; Wood & Litterick, 2017). It may be that the best measure of soil health for the potato industry is whether growers are able to maintain long-term productivity without increasing inputs. To enable immediate management decisions, measures or indicators of the likely impacts of those decisions on long-term soil health are required.

Doran and Zeiss (2000) suggested that soil health indicators should meet five criteria: sensitivity, correlation with beneficial soil functions, usefulness for relating to ecosystem processes, usefulness for decision-making by land managers and, reasonably easy and inexpensive to measure. Some have suggested a combination of physical, chemical and biological indicators should be used for a comprehensive understanding of soil health (Larkin, 2015; Lehman et al. 2015), whilst other work has shown that in potato systems at least, biological indicators are the most sensitive indicator (Nelson et al., 2009). As the capacity of soils to be productive varies, Kibblewhite et al. (2008) suggested that it would be more effective to measure changes in the characteristics of a soil over time rather than aiming for a particular “target number” for each indicator or characteristic. This still requires a decision on which parameters to measure and knowledge of which direction those parameters should be moving or what an ideal range would be. MacEwan, et al. (2009) provided a comprehensive review of tools available in Australia for monitoring soil health, although some areas, particularly the measurement of soil biology, have developed considerably in the intervening time. Regardless of improvements in available technology, the tests need to provide information on which management decisions can be based - i.e. actionable information (Wood & Litterick, 2017).

Physical indicators

Several physical characteristics of soil can be used to assess soil health (Arias et al., 2005). These include bulk density, and the related property of porosity, and infiltration rate, which is influenced by surface structure and the number, size and connectivity of internal pores. Bulk density (the ratio of oven-dried soil weight to its bulk volume), is primarily a measure of soil compaction. Soil compaction affects soil physical properties such as increasing bulk density, and changing the size distribution, tortuosity and connectivity of soil pores (Beylich et al., 2010). This in turn reduces water infiltration and percolation, leading to increased surface runoff and erosion, and reduces soil aeration, gas exchange and penetration of crop roots into the soil profile (Batey, 2009; Chamen et al., 1992; Hakansson et al., 1988; Hamza & Anderson, 2005; Li et al., 2007). Pagliai and Vignozzi (2002) argue that soil porosity is the best indicator of soil structure quality. However, it is not just porosity *per se* that is important. A range of factors which help to describe the pore structure, such as shape, size, continuity, orientation and arrangement in soil help define the complexity of soil structure and allow quantification of changes caused by management practices. Pagliai and Vignozzi (2002) also note that chemical, biochemical and biological properties, like enzyme activity, and root growth, are related to pore shape and size distribution. Another important factor, which is not described by porosity alone, but requires additional information regarding soil water content, is air-filled porosity. Others argue that the least limiting water range (LLWR), which is a function of available water, soil aeration and penetration resistance, all of which in turn are influenced by porosity, provides a better descriptor of the condition of the soil (Betz et al., 1998; daSilva & Kay, 1997).

Visual Soil Evaluation

Visual soil evaluation has been practiced by farmers for hundreds of years (Lehman, et al., 2015) with the first published description of Spade Diagnosis by Johannes Görbing appearing in 1947. These methods are based on qualitative visual assessments of features of soil structure but there is a range of published evidence showing strong correlations between these qualitative assessments and quantitative measurements of soil properties such as penetrometer resistance, permeability and earthworm counts (Mueller et al., (2009) as reviewed by Emmet-Booth et al., (2016)). In modern times there have been several attempts to produce guides or frameworks for visual soil evaluation (VSE) or visual soil assessment (VSA). Emmet-Booth et al. (2016) recently reviewed over fifteen frameworks and methodologies from across the globe dividing them into two groups: spade and profile methods (Table 5). Spade methods examine the structure of blocks of soil up to 50 cm depth whilst profile methods examine profiles up to 1.5m depth to describe the intrinsic qualities of the soil at the specific sampling location. The basis of all the reviewed systems are similar, however they are adapted to be suitable for different regions, soil types and users. These authors concluded that some systems were more suitable for use by a lay person whilst others required expertise to interpret results, and they identified the effects of texture and moisture content on VSE methods as needing further research. In Australia, the SoilPak project developed a system for the cotton industry to monitor soil health (McKenzie, 1998). Similar to other VSE methods it primarily assesses soil structure by examining aggregate size, resilience and stability. McKenzie (2013) proposed a 'whole of farm approach' that uses the SoilPak together with modern databases and laboratory testing to monitor and hence improve soil health.

Table 5: Visual Soil Examination and Evaluation Frameworks

Category	Method[a]
Manual aggregate exposure methods	Spade diagnosis
	Peerlkamp method
	Werner method
	Extended spade diagnosis
	Spade analysis
	Soil quality scoring procedure
	Visual soil structure quality assessment
	Visual evaluation of soil structure
	Thinksoils manual
Drop test procedures	Diez method
	NZ Visual soil assessment
	FAL method
Profile methods	Le profil cultural
	Whole profile assessment
	SOILpak
	SubVESS
Test kits	USDA Soil Quality Test kit
	Healthy Soils for Sustainable Farms kit
	Soil health score cards

[a]Test kits were reviewed by MacEwan et al. (2009), all other methods were reviewed in Emmet-Booth et al. (2016)

VSE methods have the advantage that they are, in comparison to extensive laboratory testing of soil samples, rapid, easy to interpret and cheap. In many cases use of a simple guide or scoring scheme means that soil science expertise is not required although it is often recommended (Anderson et al., 2007). Although these qualitative methods have been shown in several studies to relate well to more detailed quantitative analyses

(Guimarães et al., 2013; Moncada et al., 2014), the correlation can be site specific (Mueller, et al., 2009) rather than universal. This perhaps makes them more suitable for monitoring a particular site or farm over time rather than being an absolute measurement.

Soil Biota

The abundance, diversity, or presence of specific organisms in the soil can be used as an indicator of the health of the soil as these are dependent on the physical characteristics of the soil and the availability of sufficient nutrients and organic matter to sustain a complex food web. Indeed, several studies have correlated the abundance of particular groups of soil fauna to either particular soil characteristics associated with healthy or productive soil (Ayuke, et al., 2011; Boiteau et al., 2014) or to different agricultural practices (Leslie et al., 2017; Rieff et al., 2016; Sanchez-Moreno et al., 2006). Macrofauna have been used as biological indicators of soil health for some time in Australia (deBruyn, 1997) and are included in some soil health frameworks. A number of authors (Nelson et al., 2009; Pankhurst et al., 1995; van Bruggen & Semenov, 2000) have suggested that because of the close links between soil microbial communities, soil structure and nutrient (including C) cycling, that soil microorganisms are ideal indicators of soil health. Others have concluded that soil microorganisms meet many, but not all, of the criteria for suitable soil health indicators (Doran & Zeiss, 2000).

There are some challenges specific to the use of soil fauna as biological indicators, especially as identification to species level by the lay person can be difficult. The response of some of these organisms to environmental changes depends on many factors including age, type of environmental change and other stressors in the environment (Paoletti et al., 1996). A direct link between the abundance or diversity of beneficial soil fauna to productivity or yield has been tested in a very few cases (Leslie et al., 2017; Malherbe & Marais, 2015; Wang et al., 2014) and results have been somewhat inconsistent although it is acknowledged that such relationships may take several years to establish. For nematodes, the presence or abundance of specific genera may be more important for distinguishing the effects of land management (Malherbe & Marais, 2015; Zhao & Neher, 2013) although Malherbe and Marais (2015) concluded that the success of the tomato crops could not be predicted solely by biological indicators. To overcome some of the issues of identifying particular soil organisms by traditional taxonomy, several groups have developed DNA-based diagnostic tests that are also quantitative (Baidoo et al., 2017; Braun-Kiewnick et al., 2016; Ophel-Keller et al., 2008).

There is a significant amount of work that shows that the structure and diversity of soil microbial communities is related to various physical and chemical aspects of soil both in terms of the overall community structure and the abundance of particular groups. A range of tests currently exist that attempt to measure the function or activity of microbial communities including biomass, plate counts, enzyme activities and respiration (MacEwan, et al., 2009). Many studies have looked at the relationships between bacterial community structure and the soil characteristics (Burns et al., 2016; Fernandez et al. 2016; Hermans et al., 2017; Jesus et al., 2009; Kuramae et al., 2012; Wu et al., 2008) over a range of latitudes, soil types and land uses. For example, Hermans et al. (2017) examined a range of soil types and land uses in New Zealand. They found that variation in the soil, particularly C:N ratio and Olsen P, explained 51% of the variation in bacterial community structure. More interestingly, strong relationships between some soil factors (particularly total C, C:N ratio and net primary productivity) and the relative abundance of particular taxa of microorganisms were found both in this study and a meta-analysis of 102 published datasets from around the globe (Trivedi et al., 2016). The meta-analysis by Trivedi is possibly the largest currently available. Both studies concluded that there is potential for bacteria to be used as indicators of soil "condition". By assessing microbial biomass through the measurement of the total DNA extracted from soil, Horrigue et al., (2016) were able to develop a predictive model for microbial biomass based on soil descriptors, including agricultural practices. They chose to use DNA as a proxy for biomass because it was relatively easy and cheap to perform on large numbers of samples. The authors see this model as the first step towards developing other models for the prediction of microbial diversity in soils.

Work is still required to reach some conclusions as to which groups of microorganisms to monitor under which particular set of circumstances. Despite the recent advances in technology with consequent decreases in cost, it is still difficult to quantify a concept such as microbial diversity or the abundance of a particular group of microbes in a rapid and portable way. Hence these measurements are unlikely to be of practical use in land management in the immediate future. As the ability to detect and quantify microorganisms in the field improves these measurements may form the basis of practical soil health tests.

Available test kits and frameworks

Several frameworks for testing and ongoing monitoring of soil health were developed in the United States early in the 2000s. Andrews et al., (2004) developed a way of selecting indicators of soil health that could be combined to give a single number index of soil health focussing on those indicators that were most sensitive to human-induced changes in soil quality. One of the older test kits, first available in 1999, is the USDA Soil Quality test kit (Soil Quality Institute USDA, 2001) which is contains both a physical test kit and a manual and interpretation guide. The Cornell Comprehensive assessment of soil health manual and soil testing was first released in 2006 and has recently been updated (Moebius-Clune et al., 2016; Schindelbeck et al., 2016). Variations of these frameworks and test kits that have been developed specifically for different regions in Australia for example the Landcare RASH (https://watershedlandcare.com.au/documents/resources/RASHmanual.pdf), or the Northern Rivers Soil Health Card (http://www.dpi.nsw.gov.au/__data/assets/pdf_file/0007/168703/northern-rivers-soil-health-card.pdf).

The Healthy Soils for Sustainable Farming program produced both a test kit and a framework (or guide) for measuring soil health in Australia (https://futurebeef.com.au/wp-content/uploads/2011/09/Healthy-soils-for-sustainable-farms.pdf) which was developed by the Queensland University of Technology (Viljoen et al., 2008). The SoilPak system, originally developed for the cotton industry, was further developed for other growers including vegetables and a "Ute Guide" (Anderson et al., 2007) was produced for the vegetable industry which includes information on sampling and recommended laboratory tests in addition to VSE.

An alternative approach is to test for the likelihood of disease occurrence. The PreDicta Pt test (http://www.pir.sa.gov.au/research/services/molecular_diagnostics/predicta_pt) developed by the South Australian Research and Development Institute (Ophel-Keller et al., 2008) provides specific DNA quantification of ten key soil borne pathogens. Where levels of pathogen detected are low or negligible there is a lower risk or likelihood of disease in the subsequent crop (Stagnitti, 2015) which may be indicative of a productive soil. The PreDicta Pt tests includes information on the presence of several species of nematodes in addition to providing an indication of risk from the root knot nematode *Meloidogyne fallax*.

Conclusions

Soil is a complex, variable and dynamic system which makes it difficult to study in a way that allows general conclusions to be drawn with any certainty. In Australia, potatoes are grown in a wide variety of soil types, climatic regions and farming systems and it is likely that there are few aspects of soil health that can be generalised over these different conditions. It is clear that the physical structure of soil is of fundamental importance to soil health as a habitat for plants, invertebrates and microorganisms. Impacts on the physical structure of a soil affect all the organisms in that soil. Diverse soil food webs also seem to be important for soil health; soil organisms are vital to the functioning of the soil ecosystem, and maintaining the balance between different functional groups of organisms is important for long-term agricultural productivity and sustainability. These food webs are sustained by the quantity and types of organic matter available. Different land management and agricultural practices can affect soil health and hence long term productivity through changing the structure, nutrients and biology of the soil. Therefore, it should be possible to identify and implement practices that improve, rather than degrade, the soil although it is unlikely that any one practice will provide substantial increases in profitability for all soil types and potato farming systems.

There are two aspects of managing soil health that require more investment of time, money and research effort: (i) understanding the mechanisms by which the various aspects of soil health affect potato productivity, both individually and through their interactions, and (ii) providing long-term evidence of the effects of changes in management practices on productivity. Soil health can be defined as the long term sustainable productivity and provision of ecosystem services. However, many studies encompass only two to three years of data. Longer term studies do exist but they are in the minority. Such studies need the support of growers, industry and funding bodies and various level of government. Research institute facilities such as farms and long term ecological research sites are invaluable for these long term studies which, by their nature, necessitate imposing defined agricultural practices for many years. There is still much to learn about the interactions between the soil physical structure, nutrient and organic matter availability, soil biota and plant growth and health. Without understanding the mechanisms by which these different aspects of soil interact and affect crops, we will be hampered in our efforts to provide solutions to the problem of maintaining soil health and hence productivity in the long term. The range of systems in which potatoes are grown in Australia means that there are many different constraints to maintaining soil health, and understanding at the regional scale of the effects of different management practices is needed.

We have progressed considerably over the last twenty years in our understanding of soil as a living system. With increasing pressure on agricultural land to produce more food from this declining natural resource, a better understanding of how to maintain and improve the health and productivity of soil is essential. Ensuring on-going productivity from the soil requires a committed effort on the part of all stakeholders to progress research, development, extension and adoption on this vital issue.

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Appendix 2 – Workshop attendees, program and summarized group outputs

WORKSHOP

Attendees

Attendees	Institution	City/State/Country	Role
Robert Tegg	TIA	Hobart,TAS, AUS	Project Leader
Shane Powell	TIA	Hobart,TAS, AUS	Project Team Member
Calum Wilson	TIA	Hobart,TAS, AUS	Project Team Member
Sue Hinton	TIA	Launceston, TAS, AUS	Workshop facilitator
Leigh Sparrow	Bird Brains Downunder	Launceston, TAS, AUS	Project Team Member
Lyn Abbott	UWA	Perth, WA, AUS	WA domestic representative
Katherine Linsell	SARDI	Urrbrae, SA, AUS	SA domestic representative
Graham Stirling	Biological Crop Protection	Moggill, QLD, AUS	QLD domestic representative
Kelvin Montagu	Colo Consulting	NSW, AUS	NSW domestic representative
Pauline Mele	LaTrobe Uni	Bundoora, VIC, AUS	VIC domestic representative
Robert Larkin	USDA-ARS, University of Maine	Orono, ME, USA	US international representative
Richard Falloon	Plant and Food Research, Lincoln University	Lincoln, NZ	NZ representative
Denis Curtin	Plant and Food Research, Lincoln University	Lincoln, NZ	NZ representative
Tim Heysen (Thursday only)	Heysen Partners	Mt Gambier, SA, AUS	Industry/grower representative
John Doyle (Thursday only)	Berrigan grower	Berrigan, NSW, AUS	Industry/grower representative
Nigel Crump	VicSpa	Bundorra, VIC, Aus	Industry representative
Josh Opas (Thursday only)	McCains	Ballarat, VIC, Aus	Industry representative
Brenda Kranz	Hort Innovations	NSW, AUS	Hort Innovations representative
Kevin Clayton-Greene	Technical consultant	Devonport, TAS, AUS	Technical consultant

Program

Thursday November 16:

10.00 – 10.30 MORNING TEA

10.30 – 10.40 Welcome & introduction to the workshop scope/purpose

10.40 – 10.55 Brenda Kranz to outline the project/workshop and expectations from Hort innovation perspective/ Kevin Clayton-Greene to provide extendable outputs and gap analysis of potato R and D.

10.55 – 11.05 Rules of engagement/questions/suggestions on program changes

11.05 – 11.50 Introductions from the participants (brief 2-3 min on background – no powerpoints)

12.00 – 12.45 Introduce and summarise the literature review findings with interactive feedback and discussion (powerpoint)

12.45 – 1.30 LUNCH

1.30 – 2.45 Group Activity 1 – Identify/clarify the critical industry priorities for soil health

- Based on lit review and other ideas
- timelines (What are immediate/short and long term priorities)
- What are the biggest unknowns about soil health (in the vegetable industry)
- How will industry constraints (water prices, increasing input costs, need to supply product year round, etc.) constrain optimal soil health practices
- What measures of soil health are most useful/what measures are grower friendly/cost effective
- Group summaries

2.45 – 3.45 Group Activity 2 – Identify existing knowledge and/or tools ready to extend to industry/also what tools would the industry like?

- Optimal field practices, soil tests, rotation strategies, cover crops (but look beyond current extension programs)
- Measures of soil health
- The future (tools beyond 2020)

3.45 – 4.05 AFTERNOON TEA

4.05 – 4.30 Group Activity 2 continued…

- Group summaries

4.30 – 5.30 Group Activity 3 - Identify extension tasks/methods (who/what/when) – that may better communicate improved soil health practices

- What are the traits and practices of our best growers
- How transferable are these to other growers, remembering that each farm is a system in its own right, and growers need to be able to adapt practices to their own system.
- How can key practices be best demonstrated/extended?
- Who is best placed to deliver the messages to growers? Do we need to grow the capacity for extension?
- Communication concepts – field days/workshops, demonstration sites, new technologies for extension (webinars/fact sheets/etc..)
- Group summaries

6.30 – DINNER

Friday October 17:

9.00 – 9.30 Summary of day 1 – consensus on conclusions

9.30 – 10.45 Group activity 4 – blue-sky thinking and beyond - identify critical knowledge gaps

- What areas are at the cutting edge of soil health? – in terms of practices?
- How to assimilate systems thinking into managing soil health
- What new tools for measuring soil health may be about in the next 5-10 years.
-

10.45 – 11.05 MORNING TEA

11.20 – 1.10 Group activity 5 – scope prospective R&D areas that will most benefit the industry

- Scope areas of significance e.g. soil microbial ecology, soil pathogen ecology, etc…
- Short, mid and long-term perspectives
- Regional relevance

1.10 – 2.00 LUNCH

2.00 – Networking opportunities for those waiting for flights

Navigating the wealth…Workshop Nov 16 & 17 meeting notes

Group Activities

Activity 1: identify / clarify industry priorities

KEY CONCEPTS and UNDERLYING PRINCIPLES (4 groups summarised – Activity 1)

Industry constraints

Disease – main driver for fumigation. Important diseases include powdery scab, verticillium and nematodes.

Compaction – mainly issue at harvest but also when soil moisture is high

Practices still extreme in Australia eg use of mouldboard plough, elsewhere this has changed to ……and when? 10 years ago or more recently?

Pressure for available land – specifically long rotational land

Inputs higher but yields haven't increased e.g. potatoes, sugar, wheat. As margins have decreased more pressure to produce more units. One solution is leased land but this creates its own issues for soil health: in some cases less of an imperative to improve soil.

Soil degraded – not holding water

External factors e.g. weather, water allocation

Gross margins small and declining?

Industry priorities for soil health / factors affecting soil health practices

What impact does soil health (economic imperative) have on yield gap?

Interaction between pathogens/disease expression and soil properties (structure, microbial functions, chemistry).

Need definitions of major potato production soil systems (climate x soil type) in Australia

How plant variety influences soil environment; look at root architecture with climate x soil type x management overlay

Does use of pesticides have non-target effects in soil that causes yield decline (e.g. treated seed impacts on soil microbial populations)?

How to reduce tillage, plan timing of tillage, reduce horsepower (ie reduce cost – autumn preparation followed by cover crop?)

Reduce soil borne diseases (low pathogen load)

Improve water use efficiency and holding capacity

Long term priorities

Off-farm impacts on …waterways

Change in soil C

Make it easier for growers i.e. FOCUS ON COSTS

What measures of soil health are currently used in the potato industry?

Tests need to be cheap and easily interpreted by growers. Lots of tests are available such as…..but the problem is interpretation and provision of the interpretation in context of that particular farm.

Basic chemical tests (C, N, P, K, pH, CEC, EC) are being used , but not much in the way of soil physical or biological tests

Shovel test; considered useful because seeing is believing

Potato plant Yield + loss (biggest bang for buck from varieties and irrigation management)

Organic matter / soil C are good surrogates that are being used

Pathogen tests, particularly Predicta Pt, good for monitoring over time whereas other biological tests can be difficult to interpret (beneficials?, respiration?).

History and previous management, Soil particle size, water stable aggregates – water holding capacity of soil.

Concept: Measures of soil health: Organic matter/C + Predicta + beneficials (AMF, FLN) + nutrients: need for interpretation, trend rather than target value.

Activity 2 and 3: Identify / clarify industry knowledge/tools; future tools and how this information is effectively communicated/extended

KEY CONCEPTS and UNDERLYING PRINCIPLES (4 groups summarised – Activity 2 and 3)

EXISTING INDUSTRY KNOWLEDGE/TOOLS/CONCEPTS:

- Knowledge of optimal field practices/tools that aid growers:
  - History of cropping and land use (farmer knowledge)
    - Land use data maps – old and new e.g. satellites.
    - EM (provides broad measure of soil moisture, salt and clay)
    -
  - Commercial rotations and selecting alternative options (cover crops)
  - Correct usage of cover crops important (knowledge transfer) to ensure maximum grower benefits: disease suppression, soil conditioning.
  - Grower to grower knowledge transfer important in local regions.

- Learning from "best growers" that are profitable and demonstrating best practice – powerful resource – other growers may incorporate improved practices.

- Predicta Pt (help with interpretation)
- Soil fertility tests (but growers need to understand)
- Reduced tillage and traffic is desirable – not always practical in a potato crop – aim for a "potato farming system" which encourages continual plants in ground, increased diversity of crops (region specific).
- Economic analysis, but include environment and social – drives decisions
- Precision agriculture – drones, sensors, APPLICATION, yield mapping
- Information from other related areas: soil quality.org.au (with application to potatoes) – comparative data – decision support.
- General disease management (IPM)
- (see soilhealthinstitute.org) – Tier 1 measures in particluar
- Carbon mineralisation
- Beneficial nematode test to complement Predicta Pt
- Microbial biomass + Solvita "microbial respiration"
- New varieties
- Soil physical tests
- Composting
- Changes in production systems driving interest in soil health
-

Tier 2 indicators –

- BIOLOGY – good guys: bad + ugly
- Molecular assays for biology http://www.bioplatforms.com/soil-biodiversity/

- Benchmarking tools (now and into the future - biology taxa, functional traits, WTF)
- Incremental change – acceptance (embracing complexity and rejection of the silver bullet)

FUTURE KNOWLEDGE/TOOLS/CONCEPTS:

The future (beyond 2020) – soon for grower

- Integrated data – blockchain – multi faceted – associated with crop parameters e.g. yield, quality
- Long term data – long term R and D
- Machine learning
- Capacity – learning
- More solutions = but more problems – Intractable problems
- Genomics
- Cover crops better understanding/options
- Robotics
- PA uptake – managing variability

EXTENDING INFORMATION ON SOIL HEALTH:

- Needs to demonstrate specific grower benefit

- "ECONOMIC BENEFITS" need to be demonstrated → Adoption
- LOCALLY specific and MARKET specific – involving end users e.g. processors

- How to demonstrate the benefits of soil health:
- "SEEING IS BELIEVING" – On-farm demonstration is gold – trust from local growers
- On farm demonstration trials or on research farms in area (SMART FARM)
- Grower-grower communication most effective (in isolated areas – not practical)
- Agronomists and extension people (skill up in soil health) – already interacting with growers – independent and evidence based information.
- A range of formats to suit different generations of busy people: paper version, videos online, facebook, grower group pages – access when they need it.
- Grower days (not when growers are busy planting – winter is good)
- Benchmarking grower practices/trends
- "Integrated package" relevant to needs
- Social media – decision ??
- Decision support tools e.g. cartoons – complex info – simple message.
- Extending how GOOD GROWERS OPERATE: decision making/drivers, risk profiles, long-term view, innovators/early adopters, stewardship, generational changes.

- EFFECTIVE EXTENSION = Increased knowledge (empowerment) = advice (prescription)
- Regionally tailored information on soil health (soil type x climate); focus on most crtical constraint
- Reward for effort; work with banks who will provide low interest loans to farmers who follow soil health guidelines
- Market the benefits on sustainable soil management in terms of elite quality product

Activity 4: critical knowledge gaps (cutting edge, blue-sky, new tools and future perspectives)

<u>KEY CONCEPTS and UNDERLYING PRINCIPLES (3 groups summarised – Activity 4)</u>

Reinforce the link from soil health → plant health → product quality- human health.

Minimal soil disturbance systems:

- Controlled traffic (compatibility with potato production systems? – perhaps seasonal)
- Current novel practices - Pre-forming beds in advance (autumn ground preparation, winter cover crop, spring plant)
- Will robotics, engineering provide grower opportunities? Yes!

Precision ag tools may help better understand yield variability, yield gaps and localised issues:

- Precision ag mapping, measurement of productive land, localised target parameters, remote sensing, portable user-friendly sensors in the field
- APP suitability – value to soil health?

New tools:

- Omics – link to function - functional genomics – Will deliver new metrics for soil health and resilience; can this soil cycle nutrients? Can this soil combat disease? Can this soil maintain structure adequate for water infiltration?
- Nanotechnology (medical field provides direction)????
- Many tools will become cost-effective, but keys will be
  - Interpretation, bioinformatics (computing power), what do the results mean (definite research usage)…further research (build research capability in key areas)
  - Tools for growers need to be informative and easy to use (standardised tests)
- If tools can provide early detection, diagnosis or insights, they add value:
  - Early diagnosis of plant stress/infection/soil microbial changes

Utilising (understanding) potential of soil biology:

- A degraded system may have fungi lost from the system
- Capacity of soil communities to perform functions: linking community profiles with function; Tracking differences in enzyme activity (greater activation of those breaking down C)
- Diversity of the microbiome
- Utilise research from other fields –
  - GRDC – linking traits (yield?, etc.) with communities.
  - CRC for High Performance Soils

Remember the beneficials and other key measures of soil health:

- Free Living Nematodes, Arbuscular Mycorrhizal Fungi – surrogate measure of soil health
- Organic matter (C) – a key surrogate
- Can we input these things
  - OM – yes – costs and labour critical – or grow as cover crop (more practical/economical)
  - AMF inoculants – yield benefits?

Don’t forget the plant: Induced host resistance, breeding programs, micro RNA’s

Understanding the soil as a system rather than as components:

- Different production systems
- Assimilation through the whole rotation – think ‘long-term’ – how does OM flow through the system.
- Biology through the system: N cycling, fixation; C fixation; decomposition.

Activity 5: scope possible R&D areas

KEY CONCEPTS and UNDERLYING PRINCIPLES (3 groups summarised – Activity 5)

Baseline survey of principles and practices that incorporate soil health – targeted extension

Market survey to measure the importance of soil health in the food narrative; will buyers favour potatoes grown in a sustainable way? Not organically but environmentally responsible way?

Differentiation between different agro-ecological zones (specific research for specific regions)

- What are regional and local drivers of yield gaps/yield decline

- Comprehensive assessments, large scale, many paddocks (crop history important)
  Differentiation between different cropping systems (pasture potato, mixed cropping, continuous potato) and market requirements (fresh*, processing (French fries, crisping*))

  *Note interviews with fresh and crisping perspective still on-going.

  Organic matter is an important component of healthy soil systems (reinforce this idea)

  Less cultivation, tillage and disturbance are key traits of maintaining soil health – this, in most cases, is not compatible with potato cropping, there may be exceptions to this rule (Darren Long – MG produce) – such growers provide invaluable demonstration and extension opportunities.

  Industry scepticism to soil health practices (barriers to adoption) – financial implications – demonstrate benefits of incorporating soil health practices: e.g.:

- rotation length between successive potato crops reduced from 5 to 3 years (financial benefit);
- Greater return on leased paddocks that has had prior soil conservation practices compared to a degraded, unhealthy over-cropped site.
- Value on farm and throughout food chain (retailers – image of sustainable practices)
- Will inputs be decreased in soils that are "healthy" or perhaps this should be about costs of different kinds of inputs (eg cost of cover crop, savings in reduced till etc)
- To add to (this area is critical for industry take-up)
  Current extension soil health websites provide a useful resource to growers – however, advice needs to be tailored to potato growers, who face different challenges.

  Soil Microbiology (the great unknown – an evolving area)

- Need better interpretation: how it links to function, resilience: leading to productivity and profitability benefits
- How does it change with potato practices (detailed comparative analyses of native non-potato soils vs potato cropped soils)
- What makes 'good' microbial communities; is there a regional signature community that reflects a healthy soil condition
- Mycorrhiza – associations, importance – rhizosphere
- Suppressive and/or robust soils and how to build them
  Harmonization with other groups, crops working with soil health principles – BASE bioplatformshttp://www.bioplatforms.com/soil-biodiversity/, GRDC Soil Biology Initiative outcomes in Australia and overseas.

  Other diagnostic tests – link to function: nutrient cycling/hyper parasitic/aggregation/free living nematodes.

  Soil inoculation? And organic amendments

  Integration of all available soil and environmental monitoring data: on farm level, many different assessments at different times, soil variability, moisture, FLN (Predicta Pt).

  Integrated disease management

- Interactions/factors/alternative management
- Weed and volunteer management (critical for reducing soil borne disease populations)

SYSTEMS APPROACH with a LONG TERM perspective that is MULTI DISCIPLINARY (soil science, pathology, agronomy, engineering, economics, social sciences

Appendix 3 – Media articles

13 Apr 2018
Tasmanian Country, Hobart

Section: General News • Article Type: News Item • Audience : 17,528 • Page: 28
Printed size: 678.00cm² • Market: TAS • Country: Australia • ASR: AUD 4,068
words: 515 • Item ID: 939300687

DIGGING IN: Robert Tegg is leading a research project looking into soil health and potato production at the Tasmanian Institute of Agriculture.

CUPPA TIA

A RESEARCH team at the Tasmanian Institute of Agriculture is critiquing scientific studies and listening to the experiences of potato growers to identify the best strategies for sustainable soil health and where new research is needed.

TIA scientist Robert Tegg is leading the project, funded by Hort Innovation using potato industry levies and funds from the Federal Government.

Dr Tegg said an enormous amount of information already existed on soil health, but extracting what was relevant to the potato industry posed an interesting challenge.

"Understanding all the interacting components of soil health, the physical, biologica, and chemical factors, is essential in creating robust and productive soils that are able to sustain commercial potato production. Growing potatoes requires a lot of inputs, including fertiliser and irrigation, and also involves a lot of soil disturbance, particularly at planting and harvest," Dr Tegg said.

"Practices such as cover cropping and reducing tillage and traffic, particularly when soils are wet, can help improve soil health.

"These practices are not revolutionary, however the way they are implemented as a system can make all the difference.

"Improving physical soil health allows better root growth and more efficient use of nutrients and water. A soil with higher organic matter is more stable and less prone to water and wind erosion, keeping valuable soil on-farm."

Dr Tegg said managing soil health as a complete package using a "farming system" concept was essential to long-term soil health. This means farming practices outside of a potato crop, such as cover crops or long-term pastures, are likely to have the biggest positive impact on soil health.

"A healthy soil can offer more opportunities and flexibility for growers. If the soil is more robust and resilient it may allow for shorter rotation times between potato crops, which would be a massive incentive," Dr Tegg said.

"Some of the innovative growers are already experimenting with such approaches. Likewise, robust, healthy soils may give flexibility to increase planting and harvest windows, which provides more options."

The research team is interviewing potato growers over the next month to bring their stories of managing soil health to the wider community.

This project brings together up-to-date advice on monitoring soil health and case studies of growers implementing good soil-health practices and aims to distil the knowledge bank of soil health into practical information for potato growers.

Dr Tegg said a key output of the project was that research into soil health needed to be multidisciplinary and track changes over longer time periods.

"You have to look at soil health over the longer term because what you do now is going to impact on your soil in five to 10 years from now," Dr Tegg said.

TIA is also conducting a long-term soil health study at the Forthside vegetable research facility. In its 12th year, the study is backed by Agrigrowth Tasmania and monitors a section managed with cover crops, biofumigants and various rotations and measures indicators of soil health.

Appendix 4 – Multi-media format videos snapshot

TASMANIAN INSTITUTE OF AGRICULTURE

TIA is a joint venture of the University of Tasmania and the Tasmanian Government

utas.edu.au/tia

PT16003 – Snapshot of Soil health videos by potato growers for dissemination

James Addison, Moriarty, TAS. Mixed vegetable cropping with beef.

Seasonal Controlled Traffic https://youtu.be/eC0eCyPfTxw

Cover Crops https://youtu.be/62bsZANjypY

Key points: Soil preparation: compaction and quick recovery into pasture. Cover crop benefits – erosion control, adding organic matter, easier to plough,limited grazing of cover crops.
Grazing – for removing crop residues.

Leigh Elphinstone, Sisters Beach, TAS.
https://youtu.be/JZrVJSaHnwU
Primarily potato with beef production

Key points: long rotations, leases land (preferred to be out of long-term pasture).
Biofumigant benefits – nematode control, weed suppression, organic matter addition due to not being grazed, erosion control, less cultivation, easier to plough.
Grazing – for removing crop residues.

Terry Buckley, Mt Gambier, SA.
https://youtu.be/ByFck1f0ohU
Potato grower with beef production

Key points: Usage of technology, EM38, soil moisture sensors with variable rate irrigation.
Improved practices: inter-row ripping for aeration;
Cover crop benefits – erosion control, less cultivation, easier to plough, limited grazing of cover crops.
Grazing – for removing crop residues.

Hamish Henke, Mumbannar, VIC.
https://youtu.be/pdZyv_m0WF4
Potato seed grower with beef production

Key points: Soil preparation: compaction and quick recovery into pasture.
Cover crop benefits – erosion control, less cultivation, easier to plough, limited grazing of cover crops.
Grazing – for volunteer control and removing crop residues.
Protecting soil for future generations' prosperity.

Hort Innovation

Appendix 5 – fact sheet

tia TASMANIAN INSTITUTE OF AGRICULTURE

utas.edu.au/tia

Potato Soil Health Fact Sheet

Key Points

- **Build and maintain soil structure** by avoiding traffic when wet and minimising tillage.
- **Organic matter** is critical for soil health. **Keep something growing** or covering the ground as much as possible. **Manage cover crops** and select the right one for the job. **Utilise biofumigant crops** for potential disease control.
- **Useful measures for monitoring soil health include:** basic soil chemistry tests, PreDicta Pt, aggregate stability and soil mapping (EM38).
- **Financial benefits** (both on and off farm) may result from improved soil health practices.

Principles for improved soil health and management

Understanding and managing all the interacting components of soil health - the physical, biological and chemical factors - is essential to create robust and productive soils that are able to sustain commercial potato production.

Managing soil health as a complete package using a 'farming system concept' is essential for long term soil health. This means that farming practices outside of the potato crop, such as cover crops and pasture rotations, have as much a role to play as the management during the life of the potato crop.

This factsheet identifies principles and strategies that can be used to improve soil health management in a potato cropping system.

Building and maintaining soil structure

Avoid traffic when soils are wet.
Traffic (both machinery and livestock) compacts the soil. Traffic impacts may be restricted to decline of surface structure (light traffic, low ground pressure) or may penetrate to depth (heavy machinery).

Use seasonal controlled traffic farming (SCTF) if you can. Tillage destroys soil internal channels, aggregates, roots, organic matter and fungi. The less traffic and less tillage, the easier it is to build structure. This is a major challenge in potato production, but should be possible for other crops in the rotation.
SCTF requires satellite guidance and matched implement working widths, recognising that integrating harvest machinery is a challenge in mixed cropping systems.

Aim for a "potato farming system" which encourages practices outside the potato crop to improve soil health

Organic matter and cover crops

Organic matter is critical for soil structure, biology, aeration, infiltration, nutrient and water retention, internal drainage and soil resilience.

- Keep something growing in, or covering, the soil as much as possible to minimise erosion and maintain root channels.
- Biofumigant crops must be incorporated for maximum benefits.
- Manage cover crops as you would a cash crop.
- Use the most suitable cover crop mix that does the job you want - a legume for nitrogen, a tap-rooted species for 'biological tillage', a vigorous grass species for bulk production of fibrous roots and a thick stand to out-compete volunteer potatoes.

Soil tests

Basic soil chemistry tests are important to monitor crop nutrient requirements. In particular,

- Take note of **carbon levels** and how they change over the long term – they are a good surrogate measure of soil health.
- **PreDicta Pt** can quantify key soil borne pathogen levels and provide a measure of disease risk. Look out for new tests that quantify beneficials/microbial activity and arthropod presence.
- **Aggregate stability** provides a measure of soil structure and resilience to physical stresses such as wind and water erosion. Consider including this as an additional soil test.
- **Soil mapping (EM38)** can identify changes in soil type, moisture and salinity, and so help in irrigation management and drainage, which are important aspects of soil health in some environments.

Advantages of improved soil health

- **Reduced Rotation length** may be possible, such as reducing from 5 to 3 years (financial benefit).
- **Easier leasing of paddocks** with good soil health compared to a degraded, unhealthy over-cropped site.
- **Increased value on farm** and throughout the food chain with environmentally focused accreditation systems.
- **Decreased input costs** (fuel, labour) resulting from less tillage, lower powered implement demands.

Further resources for soil health information

- Soil Wealth
- Soil First Tasmania
- Soil Health Resource – Victorian Department of Primary Industry
- Soil Biology and Health - Stirling - GRDC
- Soil Quality Australia
- Soils are alive
- Healthy soils - farm ute guide
- Soils Alive - Understanding and managing soil biology on Tasmanian Farms (Tasmanian DPIPWE)
- Organic amendments & soil organic matter
- Soil health for vegetable production in Australia
- No Till Veggies
- Integrating sustainable soil health practices into commercial vegetable farming (Hort Innovation)
- Soil Management – Vegetables (WA)

This project has been funded by Hort Innovation, using the fresh potato and processing potato research and development levies and contributions from the Australian Government.

Dr Robert Tegg
Tasmanian Institute of Agriculture