Final Report

Optimising cover cropping for the Australian vegetable industry

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Delivery partner:

Applied Horticultural Research

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VG16068

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Optimising cover cropping for the Australia vegetable industry VG16068

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Content

Summary

Cover crops are one of the most useful tools for managing intensive vegetable growing soils. The integration of cover crops into vegetable production can improve soil health by building soil structure and condition, reducing erosion, adding nitrogen, improving nutrient recycling, and contributing to weed and soil-borne disease control.

The project Optimising cover cropping for the Australian vegetable industry project, ran from July 2017 to 2020, involving both research and delivery activities. The field research generated new information on the use and agronomy of cover crops to manage soil structure, soil microbial communities, specific beneficial microbes, and soil-borne diseases under Australian conditions.

The new information was combined with practical industry knowledge and international research to deliver, information on cover crops to the vegetable industry. This included 11 farm walks and two Cover Crop Coaching Clinics covering the selection, establishment, management, and termination of cover crops, and the management of soil-borne diseases and weeds.

The project also produced seven articles, 20 factsheets, six guides, four research reports, six webinars, five podcasts, and five videos which are housed on the on the Soil Wealth website www.soilwealth.com.au/my-topic/cover-crops-and-biofumigation.

These outputs are an important legacy of the project, which will continue to deliver useful information on using cover crops to restore or maintain healthy soil for profitable and sustainable vegetable growing. The knowledge, skills and experienced developed across the three partner organisations, Applied Horticultural Research, Queensland Department of Agriculture and Fisheries, and the Tasmanian Institute of Agriculture, are an important additional legacy produced by the project to ensure the vegetable industry has the capability to further develop the use of cover crops.

But the best summary left to a leading vegetable grower

“The advancements in cover cropping have been the most advanced single change to farming that I’ve seen for 30 years. It’s an absolute game-changer”

Keywords

Cover crops; biofumigation; vegetables; microbial community; mycorrhizae; soil-borne disease; agronomy; herbicides; termination; soil structure; glucosinolates

Introduction

Cover crops are one of the most useful tools for managing intensive vegetable growing soils. The integration of cover crops into vegetable production can improve soil health by building soil structure and condition, reducing erosion, adding nitrogen, improving nutrient recycling, and contributing to weed and soil-borne disease control (Larkin, 2015; Murphy, 2015).

Much of the health of soil is driven by its microbial communities. Cover crops can impact directly on soil microbial communities through the input of organic matter from the cover crop and through root activity during the growth of the cover crop, both of which boost the soil's biological activity. There is a growing interest in soil health and managing beneficial biological soil microbes in vegetable production. Arbuscular mycorrhizae fungi are the "flagship" of beneficial fungi, with wide general understanding of them by vegetable growers. An increasing number of mycorrhizae inoculum products are available on the market and used by growers. There is a need to improve understanding on how cover crops can be managed to optimise the overall soil microbial community and specific beneficial microbes such as mycorrhizae fungi.

Soil-borne diseases are also part of the microbial community of vegetable soils. Biofumigation is a process where specialised cover crops are grown, mulched and incorporated into the soil to release glucosinolates, which can be toxic to many soil-borne pests, diseases and weed seedlings (Kirkegaard and Sarwar, 1998). Critical to the effectiveness of biofumigants is the production of a high plant biomass and the production of high levels of glucosinolates. Under Australia's warm to sub-tropical conditions there is little information on the growth of various biofumigation cover crops, the amount of biomass and glucosinolates, and their efficacy against soil-borne disease.

The general principles of cover crop use in vegetable production are well understood. Cover crops are being encouraged in a broad range of vegetable growing areas and production systems, but there is a need for new information on how to manage cover crops to ensure they fit with current intensive production systems and integrate with other changes in production e.g. strip tillage. A key requirement is to adapt the international research and practical knowledge to Australia's climate and intensive vegetable production systems. For example, cover crops in Australia are more likely to be limited by water shortages than cold temperatures experienced in many northern hemisphere areas where cover crops are widely used. This "Australianisation" of leading overseas work is an important step so optimal use of cover crops in local conditions can enhance farm-level profitability and sustainability.

This project, which ran from July 2017 to 2020, had the following objectives;

- Deliver "Australianised" information on cover crops specific to the vegetable industry covering cover crop selection, establishment, management, and termination, and on the management of soil-borne diseases and weeds.
- Generate new information on the use of cover crops to manage soil structure, soil microbial communities, specific beneficial microbes, and soil-borne diseases under Australian conditions.
- Develop knowledge and capacity to promote the continual improvement of cover crop use in the Australian vegetable industry.

Methodology

The cover crops project involved both research and delivery activities from July 2017 to 2020.

Research

The location of trials and demonstration plantings across Australia and details of the main focus and cover crops trialed at these sites is provided in Table 1. Full details of the research sites are provided in the research reports.

Table 1. **Cover crop field sites and their main focus**.

Site	State	Cover crops	Focus
Bundaberg	Qld	15 biofumigants cultivars	Biofumigant growth, glucosinolate production different times of the year
Gatton	Qld	15 biofumigants cultivars, sorghum, lablab, fallow	Biofumigant growth, glucosinolate production different times of the year and efficiency agair soil-borne diseases and soil microbial commur
Cowra	NSW	Cereal rye, fallow	Cover crops and strip tillage, hay removal and microbial community
Bathurst	NSW	Oats, cereal rye, fallow	Cover crops and strip tillage
Yarramundi	NSW	Oats, Ryegrass, Oats/ryegrass/vetch, fallow	Cover crops and mycorrhizae
Richmond	NSW	Cereal rye, sorghum, sunn hemp, buckwheat, tillage radish, nemat, fallow	Cover crops and weed management and mycorrhizae
Lindenow	Vic	Sorghum, sunn hemp, sorghum/sunn hemp/tillage radish, Japanese millet, French millet, barley, cereal rye, Saia oats, ryegrass/clover, nemat, BQ much, caliente rojo, buckwheat	Demonstration planting for East Gippsland Vegetable Innovation day
Maffra	Vic	Oats/ryegrass	Cover crops and strip tillage
Devon Meadows	Vic	Cereal rye/vetch/peas, fallow	Cover crops and mycorrhizae
Forthside	Tas	Caliente, ryegrass, fallow	Long-term trial, soil structure and soil microbia communities, soil-borne-diseases
Richmond	Tas	Ryegrass, oats, millet, tillage radish, oats/tillage radish, fallow	Soil structure, soil-borne disease and soil micr community
Virginia	SA	Sorghum, Nemat, fallow	Root knot nematodes in tunnel house
Manjimup	WA	Sorghum/lablab/cowpea/ vetch/linseed, fallow	Cover crops and strip tillage
Myalup	WA	Cereal rye, field pea, ryegrass, caliente, BQ mulch, biofumigation mix	Cover crops and weed management and mycorrhizae

In addition to the research sites, the project sampled 57 vegetable crops for mycorrhizae associations on cover crops and vegetable crops, taking root samples to determine mycorrhizae colonisation levels, and soil samples to determine mycorrhizae inoculum levels. These were taken from commercial farms in Queensland, New South Wales, Victoria, Tasmania, South Australia and Western Australia.

Extension

The cover crop project delivered new information, knowledge, and tools to industry through two Cover Crop Coaching Clinics, a number of field walks, and presentations at industry forums. Due to COVID-19 restrictions during the last six months of the project, there was a greater reliance on webinars and podcasts.

The cover crop project built a wide range of legacy outputs including articles, factsheets, guides, webinars, podcasts, and videos. These are housed on the Soil Wealth Websites.

Partnerships

Partnerships were built with four other projects to effectively cover the areas of interest and the delivery of extension and training activities. The key partnerships were:

- A Strategic Approach to Weed Management for the Australian Vegetable Industry (VG15070). VG16068 shared research sites across Australia with the University of New England-run project.
- Soil Wealth and Integrated Crop Protection (VG16078). VG16068 contributed cover crop expertise to Soil Wealth demonstration sites and worked closely with the project on the integration of strip tillage and cover crops. The outputs from the project are housed on the Soil Wealth website (www.soilwealth.com.au/my-topic/cover-crops-and-biofumigation/)
- Queensland Government's Resilient Rivers project. VG16068 expanded the range of biofumigants and soil-borne diseases and included a site at Bundaberg.
- DPIPWE AgriVision 2050. VG16068 expanded the length and scope of the long-term field trial at Forthside.

Outputs

The cover crops project contributed to 11 farm walks and industry events, ran two Cover Crop Coaching Clinics, produced seven articles, 20 factsheets, six guides, four research reports, six webinars, five podcasts, and five videos. The outputs from the project are detailed below.

Events

Farm walks

1. Summer Cover crops farm walk, Richmond **NSW** 16 February 2018 (27 participants). Led by Gordon Rogers (AHR) and Adam Harber (Greensill Farming Group), the farm walk covered what can cover crops do, choosing a cover crop, how to manage cover crops and included viewing of cover crops on-site.
2. Can cover crops reduce Sclerotinia in lettuce? Richmond **Tasmania** 31 May 2018 (14). Led by Kelvin Montagu the farm walked focused on cover crops and their role in disease management. The field walk presented results on Sclerotinia in the lettuce crop following on from annual ryegrass, oats, tillage radish and Japanese millet cover crops.
3. Cover crops for managing root knot nematodes in tunnel houses, Virginia **South Australia** 3 September 2018 (32). Thirty participants from the Soil-borne Disease masterclass (VG15010 and VG15009) visited the trial and discussed the role of cover crops in managing soil-borne diseases.
4. Vegetable Centre field day, Forthside **Tasmania** 10 October 2018 (48). Robert Tegg and PhD student Brianna Walker presented results on the long-term cover crop/biofumigant site, with a demonstration of the incorporation process.
5. Cover crops and soil & tissue testing workshop, Orrvale **Victoria** 7 November 2018 (6). Kelvin Montagu covered what can cover crops do, choosing a cover crop and how to manage cover crops, at a packing shed talk.
6. Biofumigant cover crops, Bundaberg **Queensland** 21 March 2019 (26). John Duff hosted participants from the Cover Crops Coaching Clinic at the Bundaberg biofumigant trial.

7. Cover cropping: Implications for weed management field day, Myalup **Western Australia** 20 June 2019 (33). Marc Hinderager presented on the agronomy of managing cover crops and integrating cover crops and strip tillage.
8. Cover crops and soil biology, Richmond **NSW** 31 July 2019 (53). Kelvin Montagu presented at the Western Sydney University Soil Biology Masterclass and took participants on a farm visit to the mycorrhizae trial at Yarramundi.
9. Cover crop management, Virginia **South Australia** 23 October 2019 (29). Kelvin Montagu presented at the VegNET forum on cover crop selection and management.
10. Cover crops and strip tillage, Richmond **NSW** 25 October 2019 (38). Kelvin Montagu talked about cover crop management and strip tillage.
11. Vegetable Centre field day, Forthside **Tasmania** 5 December 2019 (59). International guest speaker Dr Adrian Newton from the Hutton Institute UK, presented on sustainable cover cropping systems with a farm walk, covering the pros and cons of different systems, including biofumigants.

Figure 1. **Caliente cover crop being incorporated at the TIA field day**

Cover Crop Coaching Clinic

The project delivered two Cover Crop Coaching Clinics in NSW and Queensland. The clinics, attended by 58 growers, brought cover crops into the 21-century through the combination of new science, machinery and management practices to make them work on today's farms. The coaching clinics were run by Kelvin Montagu, Adam Harber from Greensill Farming Group, and Darren Long from MG Farm, Tasmania, who is one of the leading cover crop innovators in vegetable production. Together they provided a wealth of practical and research knowledge to the growers, who rated the day well.

A third clinic to be held in western Australia was postponed due to COVID-19 restrictions.

Articles

A series of seven articles involving the cover crops project were produced. These included three articles in which leading vegetable growers outlined the benefits of the project (Appendix 3,Appendix 4, Appendix 5).

- **Cover Crop Coaching Clinic Bundaberg March 2019 (**Appendix 1**)**
- **Winter cover crops' effects on weeds: Results from TAS and WA trials (**Appendix 2**)**
- **Deon Gibson Covered in glory - Grower Success Stories – Real results from the vegetable R&D levy (**Appendix 3**)**
- **Opening the doors to a sustainable farming future (**Appendix 4**)**
- **Cover cropping pioneer aiming to educate others** (Appendix 5)
- **Should you be making hay from your cover crop?**

www.soilwealth.com.au/resources/articles-and-publications/should-you-be-making-hay-from-your-cover-crop/

- **Forthside Open Day focusses on crop and soil health for greater productivity**

https://ausveg.com.au/articles/forthside-open-day-focusses-crop-soil-health-greater-productivity/

Fact sheets

Twenty fact sheets were produced, including 15 fact sheets detailing the current commercially available biofumigant cover crops.

1. **Quantifying Soil Health after Long-Term Cover Crops** (Appendix 6) Fact sheet summarises the measurable impact of long-term cover crops on soil health.
2. **Integrated Weed Management on a Bathurst pumpkin farm** (Appendix 7) Fact sheet outlines the advantages & drawbacks of cover crop, strip tillage and residual herbicide use in pumpkins.
3. **Cover crop + Rolled ground cover + Strip till = Record farm cucumber yield** (Appendix 8) Case study highlighted how cover crops together with strip tillage produced a big yield benefit.
4. **Cover crop + Strip till: A Winning Combination for Soil Health** (Appendix 9) Case study outlined the soil health benefits of combining cover crops and strip tillage.
5. **Soil Loss in Vegetables** (Appendix 10) Outlines how replacing fallow with a cover crop is one of the easiest and most affordable options to reduce soil loss and for soil health benefits.

A series of 15 factsheets summarising growth period and incorporation for brassica biofumigation cover crops in Queensland for the following cultivars. These factsheets summarise biofumigant management, potential uses, and pest and disease issues for each cultivar or mix:

6. **Caliente (**Appendix 11**)**
7. **Tillage Radish**
8. **Terranova Radish**
9. **Blackjack Radish**
10. **Caliente Rojo**
11. **Nemat**
12. **Mustclean**
13. **Cappucchino**
14. **BQ Mulch**
15. **Biofum**
16. **Fungisol**
17. **Nemcon/Nemclear**
18. **Nemsol**
19. **Black mustard**
20. **White mustard**

Guides

The cover crop project produced the following six guides. **Cover Crops in the Wider Bay Burnett** (Appendix 12) Guide was produced summarising cover crop selection, biofumigants, termination and incorporation for the Wide Bay Burnett region.

1. **Guide to Brassica Biofumigant Cover Crops** (Appendix 13) provides comprehensive information on the use of biofumigant cover crops for managing soil-borne diseases in vegetable production systems
2. A series of guides have been produced summarising information in easy to use tables. The tables cover 52 warm and cool season cover crops. These tables will be distributed in the *Vegetables Australia* magazine as A3 inserts.
3. **Cover Crop Agronomy** (Appendix 14) Summarises the relative environmental tolerances, soil conditions, sowing information, and growth characteristics.
4. **Cover Crop and Soil-borne Disease** (Appendix 15) Summarises the potential impact of cover crops on some key soil-borne diseases.
5. **Cover Crops and Herbicides** (Appendix 16) Summarises herbicides which may be used in cover crops, and how residue herbicides from vegetable crops may affect the following cover crops.
6. **Cover Crop Termination** (Appendix 17) Summarises the options for terminating cover crops, resulting biomass and its speed of breakdown.

Reports

Four research reports detail the research undertaken by the project.

1. **Effect of cover crops on soil biological communities** (Appendix 18) Details how soil biological communities respond to the use of cover crops.
2. **Cover crops to manage mycorrhizae for vegetable crops** (Appendix 19) Details the levels of mycorrhizae associations in commercial vegetable and cover crops and boosting mycorrhizae using cover crops.
3. **Long-term impacts of cover crops** (Appendix 20) Details the impact of more than ten years of cover crop use on soil properties and soil-borne disease levels.
4. **In vitro studies to determine the biofumigant effectiveness of Brassica cover crops on mortality of soil microorganisms** (Appendix 21) Assesses the impact of biofumigant from a range of cover crop varieties on a range of common soil pathogens and beneficial microorganisms.

Webinars

Six webinars were produced.

1. Biofumigation Cover Crops PART 1: What variety and when?

In this webinar John Duff (QDAF) and Kelvin Montagu (AHR) summarise the results of trials growing more than 12 different biofumigants at different times of the year in Gatton and Bundaberg.

www.soilwealth.com.au/resources/webinar-recordings/biofumigation-and-cover-crops-part-1-what-variety-and-when/

2. Biofumigation Cover Crops PART 2 Pest & diseases & impact on soil-borne diseases

Part 2 of the webinar looks at potential pest and disease issues while growing cover crops and the potential impact on soil-borne diseases (*Sclerotium rolfsii, Sclerotinia sclerotiorum & Macrophomina phaseolina*) following incorporation.

www.soilwealth.com.au/resources/webinar-recordings/biofumigation-cover-crops-part-2-pest-diseases-impact-on-soilborne-diseases/

3. Using cover crops to manage mycorrhizal fungi in vegetable crops

The webinar presented by Dr Kelvin Montagu (AHR) covers the biology of mycorrhizal fungi, the prevalence in more than 50 vegetable crops and vegetable growing soils, and how cover crops and mycorrhizae inoculants might be managed to increase crop-mycorrhizae associations.

www.soilwealth.com.au/resources/webinar-recordings/using-cover-crops-to-manage-mycorrhizal-fungi-in-vegetable-crops/

4. Cover crops and soil biology in vegetable soils

Dr Shane Powell (University of Tasmania) and Dr Kelvin Montagu (AHR) look at diversity of biological communities in vegetable soils across five sites and the impact of cover crops on the microbial communities.

www.soilwealth.com.au/resources/webinar-recordings/cover-crops-and-soil-biology-in-vegetable-soils/

5. East Gippsland Vegetable Innovation Days - Cover Crops and Strip Tillage live webinar panel session

Presented by Dr Kelvin Montagu, the panel discussion involves the experience of leading growers Michael Evans, Mulgowie Farms; Adam Schreurs, Schreurs & Sons; Jake Ryan, Three Ryans; Pete Shadbolt, Scotties Point Farms and Michael Nash, Agnova, as they introduce cover crops + strip tillage into vegetable production

www.soilwealth.com.au/resources/webinar-recordings/east-gippsland-vegetable-innovation-days-cover-crops-and-strip-tillage-live-webinar-panel-session/

6. Cover crop trial discussion: East Gippsland Vegetable Innovation Days

Dr Kelvin Montagu (AHR, Soil Wealth ICP team), John Duff (Queensland Department of Agriculture and Fisheries) and Carl Larsen (RMCG, Soil Wealth ICP team) discuss the results of a cover crop trial at the East Gippsland Vegetable Innovation Days (EGVID) 2020.

www.soilwealth.com.au/resources/videos-and-apps/cover-crop-trial-discussion-east-gippsland-vegetable-innovation-days/

Podcasts

Five podcasts were produced covering the basics of cover crops, an overview of the project, and cover crops trials at Cowra and Bathurst. These podcasts were produced in partnership with Hort Innovation and the Soil Wealth & ICP project (VG16078).

Two "Growing Matters" podcasts were produced jointly with Hort Innovation.

1. **Basics of cover crops**
   Growing Matters - #1 Basics of cover cropping with Dr Kelvin Montagu (9min listen)

2. **Link between cover crops and soil health: An outline of the cover crop project**
   Growing Matters - #2 Link between soil wealth and cover cropping with Dr Kelvin Montagu (12min listen)

A series of three podcasts was developed in partnership with Soil Wealth (VG16078) drawing on the cover crop information from the project.

3. **Integrated Weed Management: Using cover crops and strip till**
   www.soilwealth.com.au/resources/podcasts/integrated-weed-management-using-cover-crops-and-striptill-6-minutes/

4. **Cover crop trials at Cowra NSW, with Marc Hinderager**
   www.soilwealth.com.au/resources/podcasts/podcast-cover-crop-trial-at-cowra-nsw-with-marc-hinderager-6-minutes/

5. **Benefits of cover crops and strip-till for pumpkin production: Interview with Michael Camenzuli from Bathurst**
   www.soilwealth.com.au/resources/podcasts/benefits-of-cover-crops-and-striptill-for-pumpkin-production-interview-with-michael-camenzuli-from-bathurst-6-minutes/

Videos

Five videos were produced covering two specific cover crops (buckwheat and sunn hemp); how cover crops and strip tillage work together; impact of cover crops on soil erosion and the use of biofumigation in vegetable production. These videos were produced in partnership with the Queenland Government's Resilient Rivers project, the Soil Wealth & ICP project (VG16078) and A strategic approach to weed management for the Australian vegetable industry (VG15070).

There is increasing interest in using different cover crop species to improve soil health and productivity in the Australian vegetable industry. The project produced two videos providing guidance on sowing, management, and termination of the buckwheat and sunn hemp cover crops.

1. **Cover crop spotlight on Buckwheat**

   www.soilwealth.com.au/resources/videos-and-apps/cover-crop-spotlight-on-buckwheat/

2. **Cover crop spotlight on Sunn hemp**

   https://www.soilwealth.com.au/resources/videos-and-apps/cover-crops-the-advantages-of-sunn-hemp/

3. **Cover crops and strip tillage** vegetable grower Ed Fagan (Cowra, NSW) explains how strip-tillage and cover cropping complement each other for a successful cucumber crop.

   www.soilwealth.com.au/resources/videos-and-apps/ed-fagan-explains-why-his-initial-reservations-about-striptill-and-cover-crops-were-dispelled/

Two videos are in final stages of production and will be available on the Soil wealth website

4. **Cover crops and erosion**

   www.soilwealth.com.au/my-topic/cover-crops-and-biofumigation/

5. **Biofumigation: A cover crop option for the Australian vegetable industry**

   www.soilwealth.com.au/my-topic/cover-crops-and-biofumigation/

Outcomes

The project addresses farm productivity, resource use and management, within the Vegetable Strategic Investment Plan 2012–2017. Specifically, the cover crop project contributed to 1. developing innovative techniques to improve on-farm productivity, and 2. increasing growers' ability to defend themselves against rising costs of inputs, the effect of variable climates, water and soil shortages, and diseases.

The project had the following outcomes:

1. Increased use of cover crops in vegetable production underpinned by robust Australian research on the benefits and agronomy.
2. Vegetable growers and advisers using new regional- specific cover-crop information and coaching to restore or maintain healthy soil for profitable and sustainable vegetable growing.

Outcome 1 - Increased use of cover crops in vegetable production underpinned by robust Australian research on the benefits and agronomy.

Darren Long, MG Farms

"I think the biggest advantage of these cover crop coaching clinics and Hort Innovation projects is that you get to talk to other growers. You can bounce some ideas off each other and that's what I've found – I get to go away and meet growers all around Australia who are like-minded, and we can actually talk about how they do things and what they see"

The cover crops project has delivered to vegetable growers and advisers a wide range of information to facilitate greater use of cover crops. Partnering with leading cover crop user Darren Long on the Cover Crop Coaching Clinics delivered information to growers, underpinned by the research knowledge generated by the project. This co-delivery approach proved popular with growers and was a driver of changes in practice following the clinics.

For example, there was increased adoption of cover crops in the Bundaberg region after the Cover Crop Coaching Clinic. Several producers planted cover crops as a direct result, with consultation from the project team. Cover crops planted include oats, tillage radish, nemat and millet.

Figure 2. **Grower submitted pictures of tillage radish, Nemat and Millet cover crop planted in Bundaberg following the Coaching Clinic**.

The project has delivered Australian cover crop research to growers and advisers (participant numbers in brackets) via webinars (190) and farm walks (332). These face-to-face and online events have covered all aspects of cover crop management and benefits – soil health, soil biology, structure improvements, weed management, soil-borne-diseases and biofumigant cover crops.

Andrew Johanson, Sustainable Farming Practices Manager, Mulgowie Farming Company (Appendix 4)

"Through my involvement, I've learnt a lot about soil biology and how microbes are helping to build a resilient plant"

Outcome 2 - Vegetable growers and advisers using new regionally specific cover-crop information and coaching to restore or maintain healthy soil for profitable and sustainable vegetable growing.

Tasmanian grower Deon Gibson, Premium Fresh farm manager (Appendix 3)

"*It has been a revelation for us. We've never had such healthy-looking carrots. There are no nematodes, the crops have beautiful green, healthy tops and they're in free-draining soil. And in terms of cultivation, the soil breaks down very easily and has plenty of organic material, worms and dung beetles*,".

Two coaching clinics were run in NSW and Qld, and a third postponed due to travel restrictions because of COVID-19. These Cover Crop Coaching Clinics allowed road testing of information and resulted in a shift in focus from regional guides to the comprehensive cover crop tables on cover crop agronomy, soil-borne disease, herbicides and termination. These tables split cover crops into cool and warm seasons, and allow growers to select cover crops most suited to their region's growing conditions.

Case studies have highlighted both the profitability and sustainability of using cover crops. For example, Cover crops + roller crimper + strip tillage proved a winning combination. Cucumber yield and gross income more than doubled, with many soil and weed control benefits adding up to produce impressive yield and quality results (Appendix 8, Appendix 9).

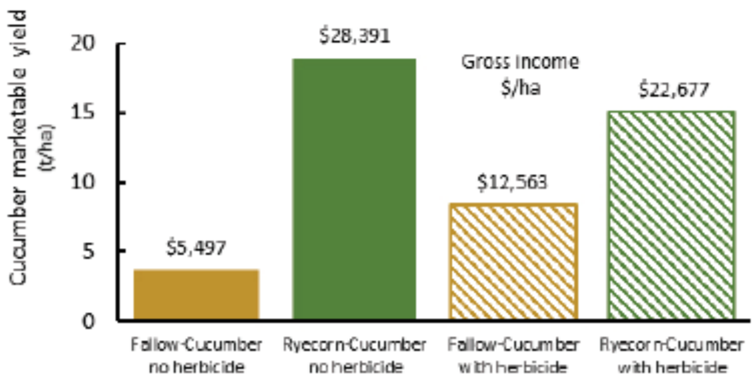

Figure 3 Cucumber yield and gross income following either a fallow or rolled ryecorn cover crop, with and without the herbicide clomazone.

In another case study, the reduction of erosion due to cover crops was highlighted (Appendix 10).

Andrew Johanson, Sustainable Farming Practices Manager, Mulgowie Farming Company (Appendix 4)

"With controlled traffic farming, cover cropping and minimum tillage, we have seen our soil water infiltration and holding capacity increase, the soil become less compacted and more friable, and yield increase, with plants showing more resilience to weather extremes"

The projects guidelines leave the vegetable industry with a strong legacy. These will help encourage and guide growers to make the most of cover crops.

Monitoring and evaluation

The cover crop project delivered beyond the planned activities and outputs detailed in Table 2. This was achieved through effective partnerships with other projects, allowing more integrated project outputs, for example, cover crops and strip tillage, and cover crops and weed management.

Partnerships with the communication channels of AUSVEG, Hort Innovation's Growing Matters podcasts and the Soil Wealth 7 integrated crop projection project allowed the project to respond to industry needs. For example, five podcasts were produced that had not been planned.

The project was also able to respond to changing environment and industry needs to produce outputs relevant to industry. For example, during the drought the project produced an article on making hay from a cover crop in response to rising hay prices.

Table 2. **Assessment of project effectiveness based on M&E Plan**.

Evaluation Question	**Achievement**	**Project learnings**
Have the four research reports been produced?	Four research reports were produced covering the major areas of the project (Appendix 18,Appendix 19, Appendix 20,Appendix 21)	Research reports were produced for the end of the project. These reports will form the basis of scientific publications to be published.
Have the three regional guides been developed?	Six guides replaced the regional guides covering specific cover crop topics of biofumigants, agronomy, soil-borne diseases, herbicides and termination (Appendix 12, Appendix 13, Appendix 14, Appendix 15, Appendix 16, Appendix 17)	The project reviewed the appropriateness of region guides and determined that guides specific to topics were more useful for growers.
Have the three webinars been delivered?	Six webinars were produced as detailed in the outputs section.	A greater number of webinars were produced due to travel restrictions associated with COVID-19. The webinars were popular with industry and well attended. They represented a good way to deliver research results to industry.
Have the three Coaching Clinics been delivered?	Two Cover Crop Coaching Clinics have been delivered (NSW & Qld) with the third clinic in WA postponed due to COVID-19. This will be delivered when travel restrictions are lifted.	The partnership between the project researchers and Darren Long of MG Farms, a leading grower and cover crop user, proved an effective delivery method. Participants were presented with practical how-to strategies and research results in the one-day session.
Were the demo farm walks conducted?	Eleven farm walks and industry presentations were conducted as detailed in the outputs section. The events were well attended with 332 participants.	Three farm walks were cancelled and replaced with online events due to COVID-19.

Have the four factsheets been produced?	Twenty-one fact sheets were produced covering a wide range of topics.	The greater number of factsheets was due to successful partnerships with other projects, allowing integration on topics such as strip tillage and weed management.
Have Facebook pages been established for new Demo Sites?	Facebook pages were used for the demo sites	
Have the six videos been produced?	Five videos were produced as detailed in the outputs section.	The videos are an important legacy output from the project. The buckwheat video has had almost 10,000 views in two years, with positive feedback on the information contained.
Additional outputs	Five podcasts and seven articles were produced covering outputs from the project.	Additional outputs were produced in response to conditions or industry needs. For example, during the drought hay prices were high so the project produced an article: Should you be making hay from your cover crop?

Effectiveness, Appropriateness & Legacy

The cover crop project outputs have aligned strongly with growers and advisers' needs and expectations. Both quantitative and qualitative feedback from events has been strong. Participants thought the events were relevant to their business (7.3 out of 10) and rated the topic, content, and delivery at (7.7 out of 10).

The webinars proved popular with growers and advisers and were a good way to deliver research findings on biofumigation, soil biology and mycorrhizae.

The output from the project has produced a strong legacy. Already the recorded webinars have had more than 500 views, with the videos exceeding 12,000 views.

The project will be distributing the four tables on cover crop agronomy, soil-borne diseases, herbicides, and termination through inserts in *Vegetables Australia* magazine over the coming year. These tables have a strong practical focus and will help growers select the most appropriate cover crop for their vegetable production system.

The knowledge, skills and experience developed across the three partner organisations are an important additional legacy produced by the project. These, together with the PhD produced, will help ensure the vegetable industry has the research capability to draw on to further develop the use of cover crops.

Table 3. **Appropriateness of project activities based on M&E Plan**

Evaluation Questions	
Have training and extension activities increased the skills and knowledge of growers and advisers?	Across the training and extension activities (webinars, Cover Crop Coaching Clinics and farm walks) 92% of participants considered that they would be able to make more informed decisions about cover crops following the events. When asked how likely they were to change farm practices or advice following the event a score of 6.7 was given out of 10. Participants thought the events were relevant to their business (7.3) and rated the topic, content and delivery at 7.7.
Have the communication activities reached the audience?	Unsolicited articles produced by AUSVEG provide qualitative evidence that growers have been reached and value the information (e.g. Appendix 3, Appendix 4, Appendix 5) Also the project team has received regular contact from growers after events and other communications, such as webinars.
Have the factsheets, how-to-guides and reports been used?	The majority of outputs have been produced at the end of the project and form a strong legacy. Where early outputs were produced these have proved popular. For example, the buckwheat video has recorded almost 10,000 views, while Benefits of combining cover crops and strip tillage has had more than 1,800 views.
Has new information from the research component been incorporated into delivered activities?	Research undertaken by the project has been included in all outputs detailed in the Outputs section. The factsheets and guides will form an important legacy for the project ensuring information is available to the industry.

Recommendations

Cover crops are one of the most useful tools for managing intensive vegetable growing soils. Their importance is increasing as vegetable production systems move to “softer” more biological approaches to tillage, integrated crop protection, weed control and nutrition.

Darren Long, MG Farms

“The advancements in cover cropping have been the most advanced single change to farming that I’ve seen for 30 years. It’s an absolute game-changer”

This project has filled an important gap, bringing cover crop information together and modifying it specifically for for the Australian vegetable industry. This has also occurred across other horticultural and agricultural sectors, e.g. vineyards and broad--acre cropping. There is an ongoing need to periodically update these guidelines based on grower experience and new research findings.

Recommendation 1 – Continuous improvement

Consideration be given to fund the ongoing delivery of the Cover Crop Coaching Clinic. These clinics are an important pathway delivery to the industry and for the continuous improvement of cover crop practices in the vegetable industry. Combining growers and researchers’ experience would also allow rolling updates to the guideline, including the ongoing “Australianising” of new cover crop information, most of which is generated in the northern hemisphere.

Recommendation 2 – Cross-sector research opportunities

Consideration be given to development of a cross-sector approach for future cover crop research. This may be across all horticulture crops or in partnerships with agriculture crops. Cross-sectoral cover crop issues could include:

1. Mixed cover crops are topical among growers, largely based on the assumption that increased diversity is better. Research is required to understand the role mixed species cover crops can play in delivering cover crop benefits and to help overcome some of the management issues e.g. termination.
2. Water limitations are a key issue in Australian production systems, restricting both the growth of the cover crop as well as impacting on stored water for the subsequent cash crop. Research is required to guide growers on species selection to minimise water use, and management practices to maximise stored soil water.
3. Terminating cover crops is highly reliant on glyphosate. Alternatives are required, which may need to integrate rolling/mulching with non-glyphosate herbicide alternatives, or other options for organic growers.
4. Cover crops have traditionally been sourced from broad acre crops and pasture species and selected mainly because of the availability of cheap seed. The selection of specific traits for cover crops is only now emerging e.g. tillage radish, root max ryegrass. This an area that would benefit from a cross-commodity approach.
5. Soil biology remains an emerging area of importance where cover crops can potentially play an important role. A cross-sectoral approach would be useful in building a better understanding on the role of cover crops in managing soil biology. For example, what does it take to permanently change soil microbiology?Can this be somewhat controlled ormanipulated, and what represents a healthy system? What role does long term use of cover crops have in this?
6. Biofumigant cover crops require further development. In this project we demonstrated that their efficiency varies with the time of year and growing conditions. Further work on additional soil-borne pathogens and nematodes is required, as it has become evident each biofumigant variety has a different glucosinolate makeup and effectiveness at different times of the year.

Recommendation 3 – Integration

Applied research, working closely with growers, is required to develop new integrated approaches using cover crops. A good example from this project was the combination of cover crops and strip tillage, with both practices providing additional benefits when combined. Integration of different practices could include:

1. Cover crops and treatments for soil-borne diseases
2. Subsoil ripping and cover crops
3. Cover crops in organic production need an integrated approach to develop termination approaches that work.
4. Cover crops and beneficial biology
5. Cover crops to manage beneficial insects

Recommendation 4 – Cover crop – vegetable sequencing

One aim of this project was to collate information on the best cover crop – vegetable crop sequence to deliver the best outcomes. However, apart from the impacts of sequencing on soil-borne diseases, there was little solid information on the most beneficial sequences.

This approach may initially focus on the influence of cover crops on diseases and pathogens of different species, and on cover crops and mixes on pathogen inoculum.

Recommendation 5 – Long-term rotation trials

Long-term approaches to managing soil health would be beneficial to Australian vegetable growers. A series of longer-term rotation trials have been established in the US, and in the UK at the James Hutton Institute. The development of a series of linked rotation trials in Australia, under differing production systems examining some of the fundamental questions around soil health in cropping systems, including cover crops, would be beneficial to producers in this sector.

Refereed scientific publications

Paper in conference proceedings

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Intellectual property, commercialisation and confidentiality

No project IP, project outputs, commercialisation or confidentiality issues to report.

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On farm trials

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Growers survey

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Appendices

Appendix 1. Cover Crop Coaching Clinic Bundaberg March 2019

Appendix 2. Winter cover crops effects on weeds: Results from TAS and WA trials

Appendix 3. Deon Gibson Covered in glory -Grower Success Stories – Real results from the vegetable R&D levy

Appendix 4. Opening the doors to a sustainable farming future

Appendix 5. Cover cropping pioneer aiming to educate others

Appendix 6. Quantifying Soil Health after Long Term Cover Crops

Appendix 7. IWM on a Bathurst pumpkin farm: Advantages & drawbacks of ground cover use, tillage and residual herbicides

Appendix 8. Cover crop + rolled ground cover + strip till = record farm cucumber yield

Appendix 9. Cover crop + Strip till a winning combination for Soil Health

Appendix 10. Soil loss in vegetables

Appendix 11. Brassica Biofumigant Cover Crop - Caliente

Appendix 12. Cover crops in the Wide Bay Burnett

Appendix 13. Guide to Brassica Biofumigant Cover Crops

Appendix 14. Cover crop agronomy summary

Appendix 15. Cover crop and soil-borne disease

Appendix 16. Cover crops and herbicides

Appendix 17. Cover crop termination

Appendix 18. Effect of cover crops on soil biological communities

Appendix 19. Cover crops to manage mycorrhizae for vegetable crops

Appendix 20. Long-term impacts of cover crops

Appendix 21. In vitro studies to determine the biofumigant effectiveness of Brassica cover crops on mortality of soil microorganisms

Appendix 1

Cover Crop Coaching Clinic, Bundaberg, March 2019

On 21st March, 28 vegetable growers and agronomist from the Bundaberg region attended the Cover Crop Coaching Clinic. The clinic was run through the vegetable levy funded project VG16068 Optimising cover cropping for the Australian vegetable industry. The practical workshop demonstrated the latest cover crop species, the benefits and how best to integrate cover crops into their vegetable production systems. Presenters included Kelvin Montague (applied Horticultural Research), Darren Long (MG farm produce), John Duff (QDAF) and Adam Harber (VegNET IDO). Darren is a vegetable farmer from Tasmania that demonstrated best management practices of biofumigant cover crops. Participants also visited a biofumigant trial featuring 12 different species of biofumigants. Producers gained first-hand knowledge on agronomic performance, pest and disease pressure and benefit of incorporation biofumigants. The trial was also funded through the project. Since the coach clinic, adoption of cover crops has increased with several producers planting cover crops as a result and with consultation from the project team. Cover crops planted include oats, tillage radish, nemat and millet.

In collaboration from AHR and the VegNET IDO (BFVG), a factsheet with information from the workshop was produced on cover crops in the Wide-Bay Burnett area which can be found on the Soil Wealth website.

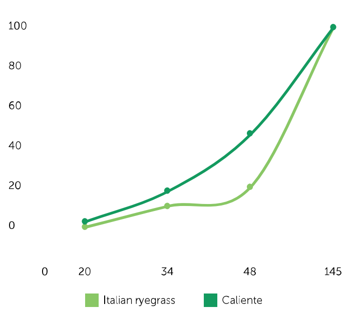
Tillage radish, Nemat and Millet crop planted in Bundaberg following the workshop.

Appendix 2

Caliente cover crops at Forthside, Tasmania.

Italian ryegrass at Forthside, Tasmania. Images courtesy of M. Coleman.

FIGURE 1: COVER CROP GROUND COVER PERCENTAGES, 20 TO 145 DAYS AFTER SOWING, FORTHSIDE, MAY-OCTOBER 2018



WINTER COVER CROP EFFECTS ON WEEDS: RESULTS FROM TAS AND WA TRIALS

Many growers are now including cover crops in their annual cycle to improve the quality of their soil, and information about soil health benefits will often influence which cover crop type (or mix of types) is selected. But what about their effects on weeds? The project team from the University of New England (UNE) investigates.

In 2018, a team from the University of New England (UNE) monitored two winter cover crop trial sites to understand the impact of several cover crop types on weed germination and growth.

The two winter cover crop sites included a long-term trial at the Tasmanian Institute of Agriculture (TIA) Vegetable Research Facility near Forthside, and a newly-established trial hosted by Ivankovich Farms near Myalup, Western Australia.

The TIA trial comprises four replicated plots each of Italian ryegrass (*Lolium multiflorum*) and Caliente (*Brassica juncea*) cover crops, as well as four fallow control plots for comparative analysis. These fallow plots received one extra herbicide treatment during the fallow period.

Cover crops were grown for 145 days before incorporation. The Myalup replicated trial includes six cover crop types, grown for 90 days before incorporation: field peas (*Pisum sativum*); cereal rye (*Secale cereale*); Italian ryegrass; Caliente; BQ Mulch (25 per cent *Brassica nigra*, 75 per cent *Brassica abyssinica* or *Brassica carinata*); and a biofumigant mix provided by David Grays (comprising *Brassica juncea* and *Eruca sativa*).

All cover crops were monitored regularly after sowing to measure the growth and canopy cover of each type, and the number and species of weeds present. Immediately prior to incorporation, final cover crop biomass and ground cover data were collected, as well as weed biomass and counts by species.

This research was undertaken as part of the three-year project *A strategic approach to weed management for the Australian vegetable industry* (VG15070), a strategic levy investment under the Hort Innovation Vegetable Fund.

INITIAL RESULTS

A faster-establishing, competitive cover crop can be more effective in suppressing both weed germination (by shading the ground and making it difficult for seed which requires light to germinate) as well as growth (by out-competing weeds that have germinated for resources and space). Figures 1 and 2 show the percentage of ground cover observed in the cover crops across both sites.

As Figure 1 shows, Caliente established more quickly than Italian ryegrass at Forthside, being at approximately 50 per cent ground cover some 50 days after sowing. Italian ryegrass established more slowly, but by the time the cover crops were incorporated (145 days after sowing), ground cover was close to 100 per cent for both.

At Myalup, cereal rye covered the ground considerably faster in the first 14 and 28 days after sowing compared with the other cover crops, and field peas were relatively slow (see Figure 2). However, by the time of incorporation into the soil (90 days after sowing), all cover crops had similar ground cover.

WEED DENSITY AND BIOMASS

Many common weeds in vegetable production were observed at the two sites including fat hen (*Chenopodium album*), chickweed (*Stellaria media*), milk thistle (*Sonchus oleraceus*) and wild radish (*Raphanus raphanistrum*).

Table 1 shows more weeds were present within Caliente at Forthside than within the Italian ryegrass and fallows, while a higher weed biomass was also found. The very thick canopy of Italian ryegrass at 145 days after sowing means that it may have been more effective at intercepting light at ground-level compared to Caliente at this late stage, where diffused light reached the ground level within the two metre high stalks. To explore the impact of light interception on weeds, this will be measured in year two for both trials.

Caliente also featured uncovered and partially-shaded wheel tracks which did not occur in the Italian ryegrass. In Caliente, this may have allowed weeds such as chickweed, commonly observed at Forthside and capable of growing in moist, partially-shaded conditions, to establish and grow well within the taller stature of this crop.

Table 1 also shows that the rapid ground cover establishment of cereal rye in Myalup correlated with a considerably reduced weed burden in the cereal rye plots at the end of the trial, both in terms of the number of weeds per square metre and the weed biomass. This shows that early ground cover establishment is important for cover crops to suppress weeds.

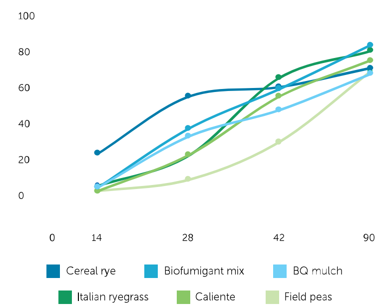
Biofumigant crops such as Caliente can have additional benefits including soilborne disease suppression, and anecdotal evidence suggests that its allelopathic effects (the chemical inhibition of one species by another) may also reduce the weed seed bank and suppress recently-germinated weeds after the crop has been incorporated into the soil. However, like selective herbicides, this effect may only inhibit seeds and seedlings of some weed species and not others. To explore the impact of the cover crop types on the weed seed bank at different depths, soil samples were collected for germination and counting of weed seeds at UNE. Analysis is ongoing, and full results will be published in the project's final report.

Each cover crop species is also likely to establish and perform differently with regard to suppressing weed growth and seed production depending on seasonal variation, local climate, paddock history, time of planting and incorporation, and weed species present.

Both the Forthside and Myalup trials will be replicated identically in 2019. Team members from the Hort Innovation-funded project *Optimising cover cropping for the Australian vegetable industry* (VG16068) are evaluating beneficial mycorrhiza and crop yield on these trial sites. Two similar summer cover crop trials are planned for Richmond, New South Wales, and the Lockyer Valley in Queensland (also a Hort Innovation-funded trial site).

The UNE team is very grateful to Hort Innovation for funding this research. In Western Australia, the team was supported by Peter and Anthony Ivankovich (Ivankovich Farms, Myalup); Ian Guthridge and Graham Blincow (Western Australian Department of Primary Industries and Regional Development); Grant Swan, John Cross and Bruce Shaw (David Grays), and Dave Stewart (Elders). In Tasmania, Philip Beveridge and Robert Tegg (TIA) provided generous support of the project and access to the TIA site at Forthside. Doris Blaesing (RM Consulting Group) and John Duff (Queensland Department of Agriculture and Fisheries) provided expert advice on cover crop variety selection.

FIGURE 2: COVER CROP GROUND COVER PERCENTAGES, 14 TO 90 DAYS AFTER SOWING, MYALUP, APRIL-JULY 2018



INFO R&D

For more information, please visit une.edu.au/iwmvegetables, or contact Michael Coleman at mcolema8@une.edu.au or 0437 403 644 or Chris Fyfe at cfyfe3@une.edu.au or 0401 200 045.

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Project Number: VG15070

Hort Innovation Strategic levy investment | VEGETABLE FUND

TABLE 1: WEED DENSITY AND WEED BIOMASS, MYALUP (WA) AND FORTHSIDE (TAS), 2018

TREATMENT	WEED DENSITY FORTHSIDE plants per m^2	WEED BIOMASS FORTHSIDE grams per m^2	WEED DENSITY MYALUP plants per m^2	WEED BIOMASS MYALUP grams per m^2
FIELD PEAS	-	-	13.5	17.7
CEREAL RYE	-	-	7.8	0.4
ITALIAN RYEGRASS	189.8	55.1	10.5	3.1
CALIENTE	262.3	125.9	15.5	2.7
BQ MULCH	-	-	18.5	2.6
BIOFUMIGANT MIX	-	-	14.5	2.5
FALLOW	22.3	26.1	-	-

Flick & Dave Photography.

DEON GIBSON

COVERED IN GLORY

Award-winning carrots are just one sign for Deon Gibson that patience has its own rewards when using cover cropping.

Inspired by 2015 Farmer of the Year Grant Sims, local Tasmanian grower Darren Long and various field days and walks, the Premium Fresh Tasmania Farm Manager started to revive cover cropping on his property. Deon is now working with others from Queensland and Victoria on a three-year project with Applied Horticultural Research scientist Dr Kelvin Montagu entitled *Optimising cover cropping for the Australian vegetable industry* (VG16068), a strategic levy investment under the Hort Innovation Vegetable Fund.

For this project, Deon has set up his 300-hectare farm at Forth on a four- or five-year paddock rotation, giving selected paddocks a 12-18 month rest with selected cover crops. The emphasis on quality over quantity has suppressed weeds, improved operational efficiencies and protected the soil rather than leaving the paddocks exposed to the elements.

"It has been a revelation for us. We've never had such healthy-looking carrots. There are no nematodes, the crops have beautiful green, healthy tops and they're in free-draining soil. And in terms of cultivation, the soil breaks down very easily and has plenty of organic material and worms and dung beetles," Deon says.

"Your soil is a living organism and you don't want it to die, so you want something growing in there – even if it's only a short-term cover crop, you're protecting that soil.

"Doing so over summer means you're not getting all the extremes with a 30-degree sun hitting the bare soil and doing lots of damage to the surface. The same applies in winter. That's where cover cropping maintains the consistency."

> "It has been a revelation for us. We've never had such healthy-looking carrots"

PATIENCE PAYS OFF

Deon says sticking with covered cropping beyond "trying one year and not the next" was netting excellent results in terms of better yields and premium prices.

"You still have to grow the cover crop – not just put it in and forget about it. I've found to get the best out of it, you give it that little bit more and you get twice the result. It's really about keeping your cool and not using your soil when it's not fit to be used," he says.

"Because of financial imperatives there's often too much of a push on the soil but, where possible, I'd rather be rejuvenating the soil than just have a marginal crop on it.

"I've seen that one bad decision can undo a paddock for four or five years where a harvest has depleted and destroyed the soil structure. Yet after cover cropping, our horsepower, fuel and irrigation requirements are reduced, and our soil isn't as tight and bashed down as we're not trying to turn it to plant a crop in the next day.

"Likewise, with strip plots all the natural drain and nutrients are still there because you haven't smashed it up. We're back on it in no time, and there's no erosion because the water filters down from the harder bits where you've worked before."

LONG-TERM GOALS

Deon says the scientific tools available are improving, such as penetrometer readings, and greater analysis by agronomists is deepening the physiological understanding of cover crops.

The project's end goal is to create a range of templates, such as booklets or guides, that highlight the estimated costs of what to grow, which cover crops and practices work best with different crops, and the expected results.

"It's my hope to follow through and produce long-term results that will benefit all. Everyone's back pocket will be helped. At the end of it, I'm sure I'll be really proud of this."

SUMMARY

- Project VG16068 aims to combine new science, machinery and management practices that growers, such as Premium Fresh Tasmania Farm Manager Deon Gibson, can use to improve their yields and ultimately increase prices.
- For this project, Deon has established a four- or five-year paddock rotation, giving selected paddocks a 12-18 month rest with selected cover crops. He has seen promising signs such as weed suppression and improved protection of soil as a result.
- A range of materials will also be released, including on the Soil Wealth and ICP website (soilwealth.com.au) that identify the approximate costs of what to grow and which cover crops and practices work best.

- *Optimising cover cropping for the Australian vegetable industry* has been funded by Hort Innovation using the vegetable research and development levy and contributions from the Australian Government.

Hort Innovation Strategic levy investment | VEGETABLE FUND

Mulgowie Farming Company Sustainable Farming Practices Manager Andrew Johanson (right) with CEO Fabian Carniel (left) and National Sales Manager Shane Quinn. Photography by Rowena Dione.

Opening the doors to a sustainable farming future

Andrew Johanson has worked at Mulgowie Farming Company for over 20 years and during that time, he has reaped the rewards of being involved in vegetable levy-funded research and development projects. Michelle De'Lisle speaks to Andrew about the activities he has been involved in, and the positive impact that they have had on the growing operation.

Andrew Johanson enjoys a varied role at Mulgowie Farming Company. As the operation's Sustainable Farming Practices Manager, he focuses on a range of different aspects of the farms, from vegetable supply forecasting to building soil health.

Andrew also coaches the farm's agronomists and managers on innovative farming methods and strategies that align to building healthier soils and delivering healthy plants that can be more resilient, high in quality and yield and, ultimately, have increased shelf-life.

However, achieving these goals requires guidance and gaining knowledge from external sources. Andrew has been involved in vegetable levy-funded research and development projects that have proved valuable not only his own role, but for the wider growing operation. Beginning as a small family-owned business in Queensland's Lockyer Valley over 75 years ago, Mulgowie Farming Company now produces 5,000 hectares of fresh vegetables across Queensland, New South Wales and Victoria. Crops grown include yellow and baby sweet corn, green beans and broccoli.

On-farm focus

Andrew's sustainable farming journey began in the early 1980s, when he worked with his father on the family farm. He then progressed to an agronomy consultancy role in the Lockyer Valley in the early 90s before joining Mulgowie Farming Company in 1996. Since then, Andrew has been involved in Integrated Pest Management research and understanding beneficial insects and, most recently, projects in precision agriculture, soil wealth and cover cropping projects.

Over the past year, Andrew and Mulgowie Farming Company have been involved in a project entitled *Optimising cover cropping for the Australian vegetable industry* (VG16068), a strategic levy investment under the Hort Innovation Vegetable Fund that is led by Applied Horticultural Research scientist Dr Kelvin Montagu.

"Through my involvement, I've learnt a lot about soil biology and how microbes are helping to build a resilient plant," Andrew says.

"With controlled traffic farming, cover cropping and minimum tillage, we have seen our soil's water infiltration and holding capacity increase, the soil become less compacted and more friable, and yields increase, with plants showing more resilience to weather extremes."

Andrew has used the information gained from his involvement in the project on Mulgowie Farming Company's five properties. For example, Kelvin has been supportive in helping the operation choose its cover crop based on crop rotation.

"It's totally different down in Victoria as to which cover crops are going to work compared to north Queensland, so Kelvin's advice has been very helpful," Andrew says.

Additionally, Kelvin has been conducting strip till trials at Mulgowie Farming Company's property in Maffra, Victoria, which produced positive results.

"Moving to zero tillage and minimum strip tillage from the result of trials – I didn't expect to see the increase in yields as quickly as we did. There has been an improvement right from the first season," Andrew says.

Touring benefits

Andrew doesn't just stay on the farm to learn about different growing practices as well as the latest in R&D.

In September, he attended a grower study tour of South Australia, Victoria and Tasmania that gave participants the opportunity to visit case study farms and share experiences in getting the most out of precision ag technologies for their vegetable growing business. This tour was part of *Adoption of Precision Systems Technology in Vegetable Production* (VG16009). It also involved seeing the iMapPESTS: Sentinel Surveillance for Agriculture, which Andrew found most interesting. The iMapPESTS project is a collaboration of government, industry and science to develop a mobile cross-industry plant pest surveillance network, which will provide actionable information to primary producers and government on endemic, established, trade sensitive or exotic pests (see page 16).

"I wondered if there were opportunities in the future for a mobile unit to be established up around Home Hill in Bowen. It was very good," he says.

When on tour in these other regions Andrew also observed other strip till planters in action. He said that going on a tour such as this was very valuable, and he has been able to share the knowledge gained with his teams at Mulgowie Farming Company.

"I run our Operational Excellence Forum once a month, and that's where we discuss innovation and new farming strategies. I've brought back what I've learnt from the soil wealth and precision ag tours and implemented it on our farms, which is making a big impact."

In 2015, Andrew went further afield when he jetted off to California, Delaware and Arizona, for the USA Industry Leadership and Development Mission. On the mission, he gained an in-depth understanding of the processes, procedures and issues facing vegetable growers in the United States. Plus, the networking was invaluable.

"Getting to know the other participants, and have those open networking friendships with people is important – now we meet up at Hort Connections to discuss where horticulture is at in Australia."

Export success

In 2018, Mulgowie Farming Company hosted a group of 40 delegates from Indonesia, Thailand, Taiwan, South Korea, the Philippines, Japan and Saudi Arabia. This was part of the AUSVEG-facilitated Reverse Trade Mission, which is delivered under the *Vegetable Industry Export Program* (VG16061).

The team discussed conventional and organic broccoli farming practices and provided the delegates with a tour of the farm and packing shed, with another positive outcome.

"We were able to show them the quality of our produce, the fresh quality aspect of Australian product and our standards. We then had a lunch where chef Alastair McLeod used our products in the culinary menu, and we got to network with the delegates," Andrew says.

"From that, we did get some export connections – we've followed through with sales (exporting to some of the people who attended)."

The final word

Andrew recommends that other vegetable growers get involved in levy-funded R&D, as it is a great networking and learning tool.

"The bottom line is to be on the cutting edge of the potential that is out there for better quality crops" he says.

"I have received a broader understanding of farming innovation, helping me to develop sustainable farming practices strategies for Mulgowie to ensure we are producing quality fresh vegetables, while looking after our environment."


Andrew Johanson and Shane Quinn.

Find out more R&D

Please contact Andrew Johanson on 07 5465 9222 or andrewj@mulgowie.com.au.

Communication of research and development projects has been funded by Hort Innovation using the vegetable research and development levy and contributions from the Australian Government.

Hort Innovation Strategic levy investment | VEGETABLE FUND

Darren Long from MG Farm.

Cover cropping pioneer aiming to educate others

In mid-2017, a project was established to support Australian vegetable growers to effectively use cover crops to boost soil health and reap productivity benefits. *Vegetables Australia* speaks with long-time cover crop advocate, MG Farm's Darren Long, who has been involved in cover crop coaching clinics as part of this project.

For over 20 years, Tasmanian potato grower Darren Long has been involved in cover cropping and biofumigation, which is the use of specialised cover crops that are grown, mulched and incorporated into the soil prior to cropping.

Darren, who runs the family-owned operation in Sheffield on Tasmania's north-west coast, has been hailed by others as a leader in this field. Along with Dave Roberts-Thompson from Table Cape Tulip Farm, Darren successfully established Soil First Tasmania in 2016 to educate other growers about cover cropping and other innovative growing practices. Premium Fresh Tasmania Farm Manager Deon Gibson said that he was inspired by Darren to revive cover cropping on his property when interviewed for the 2018 *Vegetable Grower Success Stories*.

Both growers have been actively involved in a project led by Applied Horticultural Research scientist Dr Kelvin Montagu entitled *Optimising cover cropping for the Australian vegetable industry* (VG16068), a strategic levy investment under the Hort Innovation Vegetable Fund. Darren has been taking the opportunity to collaborate with growers involved in this project and pass on the knowledge that he has gained over the past two decades.

Early days

Darren's cover crop investigation began in the 1990s when he heard that Western Australian growers were using brassica crops to control potato-related diseases.

"We went out on our own to try and replicate what Western Australia was doing in controlling diseases with using plants or cover crops, rather than using chemicals," Darren says.

However, the early years initially proved unsuccessful and Darren found that the plants weren't controlling the disease. But there were other benefits, located deeper into the soil.

"What we were finding was that we were getting really good soil health with free-draining organic matter, which went in our favour. We were using less water, less fertiliser, and eventually we cracked the code that it wasn't the plants that were providing the disease control, it was the soils. We were finding a healthier soil that is able to tolerate these diseases," Darren says.

Getting involved

The easiest avenue to learn about different growing practices, such as cover cropping, is to speak to other growers, according to Darren. Through his involvement in VG16068, he has attended cover crop coaching clinics where he has spoken to his peers and those involved in this project.

"I learn more off Deon (Gibson) than he learns off me. It's that collaboration: talking to a grower without the scientific background and just making it work on our farms. Because it's really easy to send them a brochure and search the internet but to put things into practice is really difficult. Farming has become such a tight operation and you can't afford mistakes," Darren says.

"I think the biggest advantage of these cover crop coaching clinics and having the Hort Innovation projects is that we get to talk to other growers. You can bounce some ideas off each other and that's what I've found – I get to go away and meet growers all around Australia that are like-minded, and we can actually talk about how they do things and what they see."

Further learnings

While Darren is guiding other vegetable growers along their journey into cover cropping, he is also gaining his own knowledge from Dr Montagu and his research team's findings.

"The biggest learning curve that we're getting out of Kelvin's research is what's available and what is beneficial to the soil, how it works and the different types of root systems," Darren says.

"The exposure to all of these new cover crops is taking out the guess-work. We can access material where the research tells us the companion plants that work well, which means we don't have to guess what will work or not.

"We're also starting to nail down the seeding rates we need for which cover crop. Growers can use a template – they've got a 20-hectare plot and they know what the seeding rate would be to get the best advantages out of that. We've also found other materials that we didn't know existed, like tick bean and other types of new species, that we can use in our cover crop."

Rapid advancement

Darren is surprised at how quickly cover cropping practices have changed, particularly over the past three years.

"The advancements in cover cropping have been the most advanced single change to farming that I've seen for 30 years. It's an absolute game-changer," he says.

"We haven't really increased yields; the savings are at pack-out and reducing input costs to produce the crop, and we're at a stage now where we don't even use fungicides or insecticides, and we're nearly at a point where we're not using herbicides. Brassicas, or the cover crops that we use, are controlling our weed problem."

To those growers who haven't adapted to these practices, Darren's message is clear: Have an open mind.

"You might only implement 10 per cent of what we're doing to make a change and then you'll see the differences from there. If you're a farmer and you want to change and your agronomist won't let you change, then you need to get a new agronomist," he says.

"That's the biggest key for us. We've had the one agronomist, Peter Aird from Serve-Ag, for 30 years and he challenges me more than I challenge myself."

Furthermore, Darren says that it's important to join these projects to learn some of the terminology and language.

"The key factor there is the communication between researchers and growers. Kelvin's been good because he gets growers involved, and takes us along so he can talk about the science and we can back it up with how we do it on-farm.

"We need to learn the same language so we know what we're talking about and we can educate each other."

Fast facts: Cover crops used by Darren Long

Caliente 199 –
8 kilograms per hectare
Nemat –
four kilograms per hectare

Used prior to main crop

Saia oats –
22 kilograms per hectare

Sown directly after harvest

Buckwheat/ryegrass (summer grown).

Tillage rootmax, ryegrass and saia oats for silage and hay production.

"This is a starting point for readers to try ryegrass, oats and buckwheat rates, which are probably best left to growers' discretion," Darren says.

Find out more R&D

Please contact Darren Long on 0408 997 410 or at mgfarm@outlook.com.

More about this project can be found at soilwealth.com.au/about-us/cover-crops-vg16068.

This project has been funded by Hort Innovation using the vegetable research and development levy and contributions from the Australian Government.

Project Number: VG16068

Hort Innovation Strategic levy investment | VEGETABLE FUND


Root systems are key.


Roller crimping oats.

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Quantifying soil health after long term cover cropping

Introduction. Quantifying all the interacting components of soil health - the physical, biological and chemical factors - is essential to understanding cover crop benefit.

Traditionally many measures of soil health have been subjective and non-rigorous. Typically a basic soil chemistry test may be the only quantitative test used by a majority of farmers. Yet physical and biological properties are both key components of understanding soil health, particularly their long term trends.

This factsheet identifies and provides preliminary data on some soil health measures after long term (13 years) cover cropping.

Key Points

- Manage **cover crops** as you would a cash crop.
- **Physical and biological soil tests** may complement traditional chemistry tests.
- **Organic matter** is critical for soil health. **Keep something growing** or covering the ground as much as possible (track levels over time).
- **Useful measures for monitoring soil health include:** basic soil chemistry tests, PreDicta, aggregate stability, soil community analysis, beneficials.
- **Financial benefits** (both on and off farm) may result from well-managed cover cropping.

	Total C	Organic Matter	Aggregate stability Stable		Unstable
			>2mm	0.5-2mm	<0.5mm
Fallow	3.8%	6.1%	18.4	44.9	36.7
Ryegrass	4.2%	6.8%	32.9	39.5	27.6
Caliente	4.3%	6.9%	28.6	42.8	28.6

Fine, powdered unstable soil

Stable aggregates (fine roots present)

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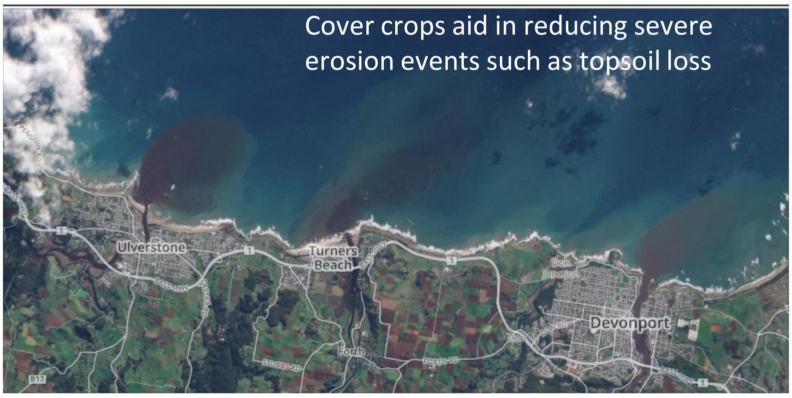
Organic matter and cover crops

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 & maintain root channels.
- 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 weeds.



Soil tests – quantitative measures

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

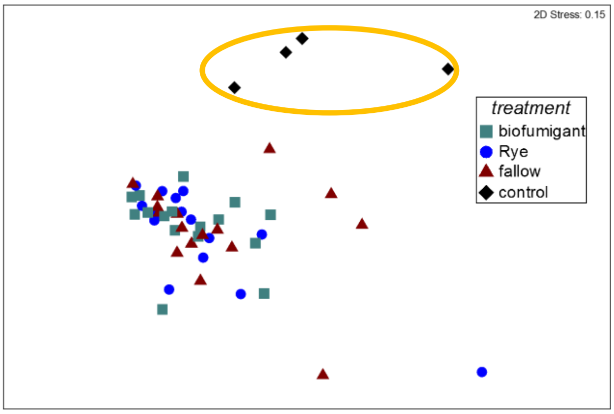
- Take note of **carbon levels** and how they change over the long term – they are a good surrogate measure of soil health.
- **Aggregate stability** provides a measure of soil structure and resilience to physical stresses such as wind and water erosion.

Biological properties

Pathogens – Available tests - **PreDicta** quantification of key soilborne pathogens and provide a measure of disease risk.

Pathogen/disease complex	*Rhizo AG 2.1*	*Rhizo AG3*	*Powdery scab*	*Club root*	*Sclerotinia*
Fallow	+	0	-	-	+
Ryegrass	0	0	+	-	++
Caliente	+	0	0	++++	++

Soil community analysis – eukaryotes, bacterial, fungal communities – fingerprints of the functionality within the soil.



Eukaryote communities – similarity matrix

Weed seedbanks– just prior to cover crop termination - data 'was obtained from the University of New England, Hort Innovation-funded project VG15070 .

Weed density (plants per sqm)	*Total*	*Chickweed*	*Nightshade*
Fallow	22	4	9
Ryegrass	189	167	0
Caliente	262	259	0

Spring/summer crop performance

Estimated yield	*Carrot (15/16)* (t/ha)	*Broccoli (16/17)* (DW/plot)	*Potato (17/18)* (t/ha)	*Carrot (18/19)** *kg per plot*
Fallow	70.5	531.7	75	14.42
Ryegrass	82.4	541.3	72.7	14.79
Caliente	86.8	544.8*	76.5	14.94

Other points – work in progress -

- Biofumigants – maximal glucosinolate levels tend to occur under higher temps (John Duff, DAFF Qld).
- Look out for new tests that quantify beneficials/microbial activity and arthropod presence, e-nose.
- Future work should utilise different biofumigants (or mixes).
- Economic analysis underway – difficult to measure the absolute benefit of improved soil structure.

This project has been funded by Hort Innovation, using the vegetable 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.

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

CASE STUDY
FEBRUARY
2020

IWM ON A BATHURST PUMPKIN FARM:

Advantages & drawbacks of ground cover use, tillage and residual herbicides

TRIAL SET UP

Grey pumpkins (var. Sampson) were planted the week of 4 November 2019, following strip tillage of terminated ryecorn and conventional tillage (rotary hoe) of terminated oats and vetch cover crop areas respectively. Clomazone herbicide was applied post-sowing pre-emergent (PSPE) at a rate of 0.4 kg a.i./ha and incorporated immediately with 25 mm irrigation water. A small control area was left untreated (no herbicide), both for the strip tilled ryecorn and conventionally tilled oats and vetch cover crop areas. A month post-sowing, most of the conventionally tilled area was inter-row cultivated.

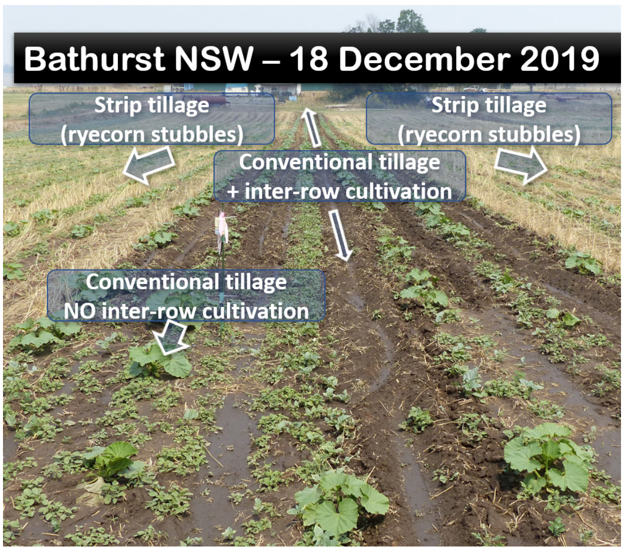

Figure 1. Early stage pumpkin plants in ryecorn stubble zones and conventional tillage zones with/without inter-row cultivation.

An inter-row weed assessment was done 40 days post-sowing, with 10 replicates per treatment. This was ideal timing as the pumpkins had not started to vine out, the conventional areas had been inter-row cultivated 10 days before and the weeds had grown up through the cover crops and were easily identifiable. Finally, a second rough inter-row assessment was carried out on 13 January 2020.

RESULTS

Weeds controlled by clomazone were wireweed (*Polygonum aviculare*), cathead (*Tribulus terrestris*), pigweed or purslane (*Portulaca oleracea*), fat hen (*Chenopodium album*), mustard (Brassica sp.), nightshade (*Solanum triflorum*) and hairy panic (*Panicum effusum*). As expected, no weeds were found where inter-row cultivation had been practised, regardless of herbicide input. Stubble with herbicide showed low weed pressure as well, whereas stubble without herbicide had the second highest weed pressure. Interestingly, conventional till with herbicide and no inter-row cultivation showed the highest weed incidence (Figure 2).

The weeds not controlled by clomazone were castor oil (*Datura stramonium*), Prince of Wales feather (*Amaranthus tricolor*), Bathurst burr (*Xanthium spinosum*) and barnyard grass (*Echinochloa colona*). Again, lowest weed numbers were found where inter-row cultivation had been practised. Stubble treatments showed similar weed pressure to the conventional till without herbicide (but with inter-row cultivation). Highest weed numbers

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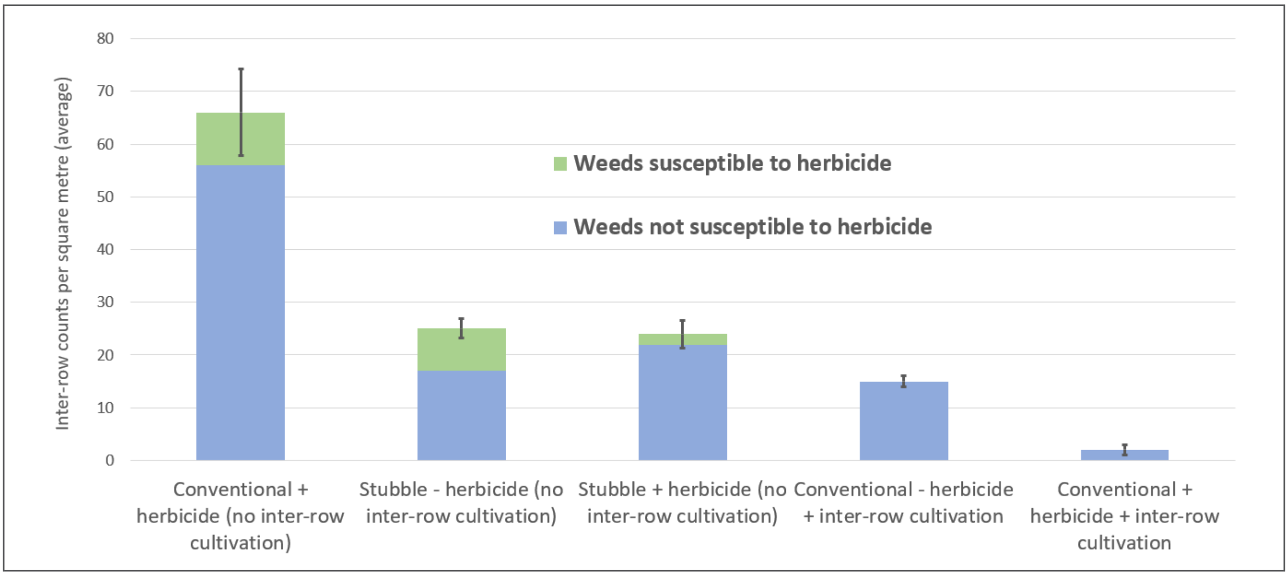

Figure 2. Inter-row weed counts per m^2 on 18/12/2019. Weeds counted that are susceptible to clomazone herbicide: wireweed, cathead, pigweed (purslane), fat hen, mustard, nightshade and hairy panic. Weeds counted that are not controlled by clomazone herbicide: castor oil, Bathurst burr, Prince of Wales feather and barnyard grass. The vertical bars indicate the standard error of the mean total counts (n = 10).

were found again for conventional till without inter-row cultivation (Figure 2).

A second assessment 4 weeks later showed no significant increase in weed numbers for all treatments (data not shown). Note that there had been almost no rain since the first assessment; nor irrigation, due to severe water restrictions in the Bathurst region.

DISCUSSION

Overall, we noted a satisfactory result from the **strip tilled cover crop combined with clomazone herbicide.** However, one of the challenges of strip tilling large stubbles (i.e. cover crops like ryecorn) is getting herbicide contact with weeds growing under the stubble cover, as well as herbicide tie-up on the stubble organic matter. Using large, coarse droplets and high water rates can help minimise this problem, but often weed escapes still occur. The herbicide clomazone is moderately soluble off stubbles and therefore readily available to plants (weeds) via root and/or coleoptile uptake. Clomazone is very similar to metribuzin in solubility. Conversely, actives like trifluralin and pendimethalin have high potential to tie up in stubble.

One advantage of **conventional tillage** is the option to **inter-row cultivate weeds.** Growers must weigh up the weed control benefit against subtle costs like time, crop injury, root pruning, soil drying, and breaking the herbicide band (sometimes resulting in higher weed pressures later in the crop life cycle, especially in less competitive crops).

CONCLUSION

Clearly there is an advantage of inter-row cultivation when there is a high pressure of weeds not controlled by any registered herbicide. There is also a clear advantage to having inter-row ground cover and no soil disturbance (i.e. strip tilled cover crop) to suppress weeds – not to mention better water infiltration rates and moisture retention.

It should be noted that the majority of weed escapes are species not controlled by the herbicide applied. This strengthens the case for integrated weed management.

COWRA CASE STUDY PART II
APRIL 2020

Cover crop + Strip till a winning combination for Soil Health

Cover crops provide multiple benefits, including reduced soil crusting, increased infiltration rates, reduced compaction, weed suppression, and nutrient cycling. Combining cover crops with strip till is proving a winner for vegetable soils and crops. In the Cowra Case Study Part I (COVER CROP + ROLLED GROUND COVER + STRIP TILL = RECORD FARM CUCUMBER YIELD) we detailed cucumber crop benefits. In Part II we dig a bit deeper to look at the soil health benefits from cover crop + roller crimper + strip till which underpinned the outstanding yield result.

In vegetable production, going from your cover crop to your cash crop can be challenging with lots of residues. In many cases it can be two steps forward for soil health during the growth of the cover crop, and one step backward because of the extra cultivation. Strip till helps keep soil health moving forward, while setting up the soil for the all-important cash crop establishment.

Stabilising soil structure

The soil at Cowra is a light sandy soil type, low in organic matter (1.2%), and prone to crusting and poor infiltration. These issues are not uncommon in many Australian vegetable production areas.

Cucumbers were directly seeded into strip tilled ground following a ryecorn cover crop and then compared to a fallow field. The cucumber crop emergence and early vigour following the cover crop – strip till combo was phenomenal; very even and 100% emergence. By contrast in the fallow area, cucumbers battled through a crust, with an uneven 93% emergence and slower early growth (Figure 1).

Figure 1. Cucumber seedling emergence in rolled cover crop + strip till area (left) and the contrasting bare fallow area (right).

The cover crop-strip till combo gave the soil fungi a chance to stabilize the soil structure. More importantly, the strip till prepared the seed bed for the cucumbers with minimal disturbance while retaining much of the cover crop residues. Fungi hyphae grew out of the soil and into the ryecorn residues, excreting compounds stabilizing the soil surface, and slowly decomposing the more complex cellulose and lignin in the ryecorn stalks. Both cultivation and bare fallow ground destroy and deplete beneficial soil fungi, negatively impacting soil structure and mineralisation. The outstanding seedling establishment and early crop vigour highlight these principles.

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COWRA CASE STUDY PART II
APRIL 2020

Protecting the soil from extremes in temperature and heavy rainfall events

Soil needs a cover! On 26 Feb 2019, Cowra's ryecorn residue-covered soil (5cm depth) was a cool 30°C compared to 38°C in the fallow. Soil temperatures between 23°C – 33°C are ideal for cucumbers, hence the 8°C cooler covered soil was a big benefit during late summer heat waves.

The soil cover also helped rainfall and irrigation enter the soil and slowed evaporation losses. This effect following a 24mm cloudburst of rain in January is highlighted in Figure 2. With the cover crop residue on the surface, the rainfall infiltrated well and was stored in the soil. By contrast the fallow area, with capped soil, showed no increase in soil moisture. Instead the rain ran off the beds and into the wheeltracks. The rainfall stored at depth under the cover crop residue lasted for weeks, saving irrigation costs and benefiting the next cash crop! This is a fantastic result for Ed and James during a dry, hot and long end to summer 2019.

Soil temperature and moisture are important drivers for many soil biological processes. Cover crops and crop residues left on the soil surface protect the soil from extreme weather events, helping cash crops grow though stressful periods and achieve maximum yield and quality.

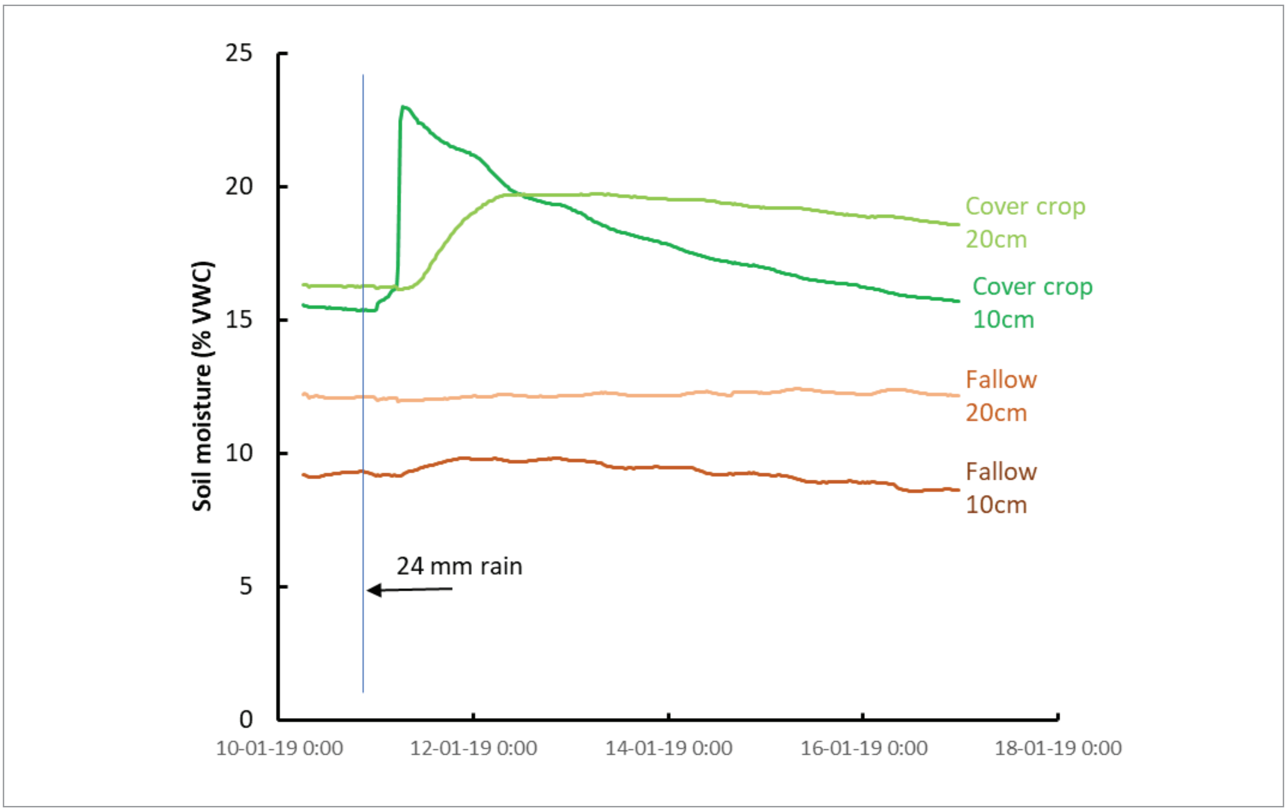

Figure 2. Impact of the rolled ryecorn cover crop residues on rainfall infiltration and storage in the soil following a 24mm rainfall event.

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Weed Control

Weeds pose a challenge both in-crop and in fallow fields. The biggest weed control benefit from this cover crop was during the winter growing period and early summer fallow months, asthe cover crop outcompeted weeds during this growing period. High seeding rates and tall cover crops are best for this desirable result. The rolled residues also suppressed weed growth after termination of the cover crop.

Importantly, in the cover crop-strip till combo, cover crop residues suppressed weed growth prior to cucumber crop vining (Table 1). In our demonstration, the best yield (18.9 t/ha) followed growth of the cover crop with NO in crop herbicide applied. Several preplant knockdowns (stale beds) and suppression from the cover crop physical barrier gave adequate weed control without herbicides.

In the fallow area, where weed pressure was high, a herbicide application (Group Q; clomazone) more than doubled cucumber yields (Table 2). However, no yield response was seen when the herbicide was applied to the rolled cover crop. Instead a small decline in yield was seen, driven mainly by reduced plant productivity. In cucurbits, the herbicide clomazone is sometimes used with crop sensitivity varying between species, soil type and application rates. Generally, cucumbers are quite tolerant to clomazone, and weed control benefits outweigh any yield penalty due to phytotoxicity as seen in the fallow area. However, when the rolled cover crop controlled weeds the herbicide application reduced plant productivity, setting 24% less fruit per plant.

Date	Fallow	Cover crop
	(Weeds/m^2)	
6 December 2018	3.5	1.0
16 January 2019	4.0	1.5
5 March 2019 (cucumbers = 2 leaf stage)	8.0	3.0
19 March 2019 (cucumbers = early vining)	11.0	7.0

Table 1. Impact of cover crop on weed count where no herbicide application.

Demonstration areas	Crop establishment (plants/ha)	Plant productivity (fruit/plant)	Marketable cucumber yield (t/ha)
Rolled cover crop			
+ herbicide	48	2.6	15.1
No Herbicide	44	3.4	18.9
Fallow			
+ herbicide	45	1.9	8.4
No Herbicide	36	1.4	3.7

Table 2. Cucumber crop establishment, productivity and marketable yield following either a rolled ryecorn cover crop or a bare fallow. Cucumbers were direct seeded following strip tillage. Herbicide (clomazone) was applied.

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Soil Nitrogen

Non-legume cover crops draw down soil nitrogen during their growth and store this in the plant biomass. This can be an advantage when paddock nitrogen status is high, due either to high nitrogen carry over from a previous crop, or high nitrogen mineralization conditions. In cucumbers high nitrogen can produce excess vine growth that detracts from the fruit yield.

In this case study, mineralisation throughout both winter and summer months created excess nitrogen in the fallow areas (brown bars), with almost 250 kg N/ha in the soil before the cucumber crop. Conversely, the ryecorn cover crop took up most of the soil nitrogen and added stability to high summer mineralisation rates.

Pickling cucumbers require relatively small amounts of nitrogen compared to potassium.

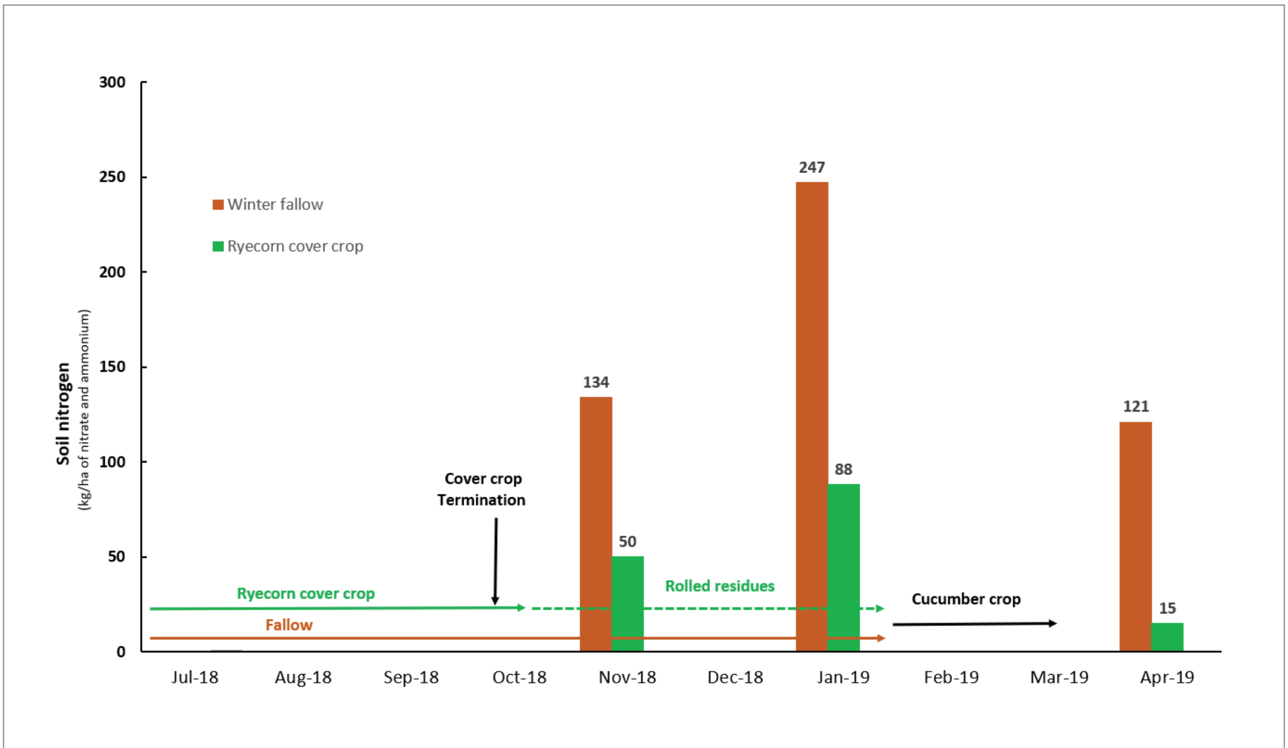

Figure 3. Soil nitrogen levels during the winter period, under either a ryecorn cover crop (green) or fallow (red), and during the summer cucumber crop (soil nitrogen includes both nitrates and ammonium in Kg N/ha).

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The bottom line in soil health...

Cover crops and ground cover provide many benefits including reduced crusting, increased infiltration rates, reduced compaction, weed suppression, and nutrient cycling. Every crop should benefit the following crop!

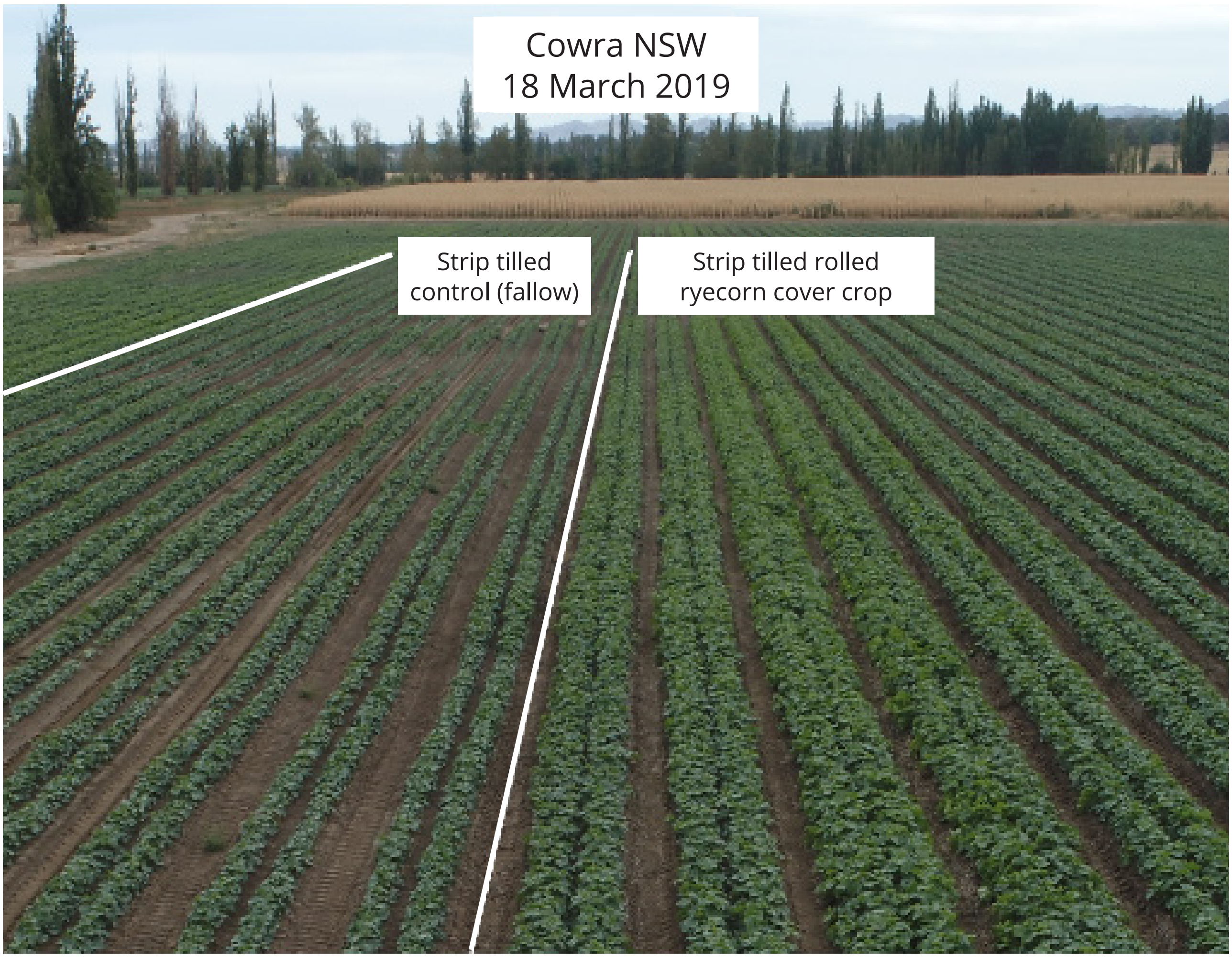

Figure 4. Cucumber crop highlighting better growth under the cover crop–strip till combo.

COWRA CASE STUDY

COVER CROP + ROLLED GROUND COVER + STRIP TILL = RECORD FARM CUCUMBER YIELD

Cover crops + roller crimper + strip tillage have proven a winning combination for a partnership between Mulyan Farms' Ed Fagan and AHR's Marc Hinderager from the Soil Wealth Project.

Cucumber yield and gross income more than doubled, with many soil and weed control benefits adding up to produce impressive yield and quality results.

Ed Fagan is passionate about reducing, even eliminating, plastic on his farm - "You never recover 100% of the plastic mulch and it becomes a major pollutant for years. We have fantastic results from a "grow your own mulch" for cucumbers this year."

Ed needs to minimise costs and be efficient with his labour and equipment. Strategically managing cover crops, crop residues and reducing tillage with strip till is a current focus on Mulyan Farms.

The business end of cucumber production

In the 7 ha operational trial, the ryecorn cover crop area produced an outstanding cucumber yield, well above farm averages. Direct seeded cucumbers established better and produced more marketable fruit per plant and overall marketable yield per hectare.

For Ed, the standout result was the combination of **higher overall yields** and **higher marketable yields** in the ryecorn cover crop areas, where 80% of the crop was marketable, compared to 62% in the fallow area. The gross income dollars speak for themselves!

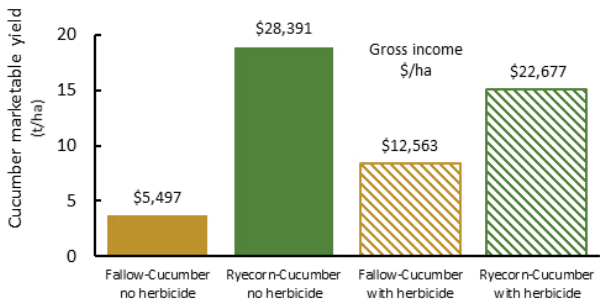

Figure 1. Cucumber yield and gross income following either a fallow or rolled ryecorn cover crop, with and without the herbicide clomazone.

How Ed and Marc managed the crops

A ryecorn cover crop was sown (120 kg/ha) in July 2018 across 7 ha with two strips left fallow. The ryecorn outcompeted weeds, providing full ground cover despite the dry, cold, winter conditions, with no fertiliser, herbicides, or irrigation costs. Ryecorn was chosen for its high carbon to nitrogen ratio and high lignin content, slowing residue break down and providing longer ground cover.

The cover crop was terminated (using glyphosate) at the flowering stage and **rolled down 7 days later**, providing a single direction for the ryecorn stubble. This produced a 6 t/ha dry matter ground cover still

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Soil Wealth NURTURING CROPS | Integrated Crop Protection PROTECTING CROPS

attached to the soil, which was not blown away or rained off beds over the summer months.

Mid-February, beds were prepared using **one pass strip tillage** in the same direction the cover crop had been rolled. The row cleaners on the strip till gear easily cleared the trash away while leaving the cover crop between the rows to protect the soil. The strip tilled rows made the sowing operation **trouble free**. A standout observation was the even crop establishment in the ryecorn cover crop area, significantly better than the fallow area.

The herbicide clomazone was applied post sowing, pre-emergence to part of the ryecorn cover crop and fallow areas. The fallow area was dependent on this herbicide for weed control, while the ryecorn cover crop area yielded best where no herbicide was applied.

Many soil and weed control benefits produced the big yield differences

Details of the soil and weed benefits will be explained in a separate case study. Briefly, the cover crop left on the surface captured most of the winter rainfall, recycled 150 kg/ha of nitrogen and slowed soil acidification.

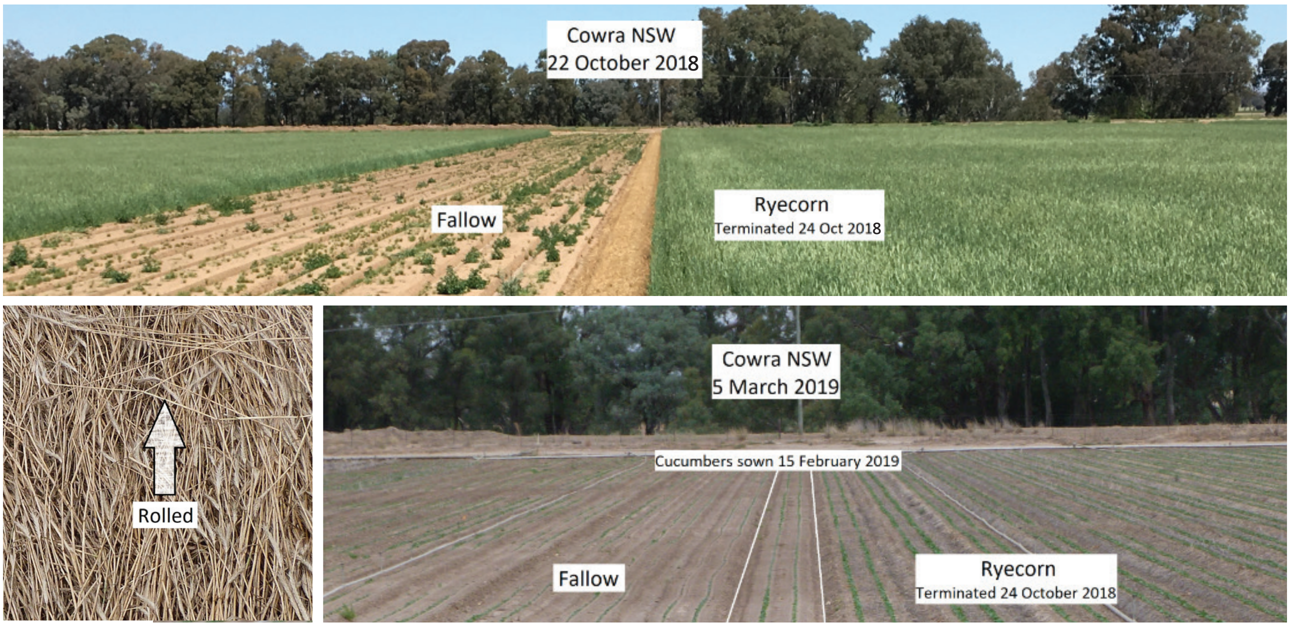


Figure 2. Ryecorn cover crop and fallow area (top). The cucumber crop in the same area 18 days after sowing (bottom). The rolled cover crop (bottom left).

The bottom line...

For the cucumber crop, the cover crop reduced soil crusting and compaction, increased water infiltration rates and moisture retention, reduced the upper soil temperatures during the mid-summer heat, and reduced weed germination and competition. Overall, this allowed the cucumbers to establish, grow better and produce an outstanding yield.

*For more pictures and details of the operational trial visit **Soil Wealth Cowra** on Facebook.*

https://www.facebook.com/SoilWealthCowra

Case study

Soil loss in vegetables

The use of cover cropping on fallow areas is one of the easiest and affordable options to reduce soil loss and for soil health benefits.

Key outcomes

Cover crops significantly reduced runoff and soil loss from vegetable fields with:

- Significant runoff evident in fallow areas compared with cover crop areas
- Significant soil lost from bare fallow areas (equivalent of 5t/ha) over Summer from rainfall and irrigation events.

Background

Soil loss is increasingly recognised as a significant issue in vegetable systems with negative impacts on waterway quality and a loss of productive resource. Cropping fields often show signs of washing after rain events.

However, the following is hard to deduce from these signs of wash:

- Has any soil moved off field?
- How much soil has moved?
- How effective is a cover crop in reducing erosion?

Objective

To monitor and quantify soil loss from fallow and cover cropped areas during irrigation and rainfall events.

Activities

A monitoring site was established over the 2018–19 Summer in the Lockyer Valley on a commercial vegetable farm. The soil type in this area is alluvial clays, undulating in topography *(Image 1)*.

A small area of a field with 15% slope was split into three treatments: 2 x commercial cover crops (lablab and a biofumigant Nemat) and a fallow area.

Sediment collection troughs were set up at the end of these treatment areas *(Image 2)*. The crop was irrigated by lateral irrigator which applied approximately 240mm. There was minimal rainfall in January and February, however, there were three events in mid to late March totalling another 240mm and the troughs were removed after this. The field was monitored for sediment loss from December 2018 through to March 2019.

Image 1. *Soil loss monitoring site prior to cover crops going in.*

Project title: VG16068 Optimising cover cropping in Australian vegetable production

Hort Innovation Strategic levy investment | VEGETABLE FUND | Queensland Government

Case study

Soil loss in vegetables

Results

This site revealed:

- Significant runoff was evident following irrigation events, with no runoff observed from the cover crop areas
- The equivalent of over 5 tonnes/ha of lost soil was captured from the fallow area over the Summer period from predominantly irrigation events
- The cover crop treatment did not lose any soil over the Summer period.

Figure 1. *Soil captured in troughs over the Summer period for the fallow and cover crop treatment.*

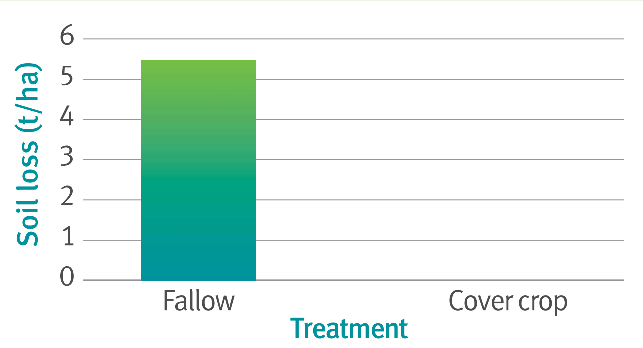


Image 2. *Soil loss site with travelling irrigator and soil loss troughs. Note the runoff evident from the fallow treatment compared with no runoff from the cover crop treatment.*

Cover crops protect soil from raindrop impact and also stabilise soil through its root system.

It also reduces runoff from the field with greater infiltration. In this case, the site had in place infrastructure such as grassed drains and grassed buffer strips to filter sediment and reduce any off farm loss from the bare fallow. However, this is not always the case and soil can move off farm.

Image 3. *Soil being removed from the fallow soil collection trough.*

The sediment collected was also analysed for nutrients.

- **Very little nitrogen was found in the sediment as it had most likely been leached or solubilised in runoff.**
- **The fallow area lost the equivalent of 0.8kg/ha of phosphorus and 3.8kg/ha of potassium in sediment over the monitoring period.**

Case study

Soil loss in vegetables

Cost benefit analysis

The costs for this site are presented in Table 1.

Machinery and labour costs are based on Queensland Government AgBiz gross margins. Other costs to be considered include:

- Loss of P and K may have to be replaced in the future
- Cost of moving and spreading soil that accumulates in drains and sediment traps.

Table 1. *Cost of biofumigant cover crop*

Field operation	Lablab cost ($/ha)	Nemat biofumigant cost ($/ha)
Cover crop seed	$80.00/ha#	$240.00/ha*
Planting (FORM + labour)	$27.49/ha	$27.49/ha
Spraying (FORM + labour)	$6.52/ha	–
Mulching (FORM + labour)	–	$24.27/ha
Incorporation – with rotary hoe (FORM + labour)	$119.49/ha	$119.49/ha
Total (FORM + labour)	**$233.50/ha**	**$411.25/ha**

 # The lablab was sown at 20kg/ha

** The recommended rate of sowing for the biofumigant cover crop is 8 kg/ha*

Challenges and benefits of cover cropping

Incorporating cover cropping into fallow management may present some challenges for vegetable growers. These include a dependence on rainfall, narrow cover cropping windows in some regions, possible impacts on commercial crops through pest, weed and disease issues and timing of operations for commercial crops.

These challenges are more than offset by the benefits of cover cropping.

- Stabilisation of soil structure and reduced erosion risk
- Improved infiltration
- Addition of organic matter
- Break crop for pests and diseases
- Suppression of soilborne pathogens by biofumigants.

On farm options to reduce soil loss

To reduce erosion risk, growers should consider the following:

- Protecting soil through cover cropping and inter-row cover. This is the most effective way to reduce erosion risk and add organic matter to your soil.
- Controlled traffic farming and minimised tillage systems will reduce erosion risk.
- Farm infrastructure such as sediment traps, grassed drains and filter strips will reduce soil loss off farm. These should be regularly maintained.

While infrastructure can be put in place to reduce soil loss off farm, any soil movement off field also removes soil, nutrients and organic matter – the most productive components of soil. Minimising soil loss off fields is the ideal management option.

Acknowledgements

We acknowledge the assistance and contribution of the participating landholder Wayne Keller.

Authors: Julie O'Halloran, Celia van Sprang and John Duff
Queensland Department of Agriculture and Fisheries, Gatton.

Hort Innovation Strategic levy investment | VEGETABLE FUND

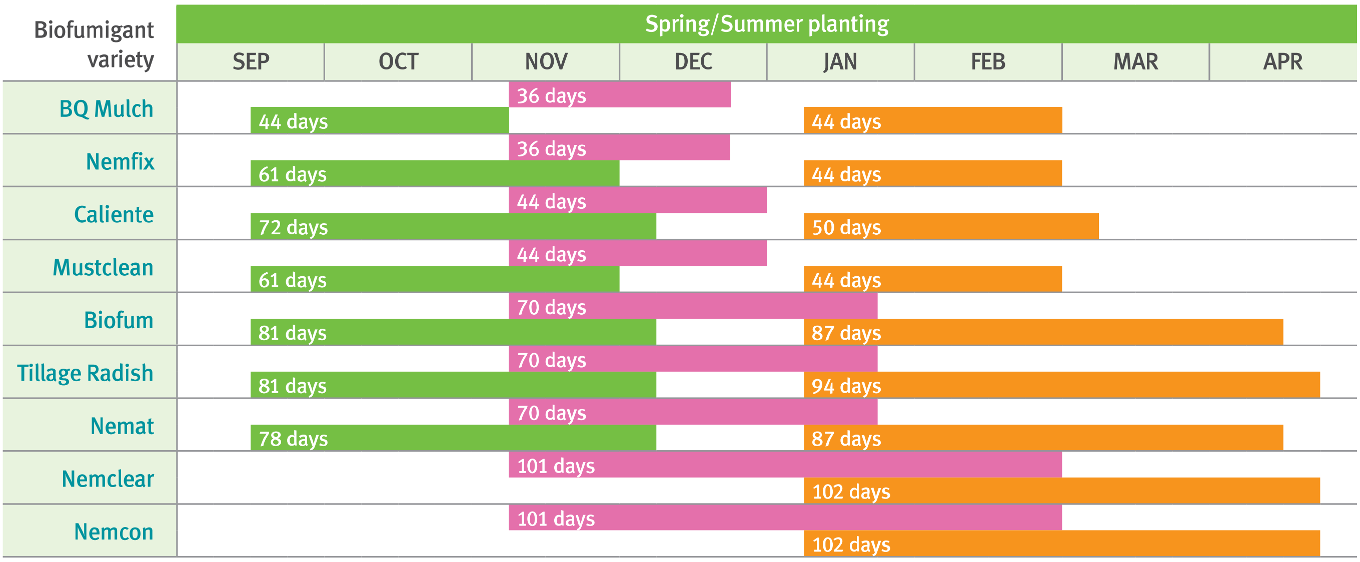
This project has been funded by Hort Innovation using the vegetable research and development levy and funds from the Australian Government. For more information on the fund and strategic levy investment visit horticulture.com.au

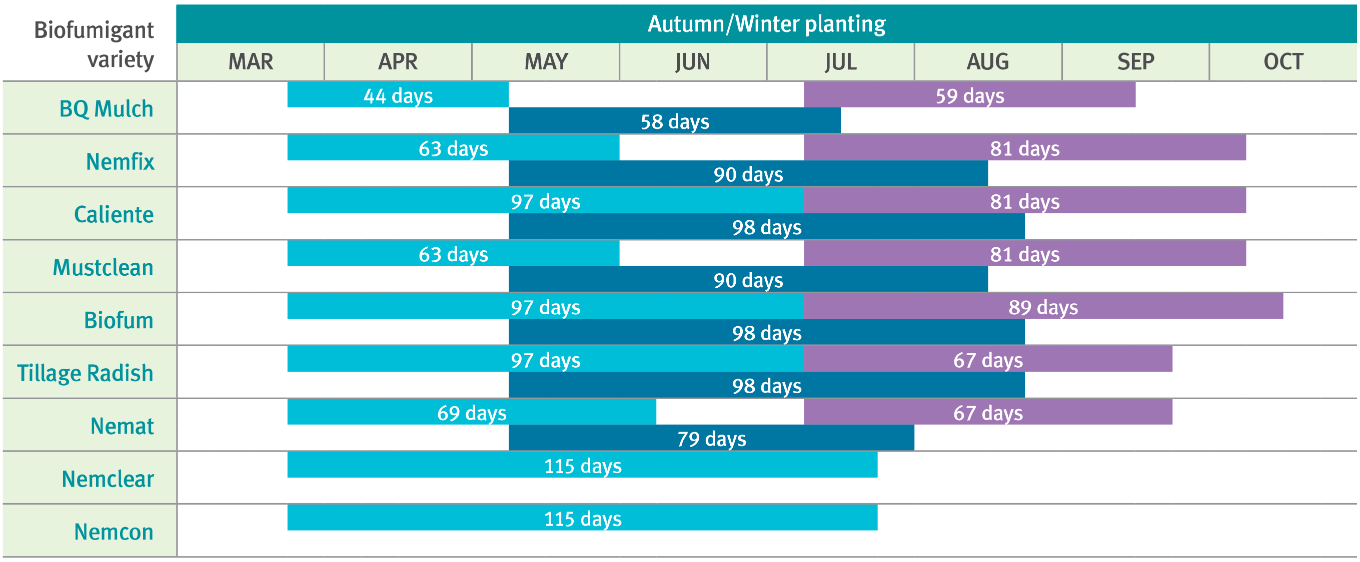
Queensland Government

Brassica Biofumigant Cover Crops

Days to incorporation

Gatton





Days to incorporation differs with each variety, and the time of the year they are planted, taking around 5–10 weeks to flower in Summer and 9–14 weeks weeks in Winter.

Brassicas are a great option to replace bare fallow over the Summer period, protecting the top soil from erosion.

These brassica varieties have the added benefit of managing certain soil-borne diseases through a process known as biofumigation.

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Brassica Biofumigant Cover Crops

Days to incorporation

Bundaberg

Biofumigant varieties	JAN	FEB	MAR	APR	MAY	JUN
Caliente	42 days		73 days			
Mustclean	36 days		53 days			
Nemfix	36 days		53 days			
Nemat	92 days		81 days			
Cappachino	92 days		93 days			
BQ Mulch	36 days		53 days			
Fungisol	92 days		93 days			
Nemsol	92 days					
Biofum	61 days		90 days			
Terranova Radish	70 days		88 days			
Tillage Radish	92 days		88 days			
Black Jack Radish	92 days		88 days			

Biofumigant varieties	JUN	JUL	AUG	SEP	OCT	NOV
Caliente	97 days			48 days		
Mustclean	97 days			48 days		
Nemfix	72 days			48 days		
Nemat	72 days			59 days		
Cappachino	97 days			70 days		
BQ Mulch	54 days			48 days		
Fungisol	103 days			70 days		
Nemsol	72 days			70 days		
Biofum	97 days			70 days		
Terranova Radish	103 days			70 days		
Tillage Radish	103 days			70 days		
Black Jack Radish	103 days			70 days		

1 Grow to 25% flowering

2 Mulch into small fragments

3 Incorporate plant material *(Rotary hoe or disc plough)*

4 Irrigate or roll to seal in biofumigant gases

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Brassica Biofumigant Cover Crops

Caliente™

Management

The crop benefits from additional fertiliser and irrigation to optimise its performance as a biofumigant. Ammonium sulphate at 120kg/ha 3–5 weeks after planting is recommended.

Potential uses

- Biofumigant
  - Suppression of *Sclerotium rolfsii* in Winter/Spring and Summer plantings, *Macrophomina phaseolina* in a Summer planting[1]
  - Range of nematodes[2] and soilborne pathogens (including *Verticillium dahliae*, *Rhizoctonia* spp., *Pythium* spp., *Fusarium* spp.)[2]
- Green manure crop
- Prevent soil loss as a result of high rainfall events
- Nursery to beneficial insects

Insect and disease issues

- **Significant insect pests include:** Cabbage cluster caterpillar, Cabbage centre grub and Aphids
- **Other common insect pests include:** Diamondback moth, Whitefly, Thrips, Rutherglen bugs, Leaf minor, Jassids and Flea beetles
- **Significant diseases include:** Downy mildew and Powdery mildew
- **Other common diseases include:** White blister, Bacterial brown rot, Virus and Phytoplasma

Refer to the APVMA for information about chemical control of pests. Always read and understand the label before using any chemical.

Botanical name	*Brassica juncea*
Synonyms	Indian Mustard
Seeding rate	10kg/ha

Growth habit

- Grows to 1m tall or more
- Deep tap root
- Bright yellow flowers
- Biomass production up to 140t/ha fresh weight

Planting	All-season crop but greatest biomass during cooler time of the year
Incorporation	• 44–50 days in Summer • 98 days in Winter

JUNE 2020

[1] *Department of Agriculture and Fisheries* [2] *Other sources*

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COVER CROPS IN THE WIDE BAY BURNETT

National Vegetable
Extension Network
WIDE BAY BURNETT

The Australian vegetable industry depends on healthy soils to maintain farm profitability and sustainability. Aggressive cultivation, short-term crops and tight rotations can take a toll on soils. Cover crops are one of the best tools for improving soil structure and health, controlling soil-borne disease and weeds, reducing erosion and nutrient loss and adding nitrogen to the soil (soil wealth).

When starting in cover crops, there are two major questions:

- What is the aim of having a cover crop aim?
- What are your management options?

With harsh climatic conditions and generally low organic matter in the region, keeping your paddocks covered and avoiding fallow periods can reduce the detrimental impact of weather events leading to long-term profitability of your soil.

Cover crop species selection
Species selection is one of the most important aspects for effective cover cropping. When choosing a cover crop species, it is important to consider several factors:

- Current soil condition
- Current season and expected climate
- Subsequent cash crop
- Cover crop aim
- Management and termination options
- Time/ window of opportunity
- Pest and disease issues

Sunn hemp, millet and tillage radish cover crop.

What is the aim of having a cover crop?

- To cover and protect the soil and thereby reduce erosion
- Maintain/ build organic matter
- Soil structure improvement – root architecture
- Add nitrogen – such as legumes
- Insect control – break/ trap crop
- Weed suppression
- Soilbourne disease control
    - Biofumigation
    - Enhanced soil

What are your management options?

- What window? Time, water and temperature
- What cover crop – main objective, next cash crop
- Cost – direct and indirect
- Termination of cover crop
- Cover-crop residue management
- Nutrient management
- Potential negatives – weeds, host pest & diseases

Perhaps the most important consideration is understanding the pest and disease host range for that species. If you are trying to control and manage your nematode population in the Wide Bay region, it is not conducive to plant a cover crop that hosts nematodes, as this will tend to exacerbate the situation.

Buckwheat cover crop. Photo by Boris Rayeni.

Cover crop species with potential benefit in the region

Functional group	Cover Crop	Comments
Brassica	Tillage radish Nemat Caliente 199	Biofumigation Deep rooted Weed suppression Soilborne disease and nematode management Nutrient cycling
Legume	Sunn hemp Lablab Cowpeas Soybean Field peas	Use a rhizobium inoculate Legumes won't fix much nitrogen if soil nitrate levels are above 100 kgN/ha. Expect legumes to fix between 100 and 200 kgN/ha — the bigger the crop, the more N fixed.
Grasses	Millet Sorghum Sudan grass Maize Sorghum x Sudangrass Rye grass	Recycle nutrients High biomass Improves soil structure
Cereals	Rye Wheat Barley Oats Triticale	Disease suppression Improve soil structure High carbon
Broadleaf	Buckwheat	Weed suppression Quick growth and breakdown Attracts beneficial insects

Disclaimer: Always consult an advisor before trying new species, especially if nematodes are an issue.

Biofumigants

Biofumigation is the practice of utilising the crops natural ability to produce soil-borne disease-suppressing chemicals. The chemicals are known as glucosinolates and are generally found in plants of the *Brassica* species (QDAF).

When the plant material is macerated (usually with a mulcher) the glucosinolates release chemicals called isothiocyanates (ITC's). These ITCs are a similar chemical to metham sodium and when managed correctly can naturally supress pests and soil-borne diseases (Serve-Ag).

Management is key to successful biofumigation. Brassicas may need irrigation and fertiliser application. At incorporation, brassica crops need to be finely mulched to release the chemicals and then incorporated into the soil as quickly as possible. Adequate soil moisture is also needed at incorporation stage.

Tillage radish 51DAP. Photo by Marc Hinderager.

Recent trials in the region suggest a promising biofumigant crop for the region is Nemat (Eruca sativa). Nemat is excellent for nematode control as its roots produce exudates that attracts pest nematodes to its root zone, traps them and stops them from reproducing, allowing for good nematode control in cropping soil (Serve-Ag)

Biofumigant crop being mulched and then incorporated immediately. Photo by Darren Long.

Tillage radish also presents many benefits as a cover crop. It has been bred to produce an enormous tap root as well as above ground biomass. It is excellent for weed suppression, ground cover, soil structure, breaking through compaction and cycling nutrients (AGF Seeds).

Termination/ incorporation

Successfully managing the physical transition from cover to cash crop will determine the effectiveness of this management system for your farming enterprise.

Photo- Ryecorn cover crop being roller-crimped and direct seeded with soybean.

Roller crimping

This method utilises a roller crimper implement to flatten the cover crop to the ground creating a mat on the surface which maintains soil moisture, reduces weed pressure and provides effective soil cover all of which lead to enhanced soil benefits. When roller-crimping it is important the plants are ‘crimped’ below the first node to ensure effective termination. Herbicide can be used prior to rolling to guarantee an effective kill. After a cover crop has been roller crimped, it is possible to direct-drill some cash crops into the residue or use strip tillage for planting.

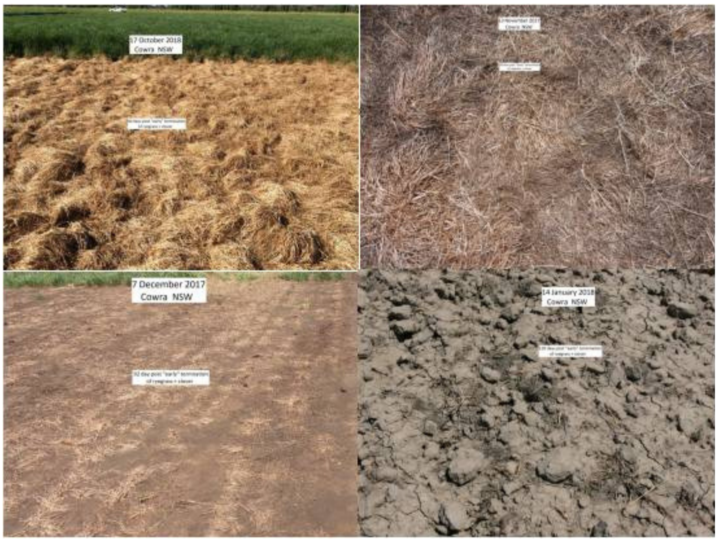
Strip Tillage

Strip-till is a system that cultivates strips of soil where the crop will be planted or sown, leaving the remaining soil area undisturbed. This method has the potential to reduce establishment costs and presents timing efficiencies while improving soil health. Strip tillage machinery can usually, in a single pass, rake aside crop residue, till the soil and accurately place fertiliser and seed/ transplant. This can drastically reduce the number of passes and intensity of tillage. There are several soil health benefits of strip-till including reduced erosion, increased water retention, reduced fuel and labour costs, reduced compaction, less weed pressure and increased soil health/ organic matter.

Strip tilled paddock after a cover crop. Credit Joe Cook.

Cucumbers following control (left) and a rolled, strip-tilled rye corn cover crop (right). Photo by Marc Hinderager and Ed Fagan.

Another option in water-limited situations is terminating cover crops early with herbicide. Cover crops with high C:N ratio, such as rye grass and cereals, can be sprayed out once ground cover is achieved as this provides weed suppression and captures any rainfall that is received.



Early termination of ryegrass led to good weed suppression, increased soil moisture and increase in cash crop yield. Photo by Marc Hinderager.

This then leads to reduced erosion and increased soil moisture. Recent reports have also found that the cover crop roots are, just as, if not more, important than above-ground biomass. “Key findings indicate that the species-richness effect of soil health is predominately related to root biomass production, which stimulates growth and diversity in microbial communities within the soil, balances the bacteria to fungi ratio, and generally creates synergy between all soil elements and processes to promote a healthy soil ecosystem.” *(Alexander Nixon, Nuffield Scholar Report on multi-species cover crops).*

National Vegetable Extension Network
WIDE BAY BURNETT

Bundaberg Fruit & Vegetable Growers

Acknowledgment: Information was adapted from information provided by Hort Innovation Vegetable levy funded projects VG16068 - Optimising cover cropping for the Australian vegetable industry and VG16078 – Soil Wealth and Integrated Crop Protection.

Written by Adam Harber, VegNET Industry Development Officer, Bundaberg Fruit & Vegetable Growers (BFVG).

Hort Innovation Strategic levy investment | VEGETABLE FUND

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Guide to Brassica Biofumigant Cover Crops

Managing soil-borne diseases in vegetable production systems

March 2020

This publication has been compiled by John Duff, Celia van Sprang, Julie O'Halloran and Zara Hall of Horticulture and Forestry Science, Department of Agriculture and Fisheries.

Table of Contents

List of Tables and Figures

Glossary

biofumigant	Plants that produce naturally occurring compounds that can suppress soilborne diseases, pests and weeds
copiotrophic	A copiotroph is an organism found in environments rich in nutrients, particularly carbon. Copiotrophic organisms tend to grow in high organic substrate conditions.
disease	The development of symptoms as a result of a plant pathogen attacking a plant
efficacy	How well the biofumigant controls/suppresses known soilborne pathogens
glucosinolates/GSLs	Naturally occurring plant compounds found predominantly in Brassica plants that are converted to toxic biofumigant compounds upon mulching and incorporation into the soil
incorporation	Process of mixing mulched plant material through the soil
isothiocyanates/ITCs	Toxic biofumigant compounds converted from glucosinolates, that suppress soilborne pathogens
myrosinase	The enzyme that facilitates the conversion of glucosinolates to isothiocyanates
pathogen	Disease causing microorganism
sclerotes	Survival structure of a soilborne pathogen which can withstand adverse conditions for years until conditions are favourable for disease development

Summary

Brassica biofumigant cover crops are increasingly considered in vegetable crop rotations as part of an integrated disease management strategy. The following summarises the key points on biofumigant cover cropping for vegetable rotations.

- Different biofumigant varieties have different levels of activity against different soilborne pathogens
- Biofumigant cover crops, while traditionally a winter crop, can be grown year round in the Lockyer Valley and Bundaberg regions
- Performance characteristics of biofumigant cover crops vary with growing season
- Growing season and days to maturity are shorter in summer months providing an option for short cover cropping windows over summer
- Biofumigants produce less biomass in summer months, but trends are for higher levels of glucosinolates for the majority of varieties during summer months
- Activity against soilborne pathogens also varies with the time of year biofumigants are grown, with trends for most varieties to be more active against soil borne pathogens when grown during warmer months
- Biofumigants have shown some activity against beneficial soil microorganisms in the laboratory such as *Trichogramma* Sp. and *Bacillus amyloliquefaciens* (Serenade® Prime)
- Biofumigants require monitoring for pests and diseases
- Management practices such as irrigation impact on the amount of plant biomass and activity against soilborne pathogens
- There are multiple options for incorporation of biofumigant cover crops that are as effective
- There are regional differences in biofumigation activity, pest and disease pressures and how they respond to different growing seasons.

Introduction

Cover crops, also referred to as green manure crops, are crops planted as a break between commercial crops. They are grown and incorporated back into the soil rather than for products that are removed off-farm like commercial crops. Cover crops provide numerous farming system benefits including:

- Increasing soil organic matter
- Fixing nitrogen in the soil (legumes)
- Increasing soil microbial activity
- Improving soil structure such as improved water infiltration and soil porosity
- Scavenging nutrients that have leached beyond the root zone of commercial crops
- Preventing soil loss via water and wind erosion
- **Biofumigants are a unique type of cover crop that produce compounds with suppression effects on soilborne pathogens, pests and weeds**

There are a variety of commercially available cover crop types, such as legumes and grasses. Brassica cover crops and specifically biofumigants are the focus of this guide. In addition to the normal benefits of cover cropping, biofumigants offer an alternative to synthetic fumigants for soilborne disease management if they can be successfully incorporated into vegetable crop rotations.

Biofumigant cover cropping is incorporated into vegetable rotations with higher seed costs and the assumption that these crops will contribute to disease management. This publication contains information to assist growers in understanding how biofumigants work and managing them for optimum efficacy against soilborne diseases.

The information in this guide has been developed through a series of field trials to assess biofumigants as cover crop options in vegetable systems. The majority of this work was conducted in south-east Queensland, particularly targeting summer cover cropping windows, to minimise soil loss off farm during storm events, as well as the benefits to soil health and disease management. While brassicas, including biofumigants are considered to be a winter cropping option, this work covered multiple growing seasons to see how different growing conditions effected the performance of biofumigant cover crops. This will broaden options for when biofumigants can be successfully incorporated into crop rotations.

Figure 1. DAF staff setting up biofumigant trials. Photo by Zara Hall

The field work has evaluated various commonly used biofumigant varieties for:

- Biofumigant activity against known soilborne pathogens
- Growing window (or days to incorporation) across seasons
- Biomass production across seasons
- Concentrations of biofumigant compounds (glucosinolates)

This information can then be used to select the biofumigant variety most appropriate for individual situations including disease spectrum and cover cropping window or season.

The known soilborne pathogens included in this work comprise: basal rot (*Sclerotium rolfsii*), Onion white rot (*Sclerotium cepivorum*), charcoal rot (*Macrophomina phaseolina*), white mould (*Sclerotinia sclerotiorum*), Rhizoctonia species and verticillium wilt (*Verticillium dahliae*).

The guide also discusses and presents data on a range of agronomic management practices of biofumigant cover crops including pest and diseases, nutrient uptake requirements, irrigation and incorporation methods.

Figure 2.DAF staff assessing for biomass production in Bundaberg. Photo: Mary Firrell

Figure 3. Lab lab cover crop in southeast QLD. Photo: Julie O'Halloran.

Figure 4. A fallow field in South-East Queensland with severe soil loss following heavy Summer rainfall

Biofumigant cover cropping

Biofumigation is the practice of growing specialised cover crops for suppression of soilborne pathogens, pests and weeds. The cover crop produces naturally occurring compounds that are toxic to many of the soilborne pathogens that impact on Australian vegetable crops.

Some soilborne diseases can survive for many years, even in the absence of a suitable host. The resting stages of soilborne pathogens, can remain dormant until conditions are favourable, resulting in the development of symptoms on the plant. For some diseases like white rot (*Sclerotium cepivorum*) in onion, the pathogen can survive in the soil for 20 years or more.

The challenge from a disease management perspective is reducing disease inoculum in the soil, whilst maintaining or enriching soil health so that crops are able to become more resilient to soilborne pathogens. An integrated approach utilising biofumigant cover crops can be an effective tool in the management of soilborne diseases in horticultural production systems, which offers growers a solution that does not involve the use of synthetic pest control.

Figure 5. Sclerotium rolfsii infected carrots. The fungus can remain viable in the soil for several years. Photo by Zara Hall

Brassica species, such as mustard, radish and rocket, have been shown to suppress soilborne diseases such as basal rot (*Sclerotium rolfsii*), Onion white rot (*Sclerotium cepivorum*), charcoal rot (*Macrophomina phaseolina*) and white mould (*Sclerotinia sclerotiorum*). They are able to achieve this through certain processes resulting in the release of naturally occurring chemicals contained in plant tissue.

Figure 6. Sclerotinia sclerotiorum in lettuce. Photo: Julie O'Halloran

Figure 7. Sclerotinia minor in lettuce. Photo: Julie O'Halloran

How biofumigation works

Brassicas naturally produce a group of chemicals known as glucosinolates (GSLs). The highest concentration of glucosinolates tends to occur at approximately 25% flowering, which is the recommended timing for incorporating biofumigants. Through the process of mulching and incorporation, glucosinolates are released from the plant cells. Once released from plant cells and with the addition of irrigation water, glucosinolates are converted by the enzyme myrosinase into isothiocyanates (ITC's), a gas that is toxic to various soilborne pathogens and pests. Irrigation and/or rolling helps to seal the gas in the soil so that they are most effective in suppression pathogens.

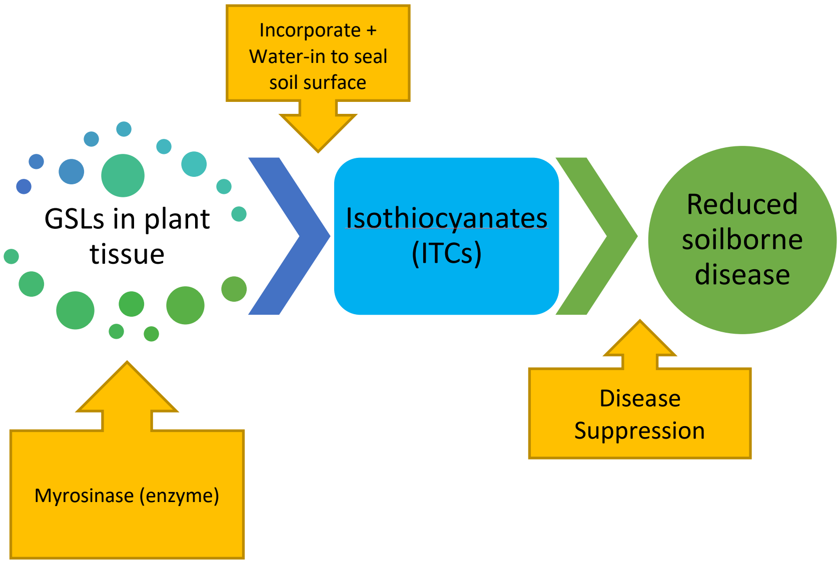


Figure 8. The biofumigation process in brassica plants.

There are over 200 glucosinolate compounds commonly found in Brassica plants. The concentration and type of GSLs will vary between varieties, as does the type of ITCs produced from the GSLs, which will determine the biofumigants' toxicity to various soilborne pathogens and pests.

All biofumigant varieties have positive soil health benefits, but some may be better suited for a particular cropping program. This will depend on the soilborne disease being targeted as well as other considerations such as cropping window and agronomic management of the biofumigant.

Biofumigant variety selection

There are many biofumigant varieties that are commercially available in Australia. These include oilseed radish, rocket and mustard varieties. New varieties are continuously being released by seed companies, as biofumigation is increasingly utilised and implemented as part of crop rotations.

Figure 9. Indian mustard biofumigant Photo: John Duff

Figure 10. Nemat Rocket biofumigant Photo: John Duff

Figure 11. Oilseed radish biofuimigants. Black Jack Radish on the left, Terranova Radish in the middle and Tillage Radish on the right. Photo: John Duff

Choosing the best variety for a particular cropping system will depend on various agronomic considerations, including compatibility with commercial cropping breaks and agronomic considerations such as soilborne pathogens or pests that require management. Table 1 lists those varieties assessed in DAF trials.

The key considerations in choosing biofumigant varieties are:

- Soilborne pathogens to be managed
- Cover cropping window (time of year and length of time in the ground) – how much time do you have to grow a biofumigant cover crop.
- Agronomic management of the biofumigant crops
  - Pest and disease management
  - Irrigation requirements
  - Nutrition requirements
- Mulching and incorporation

Table 1. Common commercially available biofumigant varieties compared in DAF trials

Trade name	***Variety***	***Species name***
Biofum	**Doublet oilseed radish & Achilles white mustard mix**	***Raphanus sativus & Sinapis alba mix***
Black Jack radish	**Oil Radish**	***Raphanus sativus***
Black Mustard	**Black mustard**	***Brassica nigra***
B.Q. Mulch ®	**Black mustard & Ethiopian mustard**	***Brassica nigra & Brassica carinata***
Caliente	**Indian mustard**	***Brassica juncea***
Cappucchino	**Ethiopian mustard**	***Brassica carinata***
FungiSol	**Ethiopian mustard & Terranova oilseed radish mix**	***Brassica carinata & Raphanus sativus***
Mustclean	**Indian mustard**	***Brassica juncea***
Nemat	**Rocket**	***Eruca sativa***
Nemfix	**Indian mustard**	***Brassica juncea***
Nemclear	**Fodder mustard**	***Brassica napus***
Nemcon	**Fodder mustard**	***Brassica napus***
Nemsol	**Terranova oilseed radish & Nemat mix**	***Raphanus sativus & Eruca sativa***
Terranova radish	**Oilseed radish**	***Raphanus sativus***
Tillage radish ®	**Oilseed radish**	***Raphanus sativus***
White Mustard	**White mustard**	***Sinapis albo***

Impact of Varieties on Disease Suppression

The type of soilborne disease that requires management, and time of year available to plant a cover crop, will impact which variety is most suitable. The impact table is a tool designed to be used to assist decision making about variety selection for disease management. The table is based on key production breaks when a biofumigant cover crop is most likely to be included as part of a cropping system and the relative efficacy of biofumigant varieties against a range of soilborne diseases.

Table 2. Matrix of biofumigant efficacy against known soil borne diseases

Varieties	Season	Biofum	Black Jack	BQ Mulch	Caliente	Cappachino	Fallow	Fungisol	Mustclean	Nemat	Nemclear	Nemcon	Nemfix	Nemsol	Terranova Radish	Tillage Radish
Basal Rot	Summer	*	**	*	**	*	**	*	***	*	*	*	*	ND	ND	*
	Autumn	*	ND	*	**	ND	*	ND	*	ND	*	*	*	ND	ND	***
	Winter/	*	**	*	***	*	*	*	***	*	ND	ND	****	**	**	*
Sclerotinia Rot	Summer	****	**	****	***	**	****	***	***	****	*	**	****	ND	ND	****
	Autumn	*	ND	*	*	ND	*	ND	*	ND	*	*	*	ND	ND	*
	Winter/	**	*	**	*	*	*	***	*	**	ND	ND	*	**	**	**
Charcoal Rot	Summer	***	**	***	****	*	***	*	****	***	*	**	***	ND	ND	***
	Autumn	*	ND	**	**	ND	**	ND	*	ND	*	*	*	ND	ND	*
	Winter/ Spring	***	**	***	***	****	**	****	***	****	ND	ND	***	**	***	****

Key - Percentage Mortality									
0 - 25	*	26 - 50	**	51 - 75	***	75 - 100	****	No data	ND

Days to incorporation

The days to incorporation were compared over multiple growing seasons and across two vegetable growing regions in Queensland; Lockyer Valley and Bundaberg. The days to incorporation varied between different varieties and growing seasons. Generally, biofumigants reached incorporation (or 25% flowering) faster and produced less biomass in summer compared to winter.

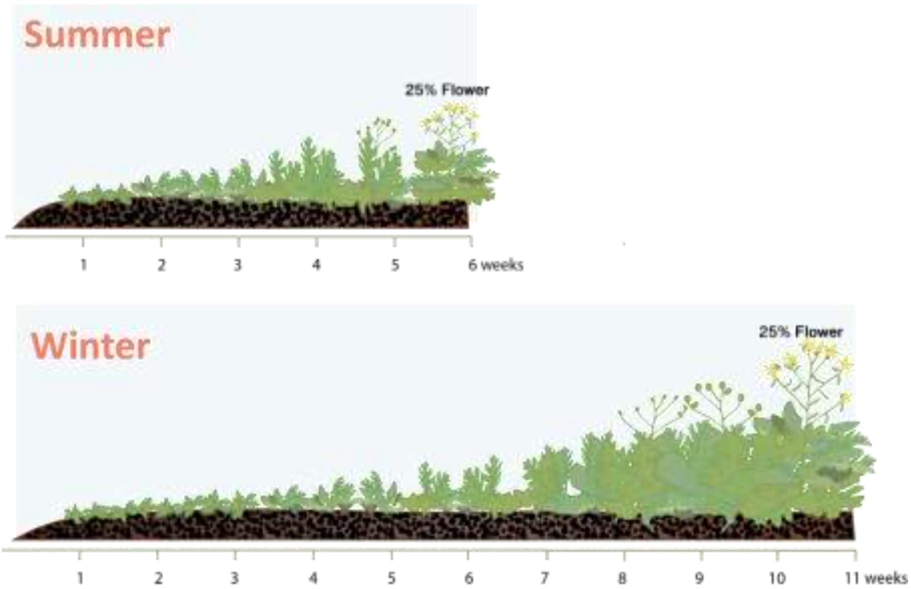


Figure 12. Graphic depicting the general findings for biofumigant cover crop days to incorporation across different growing seasons in the Lockyer Valley.

The planting window chart is a tool that is designed to assist in selecting a variety that will reach approximately 25% flowering or incorporation within a given planting window for cover cropping. The days to incorporation data includes Spring-Summer and Autumn-Winter planting windows.

Table 3. Days to incorporation for varieties in the Lockyer Valley.

Biofumigant Variety	SPRING/SUMMER PLANTING							
	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR
Biofum	81 DAYS		70 DAYS		87 DAYS			
BQ Mulch	44 DAYS		36 DAYS		44 DAYS			
Caliente	72 DAYS		44 DAYS		50 DAYS			
Mustclean	61 DAYS		44 DAYS		44 DAYS			
Nemat	78 DAYS		70 DAYS		87 DAYS			
Nemclear			101 DAYS		102 DAYS			
Nemcon			101 DAYS		102 DAYS			
Nemfix	61 DAYS		36 DAYS		44 DAYS			
Tillage Radish	81 DAYS		70 DAYS		94 DAYS			

Biofumigant Variety	AUTUMN/WINTER PLANTING							
	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT
Biofum	97 DAYS		98 DAYS		89 DAYS			
BQ Mulch	44 DAYS		58 DAYS		59 DAYS			
Caliente	97 DAYS		98 DAYS		81 DAYS			
Mustclean	63 DAYS		90 DAYS		81 DAYS			
Nemat	69 DAYS		79 DAYS		67 DAYS			
Nemclear	115 DAYS							
Nemcon	115 DAYS							
Nemfix	63 DAYS		90 DAYS		81 DAYS			
Tillage Radish	97 DAYS		98 DAYS		67 DAYS			

Table 4. Days to incorporation, Bundaberg field trials.

BIOFUMIGANT VARIETIES	JAN	FEB	MAR	APR	MAY	JUN
Biofum	61 DAYS		90 DAYS			
Blackjack Radish	92 DAYS		88 DAYS			
BQ Mulch	36 DAYS		53 DAYS			
Caliente	42 DAYS		73 DAYS			
Cappachino	92 DAYS		93 DAYS			
Fungisol	92 DAYS		93 DAYS			
Mustclean	36 DAYS		53 DAYS			
Nemat	92 DAYS		81 DAYS			
Nemfix	36 DAYS		53 DAYS			
Nemsol	92 DAYS					
Terranova Radish	70 DAYS		88 DAYS			
Tillage Radish	92 DAYS		88 DAYS			

BIOFUMIGANT VARIETIES	JUN	JUL	AUG	SEP	OCT	NOV
Biofum	97 DAYS			70 DAYS		
Blackjack Radish	103 DAYS			70 DAYS		
BQ Mulch	54 DAYS			48 DAYS		
Caliente	97 DAYS			48 DAYS		
Cappachino	97 DAYS			70 DAYS		
Fungisol	103 DAYS			70 DAYS		
Mustclean	97 DAYS			48 DAYS		
Nemat	72 DAYS			59 DAYS		
Nemfix	72 DAYS			48 DAYS		
Nemsol	72 DAYS			70 DAYS		
Terranova Radish	103 DAYS			70 DAYS		
Tillage Radish	103 DAYS			70 DAYS		

Biomass production

Biomass production to build organic matter in soils is another key benefit from cover cropping. The biomass produced by biofumigants varies with varieties. Lablab and Fumig8tor were also grown in Lockyer Valley biofumigant trials as a comparison.

As brassicas are predominantly a winter-grown crop, biomass production is greater in the cooler months, compared to summer. This is evident in varieties such as Caliente, Mustclean and Nemfix in the Lockyer Valley, and the majority of varieties that were tested in Bundaberg. However, having high biomass does not mean that these varieties will produce more GSL's.

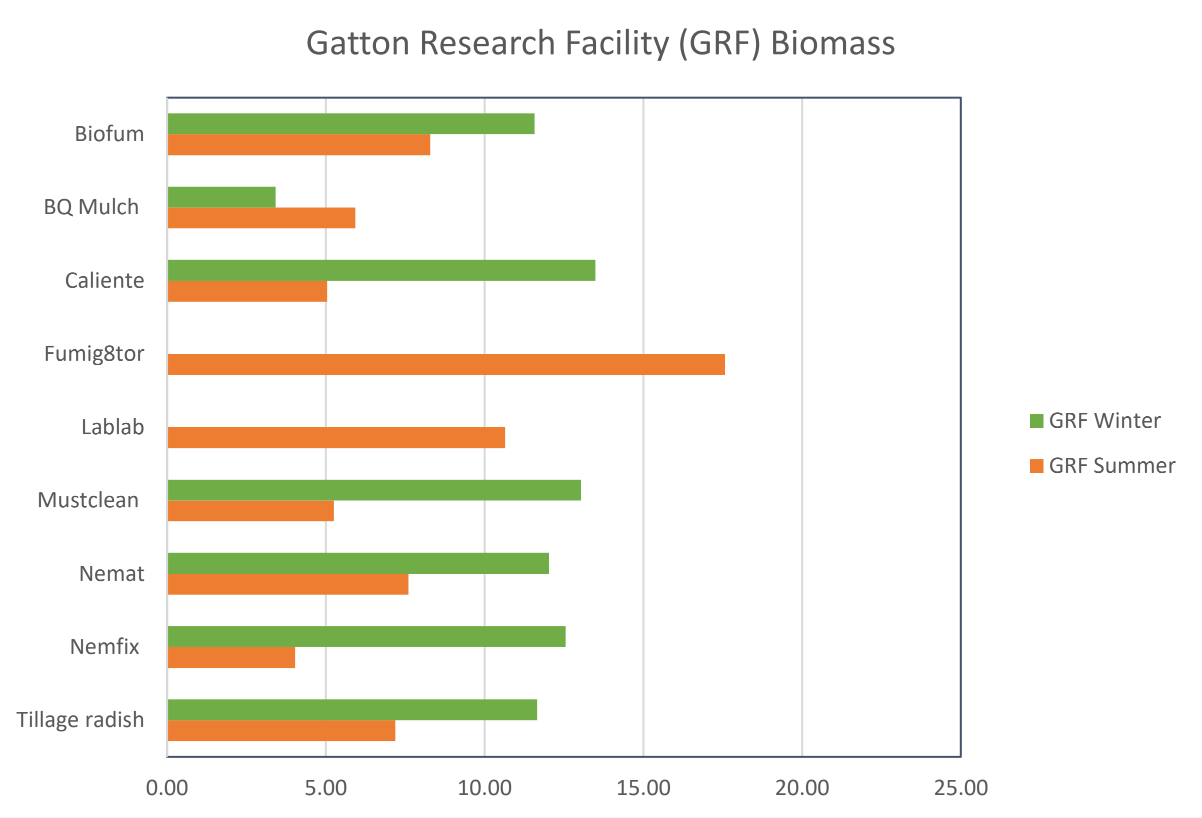


Figure 13. Biomass (t/ha dry matter) produced for lablab, fumig8tor and biofumigant varieties for summer and winter growing seasons in the Lockyer Valley.

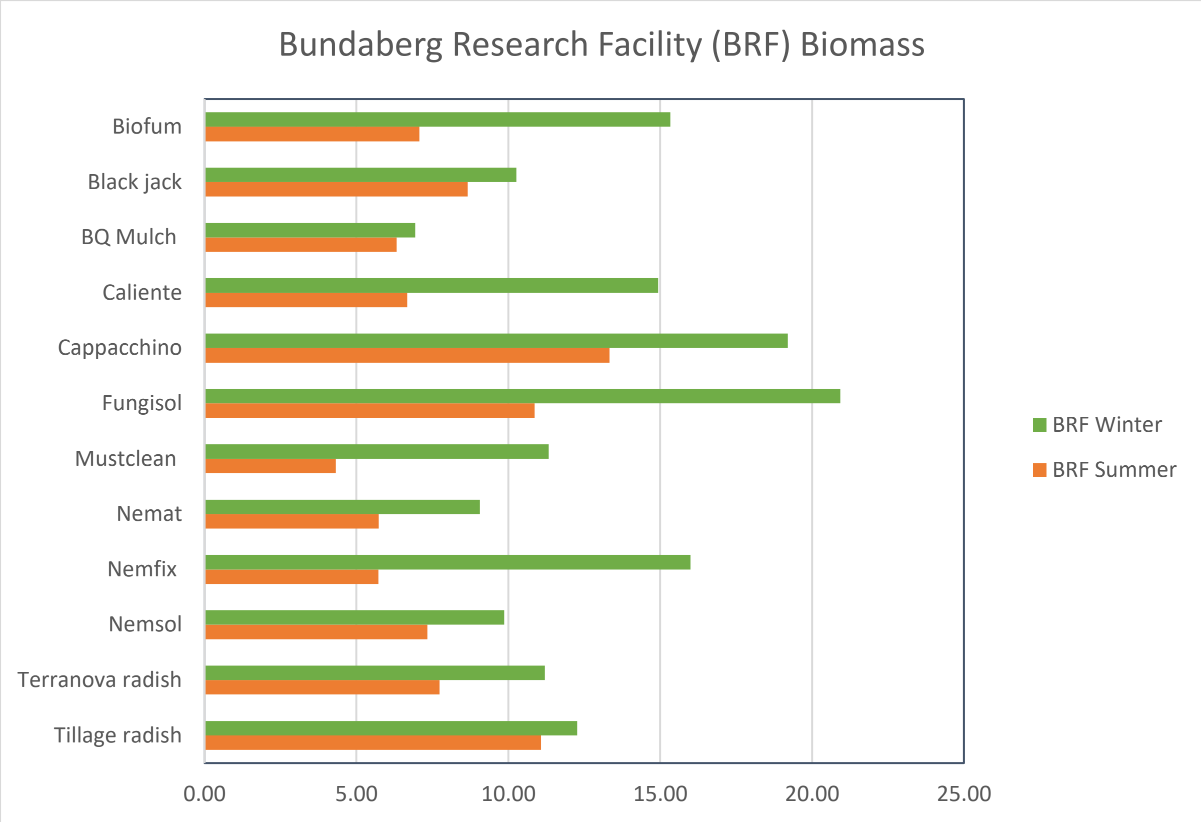


Figure 14. Biomass (t/ha of dry matter) produced for brassica biofumigant varieties for summer and winter growing seasons in Bundaberg.

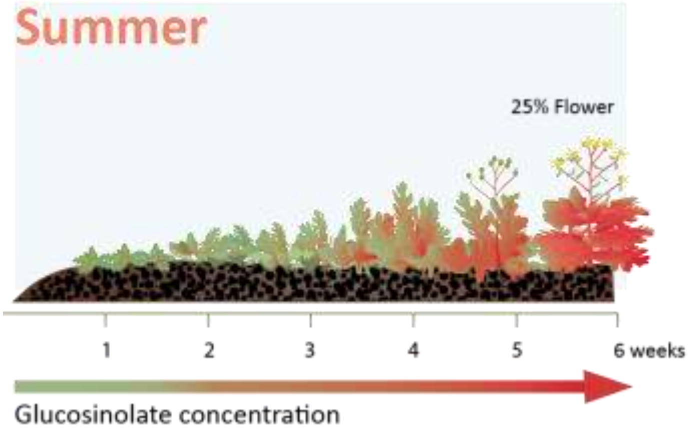
Glucosinolate production

Glucosinolates or GSLs are the precursors to the toxic compounds, isothiocyanates or ITCs, that have suppressive activity against soilborne pathogens. As the ITCs are volatile gases, GSLs within the plant are measured instead as they are less volatile. Biofumigant varieties can have a range of individual glucosinolates, with varying concentrations. While some GSLs are known to be more toxic in the ITC they are converted to, glucosinolate data in this guide is presented as total glucosinolate concentration rather than individual GSLs. However, higher total GSLs does not necessarily equate to greater activity against soilborne diseases.

Generally, glucosinolate production was higher in summer compared to winter in south-east Queensland, however, there were some exceptions (Caliente and Nemfix). Varieties such as BQ Mulch, Biofum, Mustclean and Tillage Radish produced higher concentration of GSLs in summer in the Lockyer Valley compared with winter. The seasonal difference is important as summer is a key cover cropping period for vegetable crop production in south-east Queensland and highlights that biofumigants can be considered a summer cover cropping option in this region.

In Bundaberg, the opposite was observed with higher total glucosinolate levels per hectare in winter compared with summer.

The Indian mustards, Caliente, Mustclean and Nemfix produced more GSLs when grown in the Lockyer Valley, whereas Tillage Radish and Nemat produced more GSLs grown in Bundaberg compared to the Lockyer Valley. This shows that location can play a part in the amount of GSLs being produced and possibly efficacy against soilborne pathogens, an area of research that needs more work.



This graphic indicates how GSL production increases in concentration up until 25% flowering in both summer and winter grown biofumigants. Summer grown crops tend to be faster in reaching 25% flowering and can produce more GSL's.

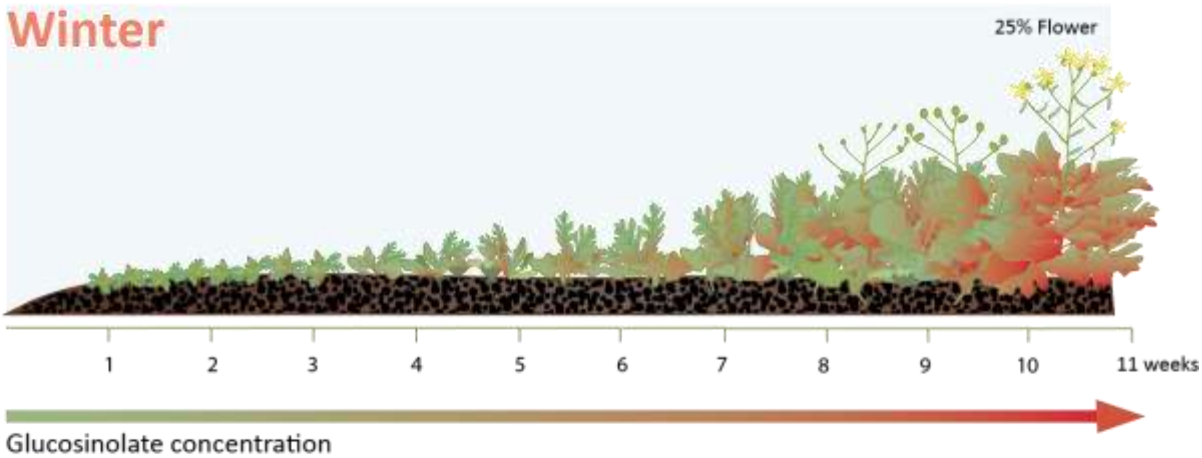


Figure 15. Graphic depicting glucosinolate production in summer and winter grown biofumigants in the Lockyer Valley

While biofumigant cover crops produce a range of different glucosinolates, this work did not identify which of the GSL's produce the most toxic compounds to individual vegetable crop pathogens.

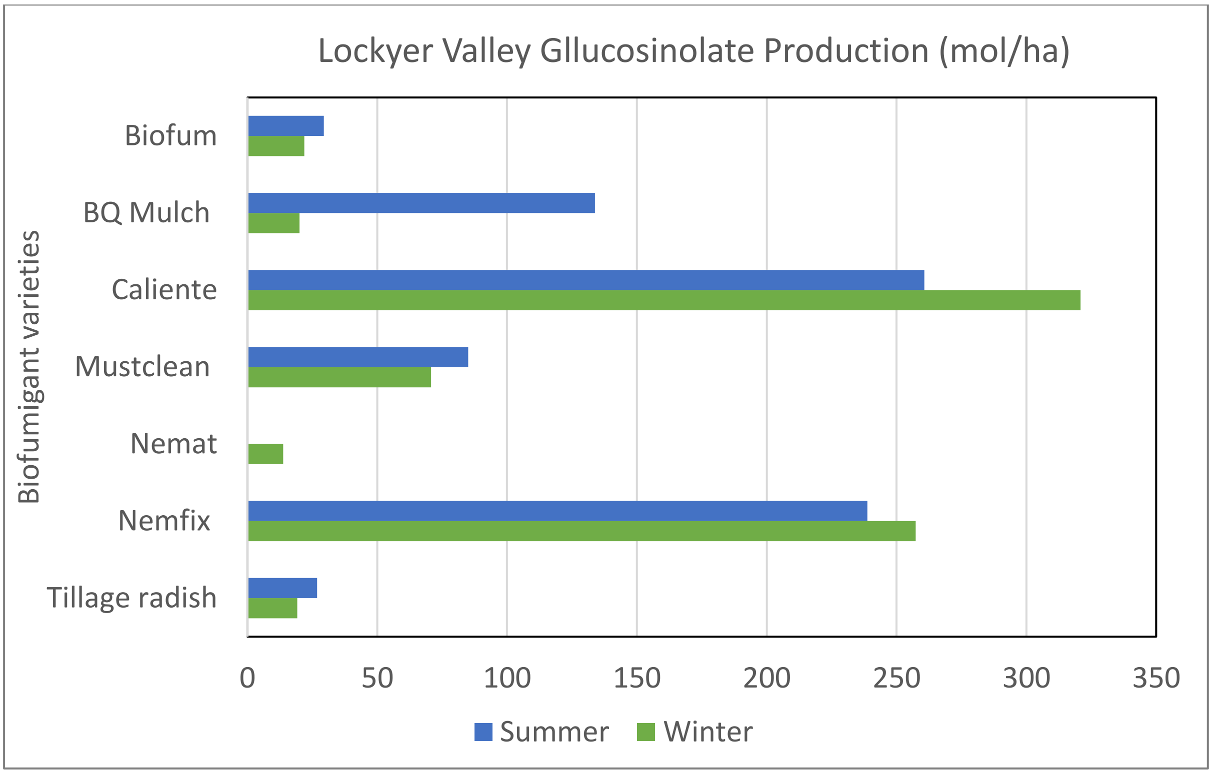


Figure 16. Total glucosinolates for each biofumigant variety for winter and summer growing seasons in the Lockyer Valley.

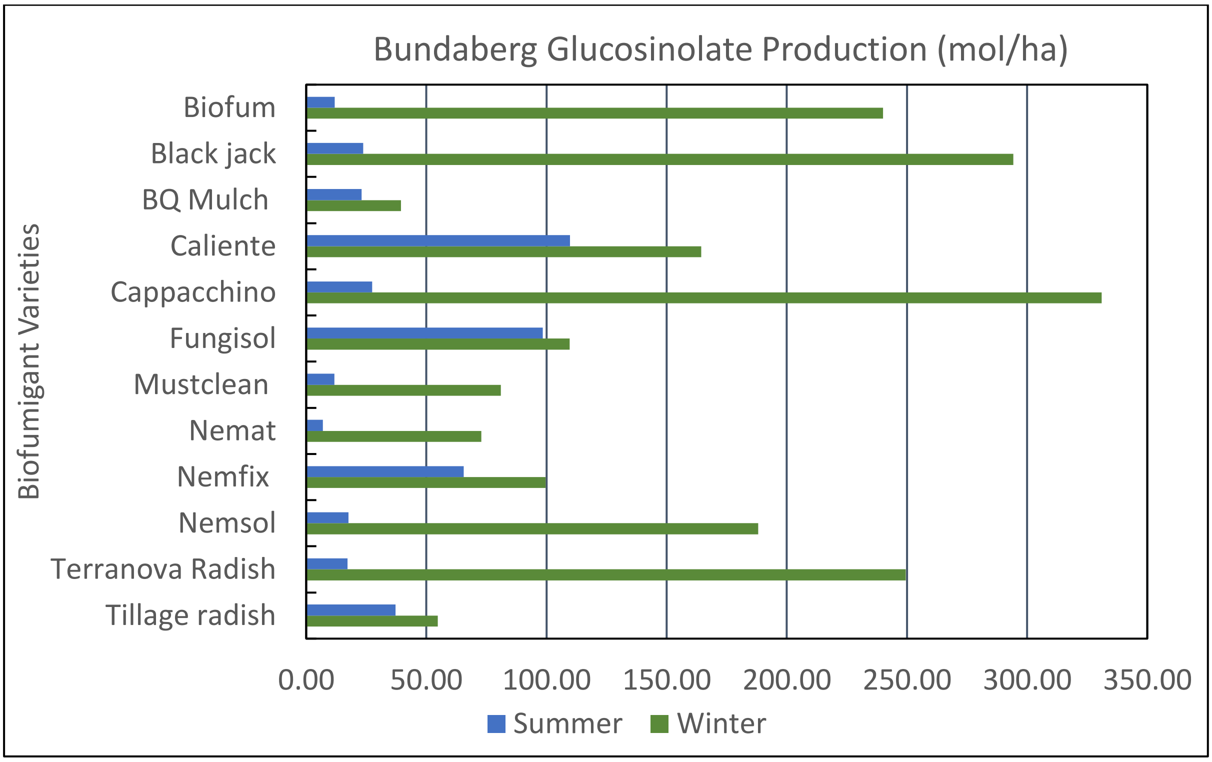


Figure 17. Total glucosinolates for each biofumigant variety for winter and summer growing seasons in Bundaberg.

Agronomic management of Biofumigants

Pest management for Biofumigants

Brassica biofumigant cover crops are prone to a similar pest spectrum as commercially grown brassica crops, such as broccoli and cabbage. Generally speaking, biofumigant cover crops will not require the intensive pest management of commercial crops for various reasons:

- There is greater flexibility in thresholds and acceptable damage limits in crops not destined for human consumption
- There are some benefits to the crop's performance as a biofumigant if it is allowed to experience a moderate level of stress, whether this is insect feeding or some other stress (such as water stress) – this results in some increase in potency in GSLs, but this is variety dependant
- The biofumigant cover crop can also provide functions beyond its soilborne disease suppression properties. For example, they can act as a nursery for beneficial insects, which would colonise vegetable crops and attack the relevant pests.

Appendix 2 is an index of pests and diseases observed in biofumigants. Chewing pests commonly encountered in biofumigant crops include caterpillars (diamondback moth, cabbage white butterfly, centre grub, cabbage cluster caterpillar and cluster caterpillar), beetles (flea beetle and red-shouldered beetle) and leaf mining flies.

Sucking and rasping pests commonly encountered in brassicas include aphids, thrips, Rutherglen bug, green vegetable bug, and whitefly.

Management of insect pests in biofumigant crops is generally not required, and may be considered economically unfeasible. Biofumigants are highly attractive to all beneficial insects particularly if flowers are present as many beneficial species are nectar feeders (e.g. parasitoids and hoverflies).

Figure 18. Beneficial insects and pollinators are attracted to biofumigant flowers. Photo: Mary Firrell

If a pesticide application is warranted, there are registered pesticides for both chewing and sucking pests in brassica leafy vegetables (mustards) (e.g. Belt® 480 SC and Movento® 240 SC). Before applying any chemical, always read, and comply with the label. For further information, please refer to the APVMA website or consult your local agronomist.

Table 5. Matrix of caterpillar, sucking, beetle and fly insect pests that affect brassica biofumigant crops.

Crop	Caterpillar insect pests			Sucking insect pests					Beetles and flies		
	Cabbage cluster caterpillar & Cluster caterpillar	Diamondback moth	Centre grub	Aphids	Whitefly	Thrips	Rutherglen bug*	Jassid	Red-shouldered beetle*	Flea beetle**	Leaf minor
Biofum	√	√	√	√√	√	√	√	√	√	√	√
Black Jack Radish	√	√	√	√√	√	√	√	√	√	√	√
BQ Mulch	√√	√√	√	√√	√√	√√	√	√	√	√	√
Caliente	√√√	√	√	√√√	√	√√	√	√	√	√	√
Cappacchino	√√√	√√√	√	√√√	√√√	√√	√	√	√	√	√
Fungisol	√√√	√√√	√	√√	√√√	√√	√	√	√	√	√
Mustclean	√√√	√	√	√√	√	√√	√	√	√	√	√
Nemat	√	√	√	√√	√	√	√	√	√	√	√
Nemclear	√√√	√√√	√	√√	√√√	√√	√	√	√	√	√
Nemcon	√√√	√√√	√	√√	√√√	√√	√	√	√	√	√
Nemfix	√√√	√	√	√√	√	√√	√	√	√	√	√
Nemsol	√	√	√	√√	√	√	√	√	√	√	√
Terranova Radish	√	√	√	√√	√	√	√	√	√	√	√
Tillage Radish	√	√	√	√√	√	√	√	√	√	√	√

Legend	
√	Present at low levels
√√	Present and approaching damage levels
√√√	Present at levels likely to cause significant damage or loss of crop
*	Can be an issue from time to time but generally not a problem
**	Only an issue at the seedling stage but plant will out-grow the pest

Table 6. Matrix of diseases affecting biofumignat cover crops that affect brassica biofumigant crops.

Crop	Fungal diseases			Bacterial diseases		Other diseases	
	Downy mildew	Powdery mildew	White blister	Bacterial brown rot	Bacterial soft rot	Phytoplasma	Virus
Biofum	X	X	√	√	X	X	X
Black Jack Radish	X	√	X	X	X	X	X
BQ Mulch	X	√√	√	√	X	X	X
Caliente	√√√	√	√√	√	X	√	√
Cappacchino	X	√√	X	√	X	X	X
Fungisol	X	√√	√	√	X	X	X
Mustclean	√√√	√	√√	√	X	X	√
Nemat	X	X	X	X	X	√	X
Nemclear	X	√	X	√√	X	X	X
Nemcon	X	√	X	√√	X	X	X
Nemfix	√√√	√	√√	√	X	X	√
Nemsol	X	X	X	X	X	X	X
Terranova Radish	X	X	X	X	√	X	X
Tillage Radish	X	X	√	X	√	√	√

Legend	
X	Disease not present
√	Present at low levels
√√	Present and approaching damage levels
√√√	Present at levels likely to cause significant damage

Fertiliser requirements for Biofumigants

Seed company recommendations for fertilising biofumigants is that they are fertilised as for any commercial brassica crop. For the purpose of the biofumigant cover crop assessments in Queensland the following was applied as a standard fertiliser program:

- a standard rate of 400 kg/ha Incitec pivot CK 77 S as a pre-plant fertiliser
- 120 kg/ha of ammonium sulphate at the 4-6 week growth stage.

As an indication of biofumigant nutrient requirements, crop nutrient uptake for the key macronutrients was calculated for a summer and winter cropping cycle for three biofumigants (Caliente™, Nemat ™ and Tillage Radish) planted at recommended field rates. Nutrient uptake data for nitrogen (N), phosphorus (P), potassium (K), sulphur (S), magnesium (Mg) and calcium (Ca) are presented in the table 7 below.

Table 8. Biofumigant nutrient uptake

			Plant nutrient uptake			
Variety	**Planting**	**Biomass (fresh weight) (t/ha)**	**Nitrogen (Kg/ha)**	**Phosphorus (Kg/ha)**	**Potassium (Kg/ha)**	**Sulphur (Kg/ha)**
Caliente ™	Summer	63	224	23	245	50
	Winter	143	498	56	609	108
Nemat ™	Summer	63	243	30	284	75
	Winter	118	485	56	574	132
Tillage radish®	Summer	158	390	59	457	114
	Winter	146	458	69	463	89

Image: Biofumigant varieties (left to right): Caliente 199™, Nemat ™ and Tillage Radish®. Photos by Zara Hall

Biofumigants have high requirements for nitrogen and potassium as well as sulphur, as the glucosinolates are sulphur containing compounds. Nutrient requirements for summer grown biofumigants were roughly half of that when grown in winter. This reflects the difference in biomass between growing seasons. Tillage radish was the exception with similar biomass and nutrient requirements whether grown in summer or winter. As biofumigants are fully mulched and incorporated, any applied nutrients will be available through nutrient recycling for future crops.

Water requirements

Research looking at the effect of drought stress on GSLs and biofumigant efficacy has shown that moderate to high water stress increases the concentration of GSLs per kg of plant tissue, even though the amount of biomass is less. Comparison of biofumigants grown under high, medium and low irrigation frequencies showed biomass was reduced by 45-55% between high and low irrigation treatments for 3 out of 4 varieties in summer. The impact of irrigation strategy on biomass was not as significant for winter grown biofumigants with at most a 24% lower biomass in Nemat with low irrigation frequency. Irrigation treatments were as follows:

- Winter growing season: The low irrigation treatment was established and then grown on rainfall only receiving 0.7 - 0.75ML / ha, medium irrigation received 1.57 – 2.27ML/ha and the high irrigation received 2.07 – 3.17ML/ha depending on harvest date.
- Summer growing season: The low irrigation treatment was established and then grown on rainfall only receiving 1.4-2.5ML / ha, medium irrigation received 2.5 – 3.2ML/ha and the high irrigation received 3.3 – 6.1ML/ha depending on harvest date.

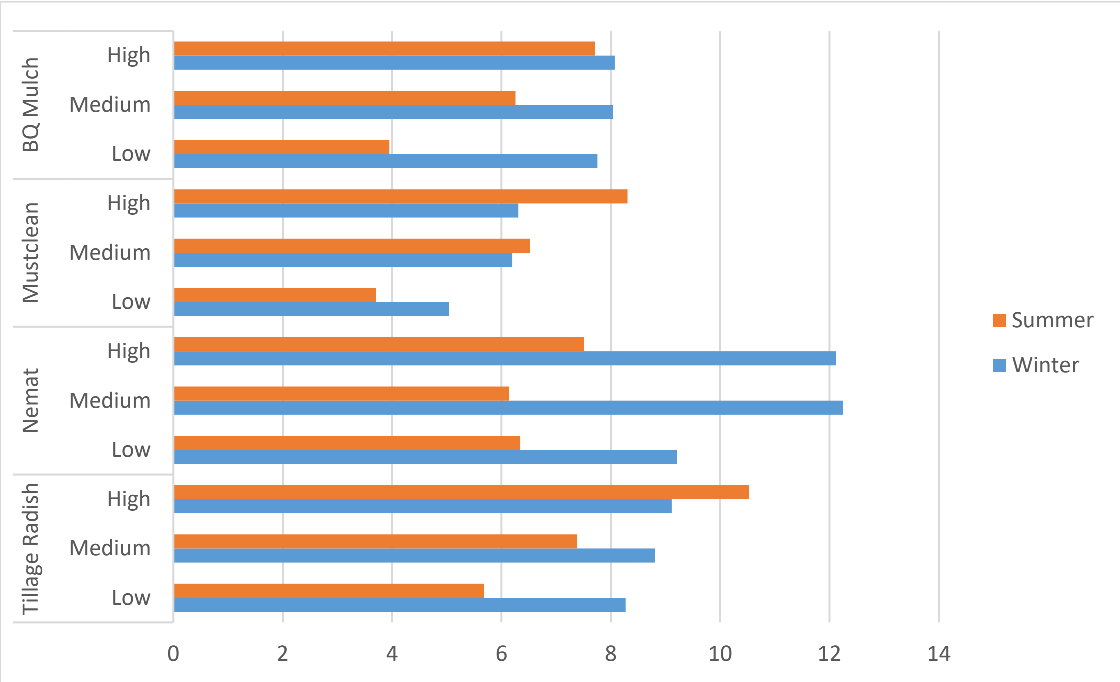


Figure 19. Biomass with varying water stress for winter and summer growing seasons in the Lockyer Valley.

Biofumigants do not have to produce high levels of biomass to be effective in suppressing plant pathogens. Results from the irrigation trial showed that low irrigation produced a lower biomass crop yet the highest production of GSLs per hectare in 3 out of 4 varieties with a winter planting. A summer planting was the reverse with 3 out of the 4 varieties producing more GSLs with the higher irrigation. While total GSLs have been measured, these values are only indicative and do not reflect the toxicity of the resulting ITCs on plant pathogens.

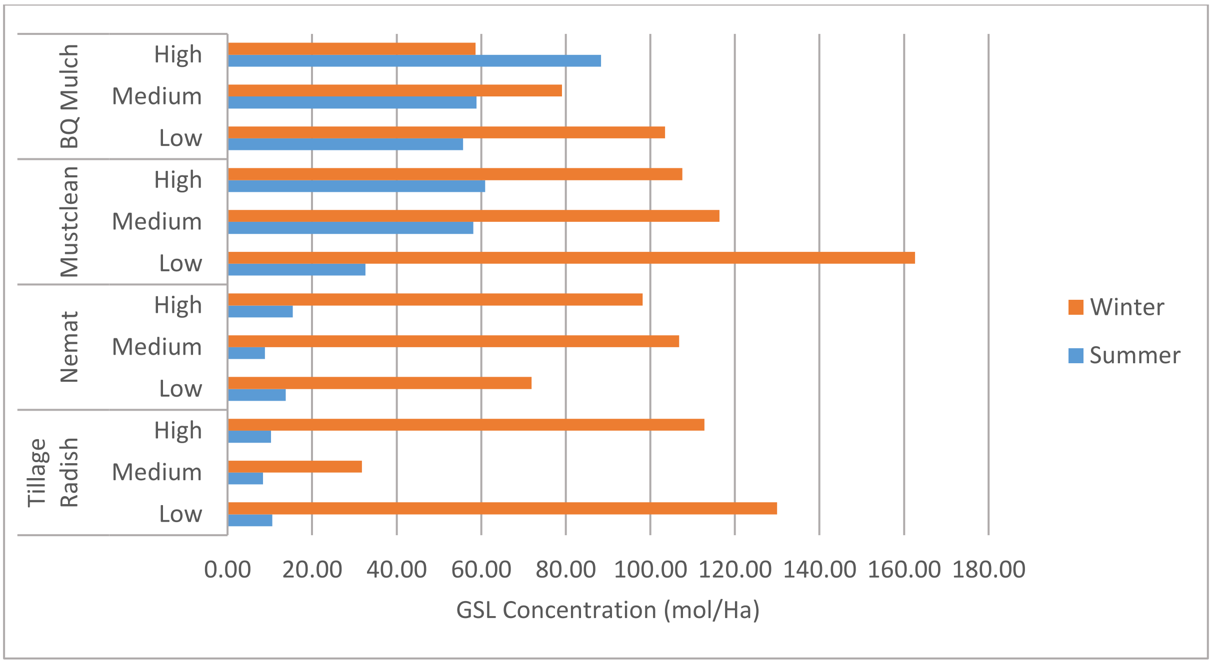


Figure 20. Total GSLs/ha with varying water stress for winter and summer growing seasons in the Lockyer Valley.

This information is beneficial when considering whether to grow a cover crop over summer or winter, as water availability can be a key consideration. Some water stress could improve disease suppressing qualities in biofumigants by increasing GSL concentration.

Figure 21. Irrigation following incorporation is an essential step to convert the biofumigant compounds to an active form and to prevent compounds from being lost to the atmosphere. Photo: Mary Firrell.

Weed Management for Biofumigants

It is recommended that weeds are managed as per a commercial crop. Pre-emergent herbicides like Dacthal® 900 WG (Nufarm) (active ingredient: Chlorthal-dimethyl) is registered for use in mustard crops as is Dual Gold (active ingredient: s-metolachlor). Care needs to be taken when using herbicides as most will have plant back issues for following cash crops.

Biofumigant crops that are left to go to seed can be a weed in their own right. To avoid this, incorporate plant material at 25% flowering stage to maximise the disease suppression properties of the crop and to avoid plants going to seed and becoming weeds themselves.

Before using any herbicide always read and comply with label requirements. For more information, consult the APVMA website.

Figure 22. Biofumigant crop with weeds present, such as fat hen (Chenopodium album). Photo: John Duff

Mulching, Incorporation and Final Irrigation of the Cover Crop

It is recommended that biofumigants are incorporated at approximately 25% flowering. This is when, according to previous research, the concentration of GSLs in biofumigants are at their highest. Where a biofumigant cover crop comprises a mixture of varieties, and the varieties flower unevenly, incorporate the crop when the first variety reaches 25% flowering (this will optimise the cover crops performance and avoid any weed issues in subsequent crops). Flowering times are also seasonally dependant. Biofumigant crops will flower earlier in summer and later in winter due to the temperature affecting the speed of growth.

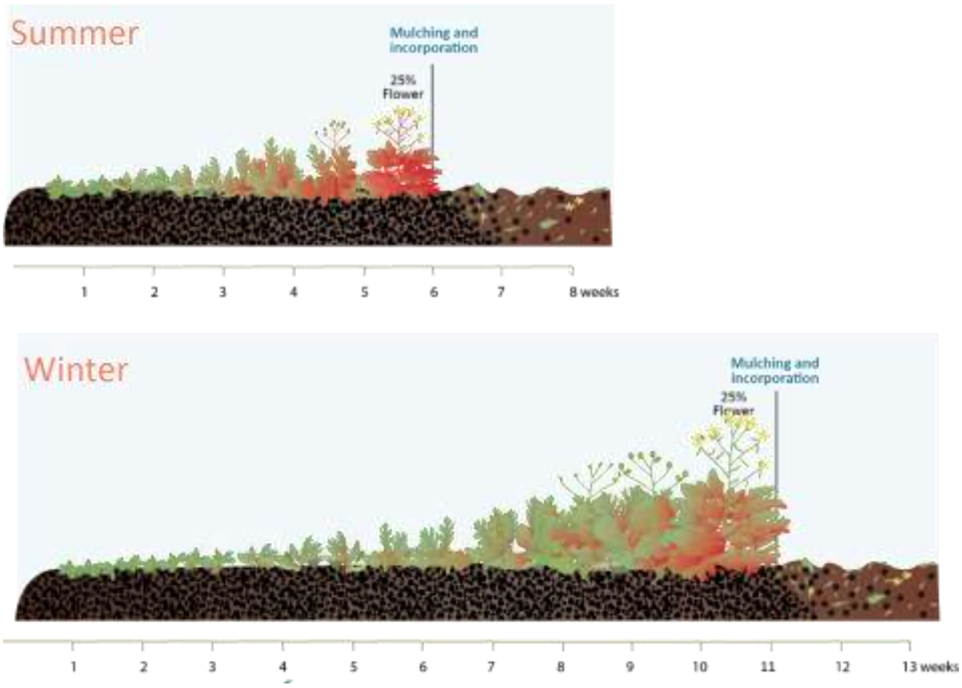


Figure 23. Indicative process of biofumigant cover cropping in the Lockyer Valley. Note indicative reduced soil disease levels (indicated by black dots in the soil) following mulching and incorporation.

Figure 24. Tillage Radish crop ready to be incorporated at Kalbar, south-east Queensland. Photo: John Duff

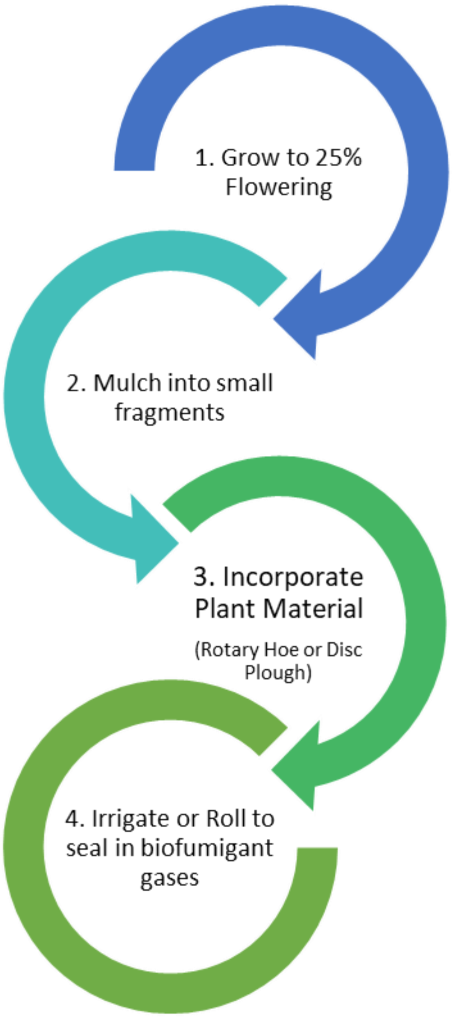


Figure 25. Steps involved in mulching and incorporation of biofumigant cover crops.

Figure 26. Incorporation underway. Simultaneous mulching of an Indian mustard crop on the left and incorporation with a rotary hoe on the right, Lockyer Valley, south-east Queensland. Photo: John Duff

Figure 27. Alternatively, the mulched biofumigant crop can be incorporated using a set of disc ploughs, Kalbar, south-east Queensland. Photo: John Duff

Figure 28. Irrigation afterwards helps to seal in the biofumigant gases. Photo: John Duff

Figure 29. Rolling can be just as effective at sealing in the biofumigant gases, particularly if you can't irrigate the ground after incorporation, Lockyer Valley south-east Queensland. Photo: John Duff

Rotary hoe has been the recommended incorporation method for biofumigant cover crops. However, as not all vegetable growers have access to a rotary hoe, DAF also looked at a range of incorporation methods for biofumigant cover crops. These include: Mulching followed by Disc Plough or Rotary Hoe, then Irrigation or Rolling, and Strip till followed by irrigation. A single biofumigant variety, Caliente, was used for this comparison.

Activity of the biofumigants against known pathogens was compared for the different incorporation methods. Generally, all incorporation methods performed well against the known pathogens, with some exceptions. Strip tillage showed the most variability in biofumigant activity. Mulch/rotary hoe/irrigation and mulch/disc plough/irrigation were similar in their biofumigant activity. There was also little difference between irrigation and rolling post incorporation.

Table 7. Efficacy matrix showing the extent of pathogen mortality after different methods of incorporation.

Pathogen	Fallow (Field Control)	Mulch + Disc plough + Irrigation	Mulch + Disc plough + Roll	Mulch + Rotary hoe + Irrigation	Mulch + Rotary hoe + Roll	Mulch + Strip till implement + Irrigation
Sclerotium rolfsii (basal rot)	*****	*****	****	*****	*****	*****
Sclerotinia sclerotiorum (white mould)	****	***	****	****	****	***
Rhizoctonia sp. (wire stem)	*****	*****	***	****	*****	****
Macrophomina phaseolina (charcoal rot)	****	****	***	***	**	**
Verticillium dahliea (verticillium wilt)	*****	****	****	*****	*****	****
Sclerotium cepivorum (onion white rot)	****	****	****	****	****	***

% Mortality	Colour	Rating
0-20	Red	*
21-40	Orange	**
41-60	Yellow	***
61-80	Green	****
81-100	Blue	*****

Spraying off the biofumigant cover crop was also evaluated to see if it still retained its suppressive characteristics once incorporated post spraying. The crop was sprayed off at 25% flowering and incorporated 4 weeks later. Total GSL levels were measured 2 weeks post spraying and 4 weeks post spraying (incorporation). Comparison of GSL data showed a progressive decline in total GSL levels by 50% at 2 weeks post spraying and by 90% at 4 weeks, incorporation.

Biofumigant activity against known pathogens varied greatly with the spray off/incorporation methods. While some of these results reflect the significant decline in total GSL with time after spraying off, others do not. Further work on this as an option for biofumigant cover crop management is required.

Table 8. Efficacy matrix showing the extent of pathogen mortality after spraying off with glyphosate and incorporating using different methods 4 weeks after spraying off.

Pathogen	Fallow (Field Control)*	Spray-off + Disc plough + Irrigation	Spray-off + Disc plough + Roll	Spray-off + Rotary hoe + Irrigation	Spray-off + Rotary hoe + Roll
Sclerotium rolfsii	*****	*****	*****	*****	*****
Sclerotinia sclerotiorum	****	***	***	*****	***
Rhizoctonia sp.	****	**	*	*****	***
Macrophomina phaseolina	***	**	*	*****	*
Verticillium dahliea	*****	*****	*****	*****	*****
Sclerotium cepivorum	****	***	**	****	****

% Mortality	Colour	
0-20	Red	*
21-40	Light orange	**
41-60	Yellow	***
61-80	Green	****
81-100	Blue	*****

*Fallow samples were taken at incorporation, 4 weeks after the biofumigant was sprayed off.

Fallow

Fallow was also included as a comparison in all work conducted on the biofumigants and as indicated, also showed good activity against those soilborne pathogens tested. Suppression of soilborne pathogens occurs to some extent in all soils, providing varying degrees of biological buffering against soilborne pathogens. Soils within the Lockyer Valley are inherently high in organic matter and soil organic matter plays an important role in maintaining the biological micro-organisms that regulate or suppress populations of soilborne pathogens.

Beneficial soil microorganisms and biofumigants

As with all forms of fumigation, biofumigation can impact living organisms in the soil, such as beneficial microbes including earthworms. Biofumigant activity against beneficial microorganisms such as *Trichoderma* sp. and *Bacillus amyloliquefaciens* (Serenade® Prime) was assessed in the laboratory. The biofumigants tested were found to be more suppressive against *Trichoderma* sp. than *Bacillus amyloliquefaciens*. There was variability in the suppression of beneficial microorganisms between varieties with some varieties suppressing more than others. Caliente in particular, showed high levels of suppression of *Trichoderma* sp. There was a trend for greater activity against beneficial microorganisms from biofumigant material grown during summer, however, this was not always the case. Therefore, if using biocontrol products such as *Trichoderma* sp. or *Bacillus* sp., it is recommended to only use these products when planting your cash crop and not in conjunction with the biofumigation crop.

The suppression of soilborne pathogens has also been linked to factors other than biofumigation. These include competition by a range of copiotrophic soil microorganisms, which thrive under the addition of fresh organic matter, proliferation of *Streptomycetes* (filamentous bacteria that have a role in breaking down plant material), and elevated soil populations of ammonia-oxidising bacteria, or the formation of additional bioactive sulphur containing compounds.

Biofumigation activity is known to increase soil bacterial diversity, but also significantly reduces soil fungal diversity, possibly due to reduced pathogenic fungi. This will obviously depend on the biofumigant variety, as different varieties contain varying types of GSLs with varying levels of toxicity when converted into ITCs.

Summary

Brassica biofumigant cover cropping is an option for vegetable system rotations as part of an integrated disease management strategy. Key information from this guide highlights several key considerations for those wanting to incorporate brassica biofumigants into their rotation.

- Biofumigant cover crops can be grown all year round in the Lockyer Valley and Bundarberg although with different performance characteristics.
- Days to maturity vary with season for biofumigants, with shorter growing periods over summer months
- Biofumigant varieties differ in their efficacy against known soilborne pathogens
- Biofumigants have shown some activity against beneficial soil microorganisms in the laboratory such as *Trichoderma* sp. and *Baccillus amyloliquefaciens* (Serenade® Prime)
- Management practices such as irrigation impact on the biomass, total GSLs and activity against soilborne pathogens

Planting biofumigant crops does come at an increased cost compared with retaining country as fallow, as well as cheaper cover cropping options. However, there are multiple benefits to using biofumigants in vegetable cropping systems, including:

- Reducing top soil loss through erosion from the summer rains
- Good biomass production, replenishing carbon in the form of biomass to the top soil to ensure water infiltration, organic matter and soil structure
- Prior planting with a biofumigant cover crop minimises and manages the impact of soilborne diseases of the subsequent cash crop
- Reducing the use of harsh and potent chemicals when controlling soilborne diseases by growing biofumigant crops as a break between cash crop rotations

Although biofumigation has been practiced for over 30 years, there is a great deal of work that can still be done to demonstrate the benefits of using these types of crops as part of everyday farm management program. There are regional differences in the biofumigation activity and across growing seasons. Pest and disease pressures also vary with regions, so the choice of biofumigant will vary both in the efficacy against soilborne pathogens, and in the range of pests and diseases they are affected by.

Growers are encouraged to investigate more into how biofumigation can be used and optimised for their own practices. Talk to other growers in your region who have used them successfully.

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Appendix

Biofumigation Check List

What is the Target Disease to be managed?

Sclerotinium rolfsii	*Sclerotinium cepivorum*	*Macrophomena phaseolina*	*Rhizoctonia sp.*

What is your cropping window?

Summer	Autumn	Winter	Spring

What Varieties are available to you at the desired time?

See Matrix on page X

How will you incorporate the plant matter?

Mulch, Rotary Hoe and Irrigate	Spray Off, Rotary Hoe and Irrigate	Mulch, Disc/Moleboard Plough, Irrigate

Appendix 2 Summary of biofumigant insect pests and diseases

Caterpillars	
	**Cabbage cluster caterpillar (*Crocidolomia pavonana*)** Cabbage cluster caterpillar is capable of very quickly stripping plants of foliage as larvae feed in clusters and move across a plant leaving only leaf mid-veins behind. Regularly checking plants for eggs will allow timely management of large infestations. **Photo by John Duff**
	**Centre grub (*Hellula* sp.)** Centre grub needs to be monitored in very young seedlings as feeding at this stage can damage the growing point. In older plants, a much higher tolerance exists for centre grub as the plant tends to be multibranching and some feeding can even encourage bushy growth. **Photo by John Duff**
	**Cluster caterpillar (*Spodoptera litura*)** Cluster caterpillar is capable of very quickly stripping plants of foliage, similar to the cabbage cluster caterpillar, as larvae feed in clusters when small and move across a plant leaving only leaf mid-veins behind. When older, the larvae wander off on their own and are typically recognised as large fat grubs with dark marking along the sides of their body. Regularly checking plants for eggs will allow timely management of large infestations. Egg masses are covered in fine brown hair from the adult moth. **Photo by John Duff**

	**Diamondback moth (*Plutella xylostella*)** Diamondback moth can be present from seedling stage through to harvest. Pesticide application may be required if numbers are extremely high or if there is concern that the crop is harbouring diamondback moth that may emigrate into nearby brassica crops. Cotesia and specialist parasitoids such as Diadegma will help to keep Diamondback moth in check. **Photo by John Duff**

Beetles and flies	
	**Flea beetle (*Phyllotreta* sp.)** Beetles will ‘spring’ away if disturbed leading to their common name, flea beetle. Feeding by adult flea beetles produce characteristic ‘shot hole’ damage in leaves. Beetles tend to prefer feeding on seedlings more than mature plants. Generally, damage by flea beetles is tolerated in biofumigant cover crops even under high insect pressure. **Photo by John Duff**
	**Red-shouldered beetle (*Monolepta australis*)** Red-shouldered beetles can migrate into the crop in large numbers and strip the plants of foliage. Regular monitoring for this pest is required in late summer and early autumn when they are most prevalent. **Photo by John Duff**
	**Leaf miner (*Liriomyza* sp.)** **Leaf miners** may be present from seedling stage onwards and generally do not reach populations that warrant management. Characteristic feeding damage by leafminers are transparent tunnels below the leaf epidermis made by the feeding larval stage. **Photo by John Duff**

Sucking and Rasping Pests	
	**Aphids (e.g. Green peach aphid, *Myzus persicae*)** Aphids that have colonised the plant and reached large numbers in the absence of generalist predators or parasitoids are capable of affecting growth and may require pesticide application in some seasons. Large infestations can actually cause the death of biofumigants, particularly the Indian Mustard types. **Photo by John Duff**
	**Rutherglen bug (*Nysius vinitor*)** Rutherglen bug sometimes reach large numbers during Summer and cause severe wilting. Pesticide applications for rutherglen bug may have limited efficacy as they tend to quickly re-colonise crops from neighbouring areas (weeds, sorghum etc) following sprays. **Photo by John Duff**
	**Whitefly (e.g. Silverleaf whitefly *Bemisia tabaci*)** Whitefly can be present from seedling stage through to incorporation. Pesticide application is occasionally necessary when large numbers of juveniles on the undersides of leaves produce copious amounts of 'honeydew' which promotes the growth of sooty mould. **Photo by Mary Firrell**

	**Thrips (e.g. Onion thrips, *Thrips tabaci*)** Thrips tend to be present from seedling stage onwards. They tend to be found close to mid veins on the underside of leaf and damaged leaves may have a silverish sheen following loss of the epidermal layer. Generally thrips will not warrant pesticide applications as some feeding damage is tolerated. **Photo by John Duff**

Bacterial Diseases	
	**Bacterial brown rot (*Xanthomonas campestris*)** Bacterial brown rot disease symptoms are yellowing areas at leaf margins. This will turn brown in older lesions. Sprays of mancozeb & copper mix can prevent disease development. **Photo by John Duff**
	**Bacterial soft rot (*Erwinia carotovora*)** Symptoms include water soaked lesions that rapidly expand and cause break down of plant tissue. The decaying plant matrial may be slimy and produce foul odour characteristic of Erwinia diseaes. Hot, wet weather favours the spread of disease. **Photo by John Duff**
Fungal Diseases	
	**Damping-off (*Pythium* sp.)** *Pythium spp.* are extremely common in soils in both tropical and temperate regions. Damping off occurs as the soft decay of the taproot or rootlets causes the plant to collapse at the soil level. Typically produces fine webbing or mycelium near the base of the plant. Warm wet weather can favour the development of this disease. Typically found attacking seedlings and small plants. **Photo by John Duff**

	**Powdery mildew (*Peronospora parasitica)*** Powdery mildew symptoms are white fluffy mycelial growth on the top side of leaves. Warm, dry and cloudy conditions favour disease development. **Photo by John Duff**
	**Downy mildew (*Hyaloperonospora parasitica*)** Downy mildew symptoms are white mycelial growth that occurs on the underside of leaves and may progress to the top side of leaves as symptoms progress. **Photo by John Duff**
	**White blister (*Albugo candida*)** White blister infection may be first noticed when yellow spots appear on the top side of leaves. The underside of the leaves have characteristic white raised fungal growths. **Photo by John Duff**
Virus and Phytoplasma	
	**Phytoplasma** Symptoms of phytoplasma infection are floral structures that are green and resemble vegetative stages e.g. flowers that resemble leaves. Phytoplasma is a type of bacteria spread by leafhoppers. Infected plants remain diseased for life. **Photo by John Duff**

	**Turnip mosaic virus (*Potyvirus*)** Virus infected plants have patches of very dark green on the top side of their leaves. The virus is spread by aphids. **Photo by John Duff**

Effect of cover crops on soil biological communities

13 July 2020

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Summary

This study aimed to determine how soil biological communities respond to the use of cover crops. It was observed that the communities – bacterial, fungal and eukaryote – found at each site were very different. The structure of the communities were primarily related to soil characteristics and at some sites significant changes in community structure were correlated to changes in soil properties within the site. Although at a broad level similar organisms were found within each site, it was possible to detect differences among cover crop and fallow treatments. This suggests that although the use of cover crops does influence the structure of the soil biological communities, the main functions provided by these communities remain stable.

Background

Cover crops provide numerous benefits to the soil depending on the soil type, climatic conditions and choice of plant species (Lehman et al 2015). These benefits can include improved water and gas transport (Abdollahi et al. (2014), providing a source of carbon (Reicosky and Focella, 1998) and for some crops, increasing soil nitrogen through stimulating the nitrogen-fixing bacteria (Lehman et al. 2015). Cover crops influence the below-ground soil biological communities, primarily through the effects of roots and root exudates (Brennan and Acost-Martinez, 2017).

The connection between the above- and below-ground ecosystems is well known and many studies have investigated particular aspects of the microorganism-plant interactions (REFS). Soil organisms are responsible for a number of important biogeochemical processes including organic matter degradation and nutrient cycling (Giffith and Philipott, 2013). They increase the availability of nutrients to plants, and can reduce plant diseases (Vander Heijden etl al. 2008). Plant growth promoting bacteria directly influence plants by modulating plant phytohormones and stimulating plant defence systems (Hanschen et al. 2015). Soil fauna also contribute to soil structure, nutrient cycling and plant health (for example Lee and Pankhurst 1992).

The importance of soil organisms for plant growth was demonstrated by Bender and van der Heijden (2015) in an artificial system with an initially sterile soil. Soil that was inoculated with organisms up to 2mm in size had increased nutrient use efficiency, reduced nutrient leaching and higher crop yields in the following two years.

However, the effects of cover crops on soil biological communities and how that in turn affects the growth of following crops is not well understood. In this study changes in the structure of the bacterial, fungal and eukaryote soil communities were determined in four different cropping systems in four different areas of eastern Australia.

Methods

Sites

Four sites were sampled in this part of the study across a range of soil types and climate regions (see Table 1). All sites included a fallow in which no cover crops were planted between cash crops.

Table 1: Characteristics and cover crops of sites in this study

	Years of Cover Crops	Cover Crops	Organic matter (%)	Texture	Relative intensity of system	Relative productivity of system
Gatton, QLD	1	Caliente Tillage radish BQ mulch Sorghum	2.1	Clay loam	High	High
Cowra, NSW	1	Ryegrass/clover +/- hay removal	3.6	Sandy loam	Low	Medium
Forthside, NW TAS	10	Ryegrass Caliente	6.5	Ferrosol	Medium	High
Cambridge South TAS	1	Ryegrass Millet Oats Tillage radish Oats/Tillage radish	3.3	Clay loam	High	Low

Amplicon sequencing of biological communities

High throughput amplicon sequencing has become a popular way to explore the diversity of organisms, particularly microorganisms in environmental samples such as soil. This method generates fragments of sequences of particular genes that are considered taxonomic markers. The sequence data is processed to remove poor quality and spurious sequences, identical sequences are grouped together and then classified against reference databases. Amplicon data processed in this way produces 'amplicon sequence variants' (ASV) which can be considered somewhat analogous to species although this is not a method that is able to accurately identify organisms to species level.

Sampling, DNA extraction and sequencing

The biological communities present in the soil were examined using high throughput amplicon sequencing of the 16S rRNA (bacteria), 18S rRNA (eukaryote) and ITS (fungi) genes. The protocol was similar to that used in the Biomes of Australian Soil Ecosystems project. Soil was collected each year from each site approximately two weeks prior to the planting of the biofumigant crop and, in some cases, at other times. Briefly, 30 – 40 cores taken from the top 15 cm of the soil were combined and homogenised. Soils were frozen as soon as possible and stored at – 20 until DNA extraction. DNA was extracted from approximately 0.5g of soil using the DNEasy PowerSoil kit (Qiagen) with bead-beating performed in a tissuelyser (Qiagen). Amplicon sequencing from the genomic DNA preparations was carried out by the Ramaciotti Centre for Genomics (University of New South Wales) using the Illumina MiSeq system. The regions sequenced were 16S rRNA V1-3 region using primers 27F/519R for bacteria, the 18S rRNA V9 region using primers 1391F / EukBr for eukaryotes and the fungal ITS2 region using primers fITS7-ITS4.

Data processing and analysis

Raw data was downloaded and processed using the DADA2 pipeline (Callahan et al. 2016) in R following the standard protocol. The 16S rRNA and 18S rRNA sequences were classified using the most recent SILVA databases and the ITS sequences were classified against the most recent available UNITE database all accessed through benjjneb.github.io/dada2.

Sequences were subject to further quality trimming with rare sequences that appear less than 50 times in all samples or in one or two samples only removed from the dataset. Multivariate exploration of the data was carried out using Primer6 (PrimerE, Plymouth). All three data sets were subject to a log (x+1) transformation, followed by a Bray-Curtis dissimilarity. The similarity between biological communities in each sample were plotted on a non-metric multidimensional scaling plots in which samples that are more similar to each other are closer to each other. The strength and significance of the difference between groups was tested with the ANOSIM test. The R value provides an indication of the strength of the separation between groups with a maximum value of 1.

Results and Discussion

Biological community diversity

At all sites, diverse communities of bacteria, fungi and a range of multicellular eukaryotes were observed (Table 2). The number of actual sequence variants are reported for the bacteria and fungi and represent a taxonomic division close to species level. The diversity of eukaryotes appears to be smaller but this is simply because the number of different phyla observed are reported as a better overview of the number of different types of organisms present. The communities have a similar diversity at all sites although Gatton appears to have a less diverse fungal community. This could be the result of either the cultivation methods used at the site or the lower organic matter compared to the other sites. The Cambridge site appears to have a greater diversity of bacteria, although this does not equate to abundance and therefore does not represent a shift in the fungi: bacteria ratio.

Table 2: Number of different ASV or phyla observed in the bacterial, fungal and eukaryotes communities in this study

	Gatton	Cowra	Forthside	Cambridge
Bacteria (ASV)	340	336	540	989
Fungi (ASV)	71	288	207	165
Eukaryotes (phyla)	37	47	56	47

Different communities are found in different locations

The composition of each of the types of communities (bacteria, fungi and eukaryotes) were compared across all sites and including all treatments. An example is provided in Figure 1 for the eukaryote communities. It is clear in this MDS plot, that the communities at each site are significantly different to each other (ANOSIM R = 0.54, $P < 0.001$). The same trend was observed in both the bacterial and fungal communities. It is likely that this difference amongst the communities is related to the differences in the soil characteristics at each site (see Table 1). At the Forthside site for example, strong correlations were observed between bacterial community structure and pH ($R^2 = 0.86$), the fungal community structure and Total N plus S ($R^2 = 0.58$) and the eukaryote community structure and total N plus pH ($R^2 = 0.70$). Other studies in agricultural systems have also found strong relationships between soil factors (including for example total C and total N) and the structure of microbial communities (Hermans et al. 2017, Trivedi et al. 2016).

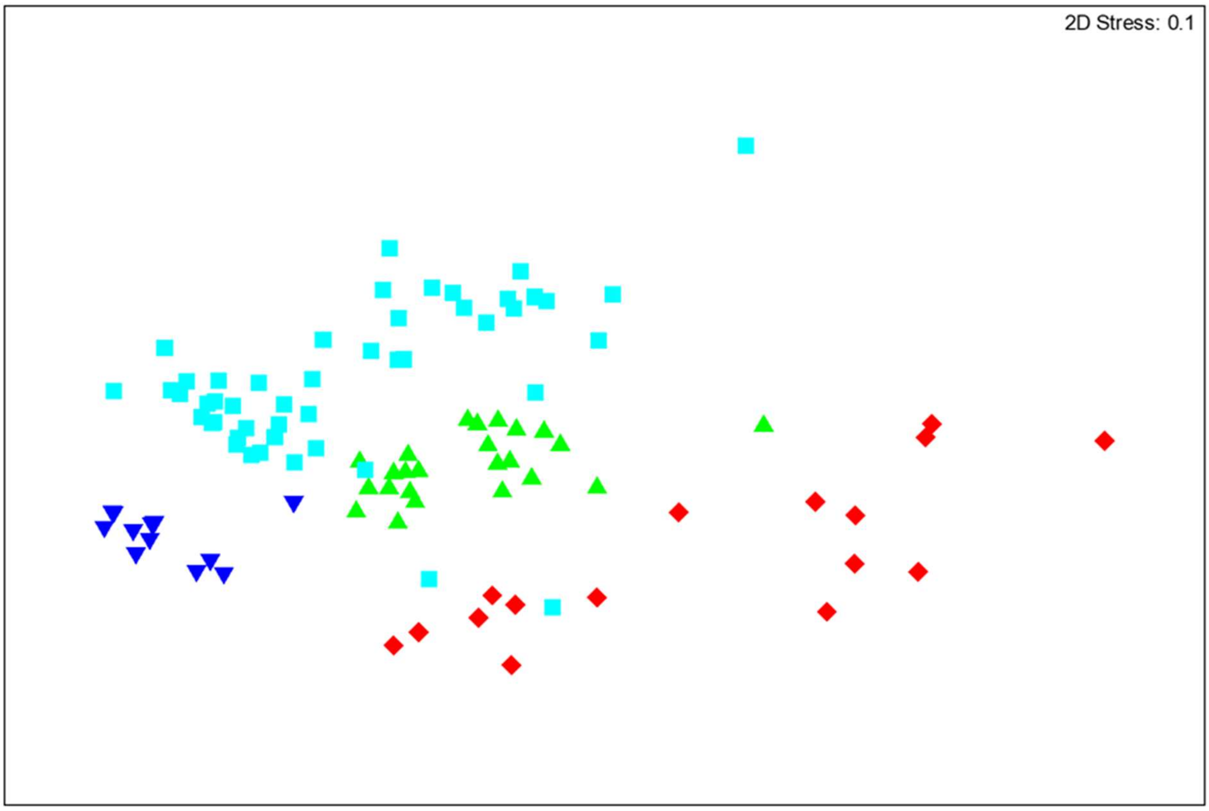

Figure 1: Similarity between eukaryote communities in all treatments at all sites (Forthside = light blue, Cambridge = green, Cowra = dark blue, Gatton = red).

The communities in the fallow treatments at each site were compared in more detail (Figure 2) to determine the differences in the soil communities at each site regardless of cover crop effects. The average relative abundance of the main classes of bacteria observed in the fallow treatment at each site are presented in Figure 2A. Although the same main groups are present in all sites, the constituents of the group 'Other' vary between sites and in addition at the ASV level there are also greater differences between sites. The most noticeable differences are the relative abundance of the Gammaproteobacteria which are much higher at Forthside. The Actinobacteria and closely related Thermoleophilia are dominant only at Cowra. Cambridge is the only site where the Bacteroidia and Alphaproteobacteria are the most significant classes. The Gammaproteobacteria, which are present as at least 10% of all the populations are a metabolically diverse group of heterotrophs. The Alphaproteobacteria are important in the nitrogen cycle and contains both symbiotic and free-living nitrogen fixing organisms and others involved in denitrification and nitrification (although these processes are also carried out by Gamma- and Betaproteobacteria). Bacteroidia class contains many anaerobic or facultatively anaerobic organisms and are often associated with the breakdown of complex compounds.

Although the Mortierellomycetes were found at all four sites, their relative abundance was higher at Gatton where the Spizllomycetes were also significantly higher proportion of the fungal community. In contrast the Forthside fungal community contained similar proportions of Mortierellomycetes, Tremellomycetes and Agaricomycetes. Both the Mortierellomycetes and Tremellomycetes contain some parasitic fungi whereas the Agaricomycetes are mushroom-type saprophytes. The Cambridge fungal communities were broadly similar to those Forthside although it should also be noted that Glomeromycota were only detected at the Forthside site. Cowra fungal communities differed from the other sites as they contained a greater proportion of the related Dothideomycetes and Sordariomycetes both of which contain potential plant pathogens as well as endophytes and saprophytes.

The eukaryote communities were dominated by a different phylum or organism at each site. At Cowra the Phragmoplastophyta (terrestrial green algae) were approximately 50% of the population. The Ciliophora (a phylum of protozoa) are approximately 40% of the population at Gatton. The Cercozoa (a type of amoeba) and Peronospromycetes (heterokont water moulds) together make up approximately 50% of the community at Forthside and the community at Cambridge is dominated by the 30% Peronospromycetes (~30%) and 10% Ciliophora. Other amoeba, algae and moulds as well as nematodes and arthropods were also detected in smaller proportions across the sites.

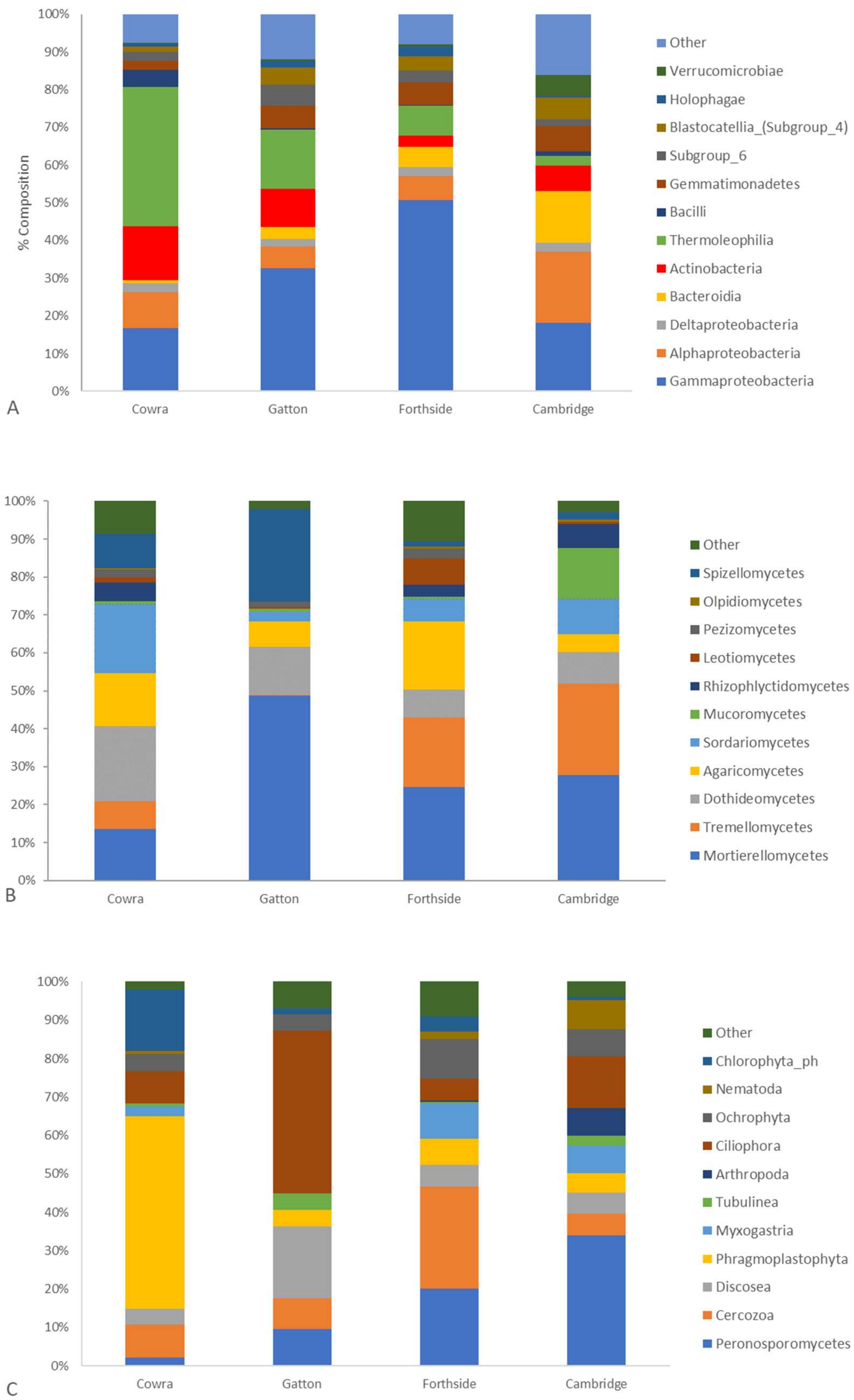

Figure 2: Composition of bacterial (A), fungal (B) and eukaryote (C) communities in fallow treatments at the class (A and B) and phylum (C) levels

Effect of cover crop on soil biological communities: comparison to fallow

Within each site, the similarities or differences in the biological communities in each treatment were compared (Figures 3–5). The global ANOSIM values, indicating whether there was a difference between treatments, is presented in Table for all 3 communities. Similar patterns in the differences among communities in the different treatments were generally present in all three communities although this is not always the case. The bacterial communities are much more diverse and hence significant changes in a small part of the community may not be detectable as for example at Cowra. However, the bacterial communities at Gatton and Cambridge had stronger differences amongst the treatments than the fungal or eukaryote communities at these sites. Therefore, which community provides a more sensitive indication of change depends on the specific soil and community present.

Table 3: ANOSIM Global R values (p value)

	Gatton	Cowra	Forthside	Cambridge
Bacteria	0.69 (0.001)	0.05 (0.35)	0.14 (0.001)	0.41 (0.001)
Fungi	0.13 (0.1)	0.36 (0.002)	0.16 (0.001)	0.29 (0.002)
Eukaryote	0.34 (0.005)	0.42 (0.002)	0.07 (0.005)	0.41 (0.001)

The effect of the cover crops was different at each site most likely due to different soil characteristics, different cover crops and different cropping systems. That is, the presence of a cover crop did not result in clear and consistent changes such as an increase (or decrease) in a specific group of organisms.

At Cowara site the fallow was the more different to the other treatments than the two cover crops (Hay or Ryegrass/clover) were to each other in both the fungal and eukaryote communities but not in the bacterial communities (Table 4). The diversity of all treatments was similar – the changes in the communities were in shifts in the abundance of particular groups or organisms.

The results at Gatton were somewhat limited by the small number of replicates and no statistically significant differences were observed between treatments because of this. However, some of the treatments at the Gatton site were sampled more than once and this provided an interesting opportunity to begin to determine the effect of sampling communities before and after incorporation of the cover crop. In Figure 3A (enlarged in Figure 6), the bacterial communities appear to cluster depending on the time of sampling. However, further replication is required to confirm this.

Table 4: Pairwise ANOSIM R (p values) for communities at the Cowra site

	Fallow–Hay	Fallow–Ryegrass	Hay–Ryegrass
Bacteria	-0.02 (0.4)	0.2 (0.2)	0.02 (0.4)
Fungi	0.41 (0.03)	0.46 (0.03)	0.20 (0.1)
Eukaryote	0.54 (0.03)	0.65 (0.03)	0.08 (0.2)

At Forthside the effect of the treatments was confounded by a significant block effect. The soil characteristics, primarily pH, in the southern two blocks were different to those in the northern two blocks. In Figures 3C, 4C and 5C, the communities in the treatments do not appear to cluster strongly based on treatment. Two-way crossed ANOSIM tests which take this block effect into account show that there are small, but significant, differences in all the communities (Table 5). The most significant changes are between the fallow and two cover crop treatments, particularly in the eukaryote communities. This provides some evidence that the presence of a cover crop has a lasting effect on the soil biological communities.

Table 5: Pairwise ANOSIM R (p values) for communities at the Forthside site

	Fallow - Biofumigant	Fallow - Ryegrass	Biofumigant – Ryegrass
Bacteria	0.10 (0.05)	0.17 (0.001)	0.16 (0.002)
Fungi	0.16 (0.001)	0.14 (0.001)	0.19 (0.002)
Eukaryote	0.54 (0.03)	0.65 (0.03)	0.08 (0.2)

A highly significant block effect (ANOSIM R = 0.71, p= 0.001 for the bacterial communities) was also observed at the Cambridge site and correlated with a change in soil texture and pH as the blocks were located closer to the dam. This location also resulted in ducks destroying one of the vegetable crops in some blocks. In Figures 3D, 4D and 5D the fallow treatment clusters separately from all the cover crop treatments. In Figure 5D the two separate blocks can be seen with the communities from the fallow treatments on the edge of each block. This block effect is stronger than the effect of the cover crops on the communities and there were not enough replicates to be able to statistically test the difference between the fallow and each of the cover crops.

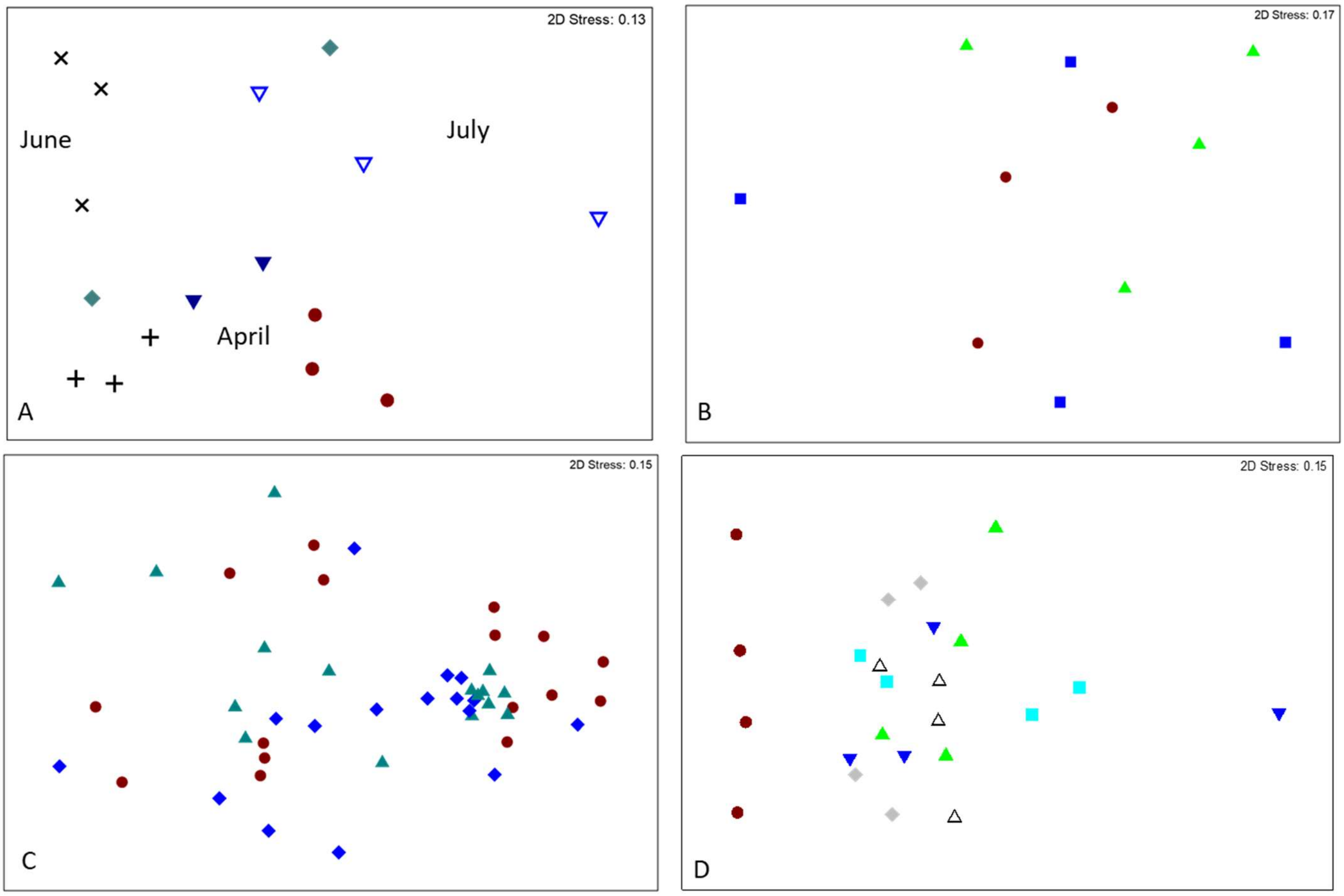

Figure 3: Similarity of bacterial communities amongst fallow and cover crop treatments at Gatton (A), Cowra (B), Forthside (C) and Cambridge (D). All fallow treatments are brown circles.

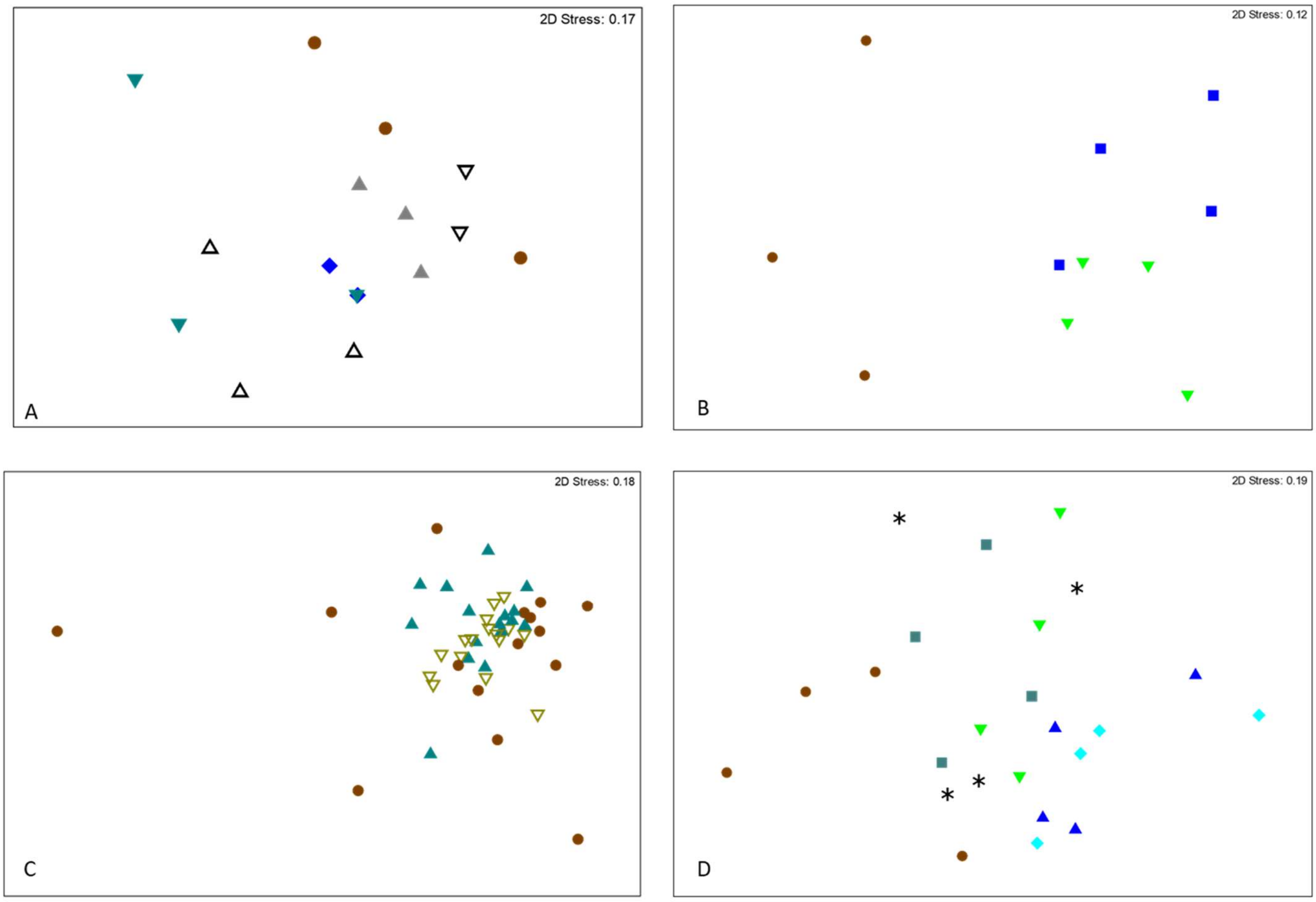

Figure 4: Similarity of fungal communities amongst fallow and cover crop treatments at Gatton (A), Cowra (B), Forthside (C) and Cambridge (D). All fallow treatments are brown circles.

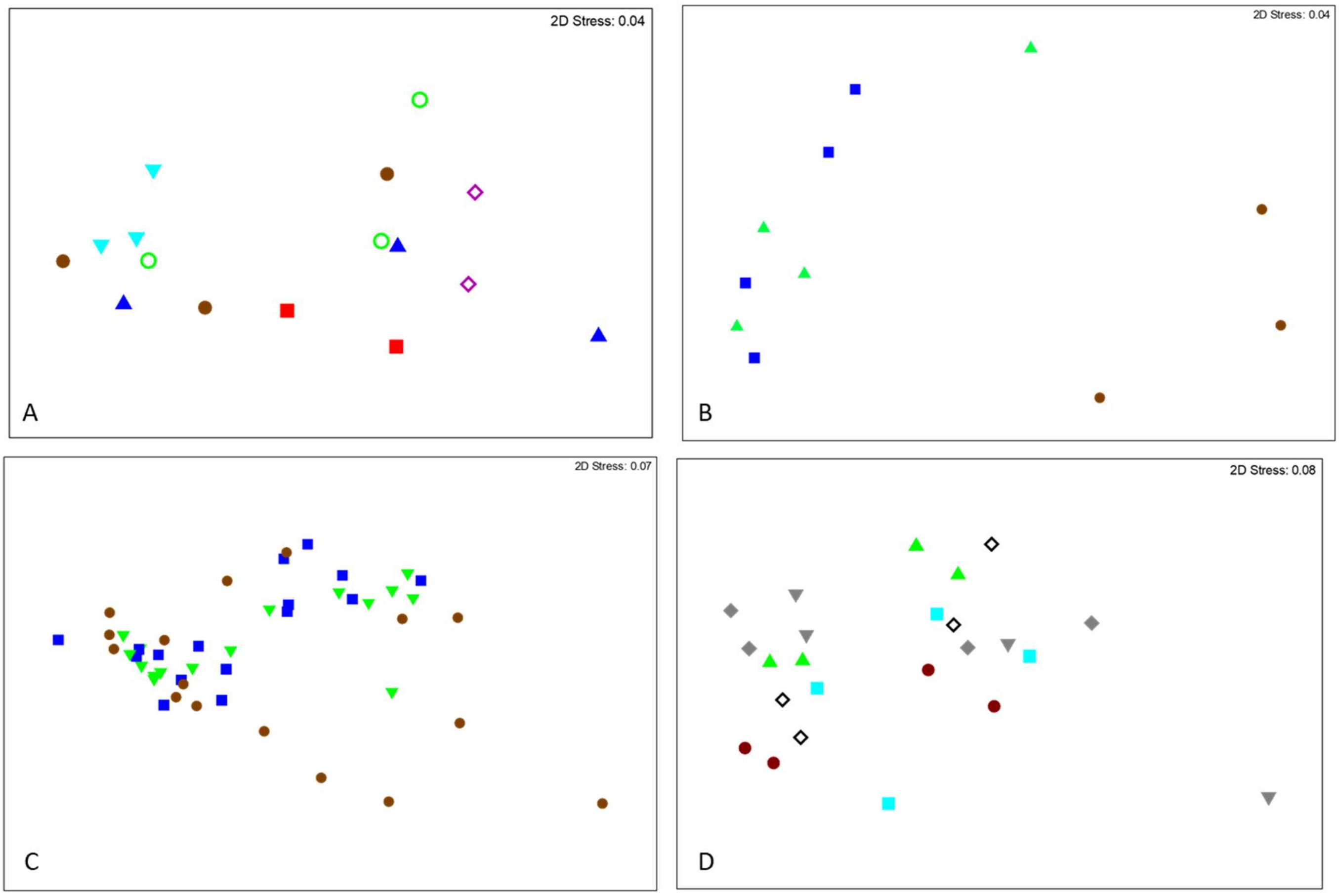

Figure 5: Similarity of eukaryote communities amongst fallow and cover crop treatments at Gatton (A), Cowra (B), Forthside (C) and Cambridge (D). All fallow treatments are brown circles.

Effect of biofumigant cover crops on soil biological communities

Biofumigants cover crops have been shown to reduce plant fungal diseases (e.g. Larkin et al. 2011) and nematode infections (e.g. Fatemy and Sepideh, 2016) however results are often variable (e.g. Larkin et al. 2011, Vervoort et al., 2014). Both Forthside and Gatton included biofumigant crops in their cover crop rotations in addition to non-biofumigant cover crops which allowed a comparison between the effect of cover crops and the effect of biofumigants. At Forthside, samples were collected after harvest of the summer vegetable crop and approximately two weeks prior to the planting of the cover crop. This time was chosen as the time of year that the soil was most stable. However, it is also the point in the cropping cycle that is the longest time since biofumigant plants were present and the same vegetable crop was planted in the intervening time in all treatment plots (fallow, ryegrass and biofumigant). Other studies have observed changes in the soil communities in the days after incorporation of a biofumigant that then became smaller over time (Wei et al. 2016) and it is possible that the similar changes were occurring here. At Forthside, differences between the communities in the ryegrass and biofumigant (Caliente) treatments were observed in the bacterial and fungal but not eukaryote communities. In contrast, at Gatton, samples were collected at two different times and this had had an effect, particularly on the bacterial communities (see Figure 6). Unfortunately, there were not enough replicate samples for testing to be statistically significant but the results do suggest that the bacterial communities are affected by the incorporation of the biofumigant crop in a different way to the non-biofumigant cover crops (Sorghum). Samples were collected in April from the fallow, Sorghum and BQ mulch (biofumigant). These samples are clustered together. In June, the BQ mulch was incorporated and then the soil sampled. These samples cluster together away from all the others. Finally, the sorghum samples collected in July form a third cluster. This suggests that the incorporation of both the sorghum and the BQ mulch affected the bacterial communities but shifted them in different ways. Inspection of the relative abundance of different classes within the bacterial communities revealed that Sorghum incorporation results in an increase in the Gammaproteobacteria and a decrease in Bacilli. Incorporation of the BQ mulch also resulted in an increase in the relative abundance of Gammaproteobacteria and also in the Bacteroidia with a decrease in the Actinobacteria and Thermoleophilia (which are closely related to the Actinobacteria). Larger sample numbers taken at identical times after incorporation are required to confirm that this is occurring consistently.

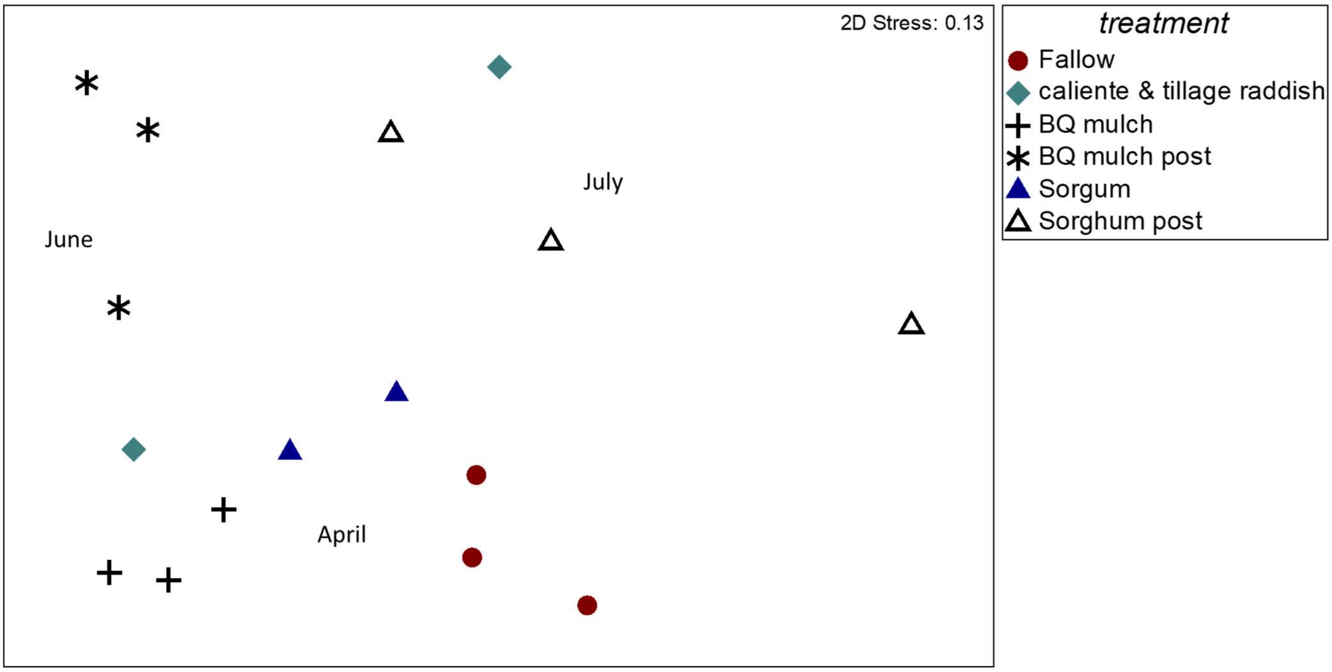

Figure 6: Differences in bacterial communities at the Gatton site showing both treatment and sampling times.

Conclusion

The presence of cover crops affects soil biological communities. Other studies have observed a significant influence of cover crops on microbial community diversity and structure (e.g. Friberg et al. 2009, Wang et al. 2014, Li et al. 2017). However, in our study it appears that the use of cover crops does not affect the structure or composition of these communities as much as soil characteristics such as texture, pH and nutrient levels. This means that the ecosystem services provided by these communities are maintained throughout the cropping cycle. It is also likely that, at least for the sites studied here, there is some resilience in the soil communities and their ability to maintain a stable core structure despite the different cover crop treatments. Progress is being made in understanding the links between soil biological communities and crop success (Gumiere et al. 2019, Jeanne et al. 2019) but greater understanding of the site-specific factors influencing this relationship is still needed.

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Optimising cover crops for the Australian vegetable industry

Long-term impacts of cover crops – Forthside, Tasmania

13 July 2020

Project Team

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Stakeholders and contributing companies

Applied Horticultural Research, Serve-Ag, Simplot Australia, McCain, Premium Fresh, Harvest Moon

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Summary

Biofumigant crops have been grown in greater quantities during recent years due to the fact that they may provide growers with opportunities to enhance subsequent crop productivity and improve soil health. However, within Tasmania, anecdotal and reported results on biofumigant crop use have lacked the robust evidence and rigor of a properly constructed scientific research project. This study utilized a long-term trial site located at Forthside Research Station, NW Tasmania, that had over ten years of continuous winter-planting treatments (biofumigant – Caliente, Tetilla Rye, fallow control) initiated in 2006. This specific project measured key soil chemical, physical and biological responses to these on-going winter cover crop treatments from 2016 to 2020, which overall represents a cumulative period of 15 years of these continuous treatments. The site has 12 established large plot units (each approximately 80 x 36 metres) which accommodated the three winter-planting treatments replicated (blocked) a total of 4 times. The other key variable over the four seasons included the spring-summer crop being planted which began with broccoli in 2016, followed by potato, carrot and finally bean in 2019. Within these commercial crops key productivity and economic analysis were conducted. Investigation of key soil biological, physical and chemical parameters were assessed periodically throughout the duration of the whole trial period.

The biggest impacts of cover crop treatments on soil chemistry was shown in the soil C (organic matter) levels which tended to be approximately 0.2-0.4%C (0.4-0.8% OM) higher in both the cover crop treatments (Caliente, ryegrass) compared with the fallow treatment. Other key chemistry measures were generally more reflective of overall site characteristics with a lower soil pH recorded on the Southern side (blocks 1 and 2) compared with the Northern side (blocks 3 and 4). Physical soil characteristics were predominantly measured through aggregate stability and penetration resistance measurements. Aggregate stability, using the wet sieving technique, showed that both cover crop treatments were enhancing proportions of aggregates in the larger more stable category size (>2mm) compared to the fallow treatment, indicating a benefit in stabilising soil structure. Penetration resistance measurements to a depth of 400mm showed no specific cover crop treatment impacts but rather a response to commercial crop site management practices.

Biological responses were a key focus of the measurements taken during this project, specifically through tracking broader soil communities and more specific pathogens of interest. The composition of the soil biological communities were most closely correlated with soil characteristics, especially soil pH, resulting in a clear difference among samples from the north versus the south side of the site. The communities varied year to year, this may have been due to seasonal differences, effects of the preceding crop and changes in the soil characteristics. Overall these changes were subtle and in general consisted of different proportions of organisms rather than the presence or absence of particular species in different years. The biggest effect of treatments on the soil is cultivation of the soil: samples from an undisturbed soil (under the fence line) were significantly different to all other samples within the site. Considering the effect of the within-site differences, the biological communities were different among the fallow, ryegrass and biofumigant cover crops. More pronounced differences in the biological communities may be observed in samples taken immediately after incorporation of the cover crops. The biological communities at this site are

diverse and seem resilient to changes in environmental conditions. This means that the ecosystem services provided by these communities are also likely to be resilient to fluctuations in conditions throughout the year.

Key soil pathogens of interest to the potato and vegetable industry were also measured on an annual basis with patterns reflective of both the commercial cropping rotation and the cover crop treatment. Some pathogens, specifically *Rhizoctonia solani* AG2.1 and *Plasmodiophora brassicae* were increased significantly under the Caliente cover crop treatment while most other soilborne pathogens remained at comparable levels across the fallow, ryegrass and caliente treatments.

Weed species assessments throughout the duration of the trial identified that the fallow treatment had a lower proportion of weeds and associated weed seed bank. The most dominant weed across the site was chickweed, which was able to establish and maintain significantly higher levels within the Caliente plots > ryegrass plots > fallow plots.

The impact of both cover crop treatments on the yield, quality and financial profitability of the commercial crop produced variable results. In the brocolli crop, while there was no significant difference between in field yields across all treatments the overall packout quality was reduced in the Caliente treatment, due to the impact of *P. brassicae* and club root disease, which is hosted by the brassica biofumigant. This needs to be considered in context, as a normal rotation would not include multiple brassica biofumigant plantings followed by a brassica crop. All other commercial crops grown produced generally low disease, a result of low pathogen levels across the site. In the potato and carrot yields there were no significant different across all treatments with the fallow, ryegrass and Caliente units yielding 75, 72.8 and 76.5 tonnes/ha for potato and 128, 132 and 133 tonnes/ha for carrot, respectively. For the bean crop harvested in 2020 the ryegrass treatment yielded the greatest at 7.28 tonne/ha, although this was not significantly different to the fallow and Caliente treatments that produced 6.65, and 6.68 tonnes/ha, respectively. Although yields tended to be slightly greater under cover crop treatments, the additional costs associated with growing and managing cover crops lead to generally negligible differences between the cost-benefit scenarios when comparing cover crop treatments with fallow.

The key results from this long term trial on a highly productive soil indicates that the cover crops tested, Caliente and ryegrass, provide multiple benefits to soil properties and that on some occasions this can be associated with slight but generally minor increases in yield, compared to the fallow treatment. The costs associated with managing cover crops are greater than that of a fallow and may represent a minor impediment to greater grower adoption. However, key measured benefits of greater carbon in the soil and improved structural stability seen under the cover crop treatments, for which the financial benefit can't be measured, represent key outcomes that are building blocks of long term sustainable production systems.

Background and significance

Declining soil health resulting in reduced agricultural productivity is an increasing problem in most intensive agricultural systems worldwide. The pressure to increase yields by mechanization and intensification has caused widespread decline in the resilience, condition and fertility of agricultural soils. This is true in the Australian vegetable industry, which is committed to maintaining intensified systems of production. However, many current practices of intensive vegetable systems are environmentally and/or socially unsustainable due to erosion, pollution and consumption of resources. Many of these problems are symptomatic of poor soil health (Pankhurst et al., 1997). Therefore, a significant challenge for Australian, and more specifically Tasmanian vegetable production is to continue to improve yields while improving and maintaining soil health.

Cover crops are likely to be an important aspect of this change and have been shown to improve soil health by improving structure, controlling soilborne disease and weeds, reducing erosion risk, and improving nutrient status (Larkin, 2015, Murphy, 2015). Much of the soil fertility's is facilitated by its biological ecosystem, and most of the benefits of cover cropping are due to the input of organic matter from the cover crop boosting of the soil's biological activity.

Biofumigation refers to the use of specialised cover crops which are grown, mulched and incorporated into the soil prior to the planting of the next commercial crop. Critical to their effectiveness is the production of a high biomass which is incorporated into the soil. Additionally they produce high levels of the key chemicals, the glucosinolates (GSLs) which upon maceration and incorporation into the soil release isocyanates (ITCs) which are highly toxic to many soil-borne pests, diseases and weed seedlings (Kirkegaard and Sarwar, 1998). Timing of biofumigant incorporation is critical in maximizing beneficial effects.

However control of soil pathogens by biofumigants varies with cultivar, soil type and climate and may be ineffective in cooler climates such as Northern Tasmania (Hanschen et al., 2015, Johansen et al., 2016). The degree of disease suppression from biofumigation relative to suppression due to the effect of the biofumigant's organic matter boosting the microbial community is also unknown (Larkin, 2015). Indeed, non-biofumigant cover crops regularly show soilborne disease suppression (Larkin, 2015, Sparrow, 2015).

Much remains to be learned about varieties, agronomy, and integration of cover crops into vegetable cropping systems to have the maximum impacts on weeds and soilborne diseases, while maintaining or increasing farm income. In particular, detailed knowledge of the effects of cover crops on soil microbiology and its subsequent impacts on the farm system are largely unknown, and long term trials are particularly lacking (Mbuthia et al., 2015). New research is required to answer these questions under Tasmanian conditions, and the long term nature of the cover cropping trial at Forthside makes this study of particular value.

Biofumigant cover crops have been grown in greater quantities during recent years due to the fact that they may provide growers with opportunities to enhance subsequent crop productivity and improve soil health. However, within Tasmania, anecdotal and reported results on biofumigant crop use have lacked the robust evidence and rigor of a properly constructed scientific research project. <u>This project aims to provide scientific evidence that quantifies the biological and economic benefits to support the correct usage of cover crops within Tasmania.</u>

Materials and Methods

Trial Site and key treatments

This study utilized a long-term trial site on a ferrosol soil located at Forthside Research Station, NW Tasmania, that had over ten years of continuous winter-planting treatments (biofumigant – Caliente, Tetilla Rye, fallow control) initiated in 2006. This specific project measured key soil chemical, physical and biological responses to these on-going winter cover crop treatments from 2016 to 2020, which overall represents a cumulative period of 15 years of these continuous treatments. The site has 12 established large plot units (each approximately 80 x 36 metres) which accommodated the three winter-planting treatments replicated (blocked) a total of 4 times. The other key variable over the four seasons included the spring-summer crop being planted which began with broccoli in 2016, followed by potato, carrot and finally bean in 2019. Within these commercial crops key productivity and economic analysis were conducted. Figure 1 shows a pictorial timeline of the trial and key crops grown with key planting dates provided in Table 1. Investigation of key soil biological, physical and chemical parameters were assessed periodically throughout the duration of the whole trial period.

For treatment evaluation the 12 large plot units was broken into a further 4 sub-units providing a total of 48 individual small plot units. From these individual units, which were geo-referenced, specific soil sampling, crop monitoring and assessments were taken as described below.

Table 1. Timeline of key planting dates and activities over trial duration.

Activity	2016/17	2017/18	2018/19	2019/20
Cover crop planting	16-20 Jun 2016	Jun 2 2017	May 16 2018	Jun 20 2019
Cover crop incorporation	22 Nov 2016	30 Oct 2017	10 Oct 2018	12 Oct 2019
Commercial crop grown	broccoli	potato	carrot	beans
Commercial crop planting date	27 Jan 2017 (transplant)	11 Nov 2017	27 Nov 2018	14-23 Nov 2019
Commercial crop harvest date	10 - 27 Apr 2017	4 Apr 2018	10-25 May 2019	26 Jan-4Feb 2020

Crop planting and management

Paddock and site preparation for both the autumn/winter cover crop and spring/summer commercial crop followed standard industry practice for ground preparation, weed control, fertilizer application, crop planting and irrigation scheduling. Management of the commercial crop was through qualified agricultural consultants and the whole paddock was managed as a single unit, meaning that costs were fixed across the whole paddock. Management of the Caliente and ryegrass cover crops and fallow treatments were guided by industry stakeholders. Fallow management, including herbicide usage and cultivation, was based on best practice principles. Cover crop planting treatments, their management and termination were based on commercial crop schedules and environmental conditions at the time of incorporation. For example, where biofumigant incorporation was conducted under ideal conditions (no rainfall, ideal soil moisture) rolling was utilised to seal the soil surface. Where conditions were sub-optimal (high soil moistures) irrigation and/or rainfall was used to seal the soil surface after incorporation. Costs in managing the autumn/winter cover crop treatments and the associated fallow treatment varied and were taken into account when undertaking economic analysis.

Soil sampling

Soil sampling occurred annually just prior to planting of the cover crop treatments (March – May). The sampling process involved collecting 30-40 soil cores of 0-15 cm depth from each of the 48 individual sub-unit plots. Collection in each individual plot followed a standard W-pattern with the 30-40 cores pooled and thoroughly mixed (approximately 1kg soil). For soil biology measurements sub-samples (community analysis -50g – stored at -20°C, and pathogen detection – 500g – dried at 40°C) were taken from all 48 plots and analysed separately. For soil chemistry, subsamples (200g) were taken from the 4 sub-unit treatments and pooled (800g) to have 12 individual large plot samples for analysis.

Soil chemistry properties

The twelve soil samples collected annually from each large plot unit were dried at 40°C, sieved to < 2mm and sent to AgVita (Devonport, Tasmania) for soil chemistry analysis. Full chemistry (Code ES22, AgVita Analytical) analysis was undertaken.

Soil physical properties

Aggregate stability

Aggregate stability was measured twice yearly, in the winter months just prior to cover crop incorporation and in the summer/autumn months just prior to commercial crop harvest. Samples were collected from plots manually using a shovel to a depth of 15cm (~1kg sample size) and placed into storage containers for air-drying prior to wet sieving analysis. Wet sieving analysis was conducted using techniques previously described (Almajmaie et al. 2017). Briefly, aggregate stability was determined on the 2.00–5.00 mm aggregate fraction for each of the samples. Approximately 50 g of aggregates were slowly immersed in distilled water and mechanically raised and lowered for fifteen minutes (oscillation speed was 15 cycles per minute) on top of a 2mm sieve with a 250 µm sieve below. Aggregate stability was determined as the proportion of aggregates retained in each respective sieve, broken into the three categories: <250 µm, <2 mm, <5mm, with each sample tested in duplicate.

Penetration resistance

Penetration resistance was measured twice yearly, in the winter/spring months just prior to cover crop incorporation (Oct 20 2016, Oct 18 2017, Oct 25 2018, Aug 29 2019, Jun 10 2020) and in the summer/autumn months just prior to commercial crop harvest (28 Apr 2017, Mar 7 2019, 22 Jan 2020). Measurements were always taken at a consistent time period either a few days after rainfall/irrigation when soils were at or near field capacity. Penetration measurements (Rimik Agricultural Electronics CP20 Cone Penetrometer) were conducted at 25mm intervals to a depth of 400mm, with a minimum of 10 individual measurements per 48 individual small plot units (480 assessments in total).

Soil Biology measurements – soil communities and pathogens

Amplicon sequencing of biological communities

High throughput amplicon sequencing has become a popular way to explore the diversity of organisms, particularly microorganisms in environmental samples such as soil. This method generates fragments of sequences of particular genes that are considered taxonomic markers. The sequence data is processed to remove poor quality and spurious sequences, identical sequences are grouped together and then classified against reference databases. Amplicon data processed in this way produces 'amplicon sequence variants' (ASV) which can be considered somewhat analogous to species although this is not a method that is able to accurately identify organisms to species level.

Sampling, DNA extraction and sequencing

The biological communities present in the soil were examined using high throughput amplicon sequencing of the 16S rRNA (bacteria), 18S rRNA (eukaryote) and ITS (fungi) genes. The protocol was similar to that used in the Biomes of Australian Soil Ecosystems project (Bissett et al. 2016). Soil was collected each year approximately two weeks prior to the planting of the biofumigant crop (generally late May). Briefly, 30 – 40 cores taken from the top 15 cm of the soil were combined and homogenised. Soils were frozen as soon as possible (within 72h) and stored at – 20 until DNA extraction. DNA was extracted from approximately 0.5g of soil using the DNEasy PowerSoil kit (Qiagen) with bead-beating performed in a tissuelyser (Qiagen). Amplicon sequencing from the genomic DNA preparations was carried out using the Illumina MiSeq system by the Ramaciotti Centre for Genomics (University of New South Wales). The regions sequenced were 16S rRNA V1-3 region using primers 27F/519R for bacteria, the 18S rRNA V9 region using primers 1391F / EukBr for eukaryotes and the fungal ITS2 region using primers fITS7-ITS4.

Data processing and analysis

Raw data was downloaded and processed using the DADA2 pipeline (Callahan et al. 2016) in R following the standard protocol. The 16S rRNA and 18S rRNA sequences were classified using the most recent SILVA databases and the ITS sequences were classified against the most recent available UNITE database all accessed through benjjneb.github.io/dada2.

Sequences were subject to further quality trimming with any sequences that appear less than 50 times in all samples or in one or two samples only were removed from the dataset. Multivariate exploration of the data was carried out using Primer6 (PrimerE, Plymouth). All three data sets were subject to a log (x+1) transformation, followed by a Bray-Curtis dissimilarity. The similarity between biological communities in each sample were plotted on a non-metric multidimensional scaling plots in which samples that are more similar to each other are closer to each other. The strength and significance of the difference between groups was tested with the ANOSIM test. The R value provides an indication of the strength of the separation between groups with a maximum value of 1.

Pathogen quantification using PreDicta

Soil samples (500g) that had been collected and dried at 40°C were sent to SA for commercial pathogen detection using the PreDicta testing technology. Essentially, DNA was extracted from soil material using established protocols of the commercial Root Testing Service of the South Australian Research Development Institute, Adelaide, South Australia, Australia (Ophel-Keller et al. 2008). Specific pathogens detected included those available for potato and vegetable crops.

Weed assessment

Weed assessment was measured approximately 10 times across the duration of the trial, with the key sampling dates being in the cover crop treatments just prior to cover crop incorporation and in the summer/autumn months just prior to commercial crop harvest. Sampling methodology within the cover crop period involved placing a $1m^2$ quadrat randomly into the plots and measuring type and numbers of weed species present. For assessment within the commercial crop a set length of randomly selected row and width of crop was assessed (e.g. 2m of a single row of potatoes). A minimum of twelve sub-plots were assessed per individual treatment.

Biofumigant crop growth and glucosinolate production

Just prior to cover crop incorporation $1m^2$ plots were harvested to ground level from all treatment plots, samples were weighed immediately for shoot fresh weights, oven dried and re-weighed for shoot dry weights. A minimum of 12 sub-plots per treatment were assessed. At the same time 6 randomly selected Caliente plants from each of the four main plots were collected. Each of the four samples was immediately oven dried at 70°C, ground to 2mm and posted to Gatton Research Facility, Queensland Department of Agriculture and Fisheries, for glucosinolate analysis.

Commercial crop yield and disease measurement

The commercial crops grown for the four years were managed and grown by lease agreement with a range of companies (Harvest Moon, Premium Fresh, Simplot). Key growth, yield and disease parameters were assessed both throughout the growing season and at harvest. In 2016/17 broccoli was assessed at six weeks post-transplant for shoot dry matter and club root disease, and at harvest for root, shoot and head DM, and club root disease. Club root assessment involved assessment of five roots from separate plants from each of the sub-plots 1, 2, 3 and 4 from all 12 large plots, a total of 240 plants in total. Yield parameters were taken from 3 randomly selected plants per each single 48 sub-plots, a total of 144 plants in total. In 2017/18 the potato crop was assessed at twelve weeks after planting for root gall infection, and at harvest for tuber yield and disease parameters. Root gall infection involved assessing ten plants per individual large plot unit for presence/absence of root galls. At harvest 20 plants from each of the 48 individual plots were hand dug, total weights and graded weights (into commercial categories with tubers <40 g excluded from marketable yield) per plot calculated and 100 tubers randomly selected per plot and assessed for visual tuber disease. In 2018/19 carrot was assessed at maturity for yield and disease. All 48 of the individual plots were assessed by digging 6 rows from a 1m length of bed (approximately 130-150 carrots per plot), removing carrot tops, washing the carrots in water, grading into the relevant size and quality groups (see grading categories below in Economic analysis), counting numbers and weights per group. One hundred carrots were then assessed for visual disease with 20 representative carrots (those including disease and symptomless ones) photographed and peeled for DNA pathogen analysis by

SARDI. In 2019/20 the bean crop was assessed at maturity for yield and disease. All 48 of the individual plots were assessed by harvesting the plants from a $1m^2$ quadrat (28 plants). Both the percentage of plants and percentage of pods infected with *Sclerotinia* were counted. Numbers of marketable pods and total weight of pods were measured from which yield was assessed.

Economic analysis

Economic analysis of the commercial crop outcomes was undertaken on the basis that all costs incurred within the commercial crop are constant and fixed across the site and treatments, so were not accounted for. The variation to cost basis was through the variable costs associated with managing the cover crops and fallow treatments. Essentially differences in input costs varied between treatments based on seed costs, ground preparation, herbicide treatments and incorporation procedures.

The value of each crop was measured by obtaining the factory price specifications for the given crops. Please note that a price and specific pack out value was not available for broccoli. In 2017/18 for potato a value of $350/tonne was provided for the potato crop. In 2018/19 the price specifications for the carrot crop were, Oversize: Length >250mm and/or diameter >40mm - $0.06/kg, Premium: Length 150-250mm and diameter 25-40mm - $0.1745/kg, Baby: Length 80-150mm and diameter 15-28mm- $0.1745/kg, Thin: Length >150mm and diameter <25mm - $0.01/kg, Mishapen: those with visual deformities including twisted, forked, root protrusions and stumping - $0.00/kg. In 2019/20 a price of $0.75-0.95/kg was provided for marketable bean pods. These prices were used to compare the economic outcomes of the control fallow treatment with the alternate cover crop treatments, ryegrass, or Caliente.

Statistical analysis

Data were tested to ensure normality and log transformed where non-normal and then assessed using one-way or two-way analysis of variance (ANOVA) to determine the statistical significance of variation between treatment means and their interactions. Where significant differences (P<0.05) were found the least significant difference (LSD) was determined using GENSTAT v. 14.2 (VSN International Ltd., Hemel Hempstead, UK). For penetrometer readings a mixed model was fitted assuming a randomised block design consisting of 4 replicates and 3 treatments (crops), with the analyses using proc mixed in SAS v 9.4.

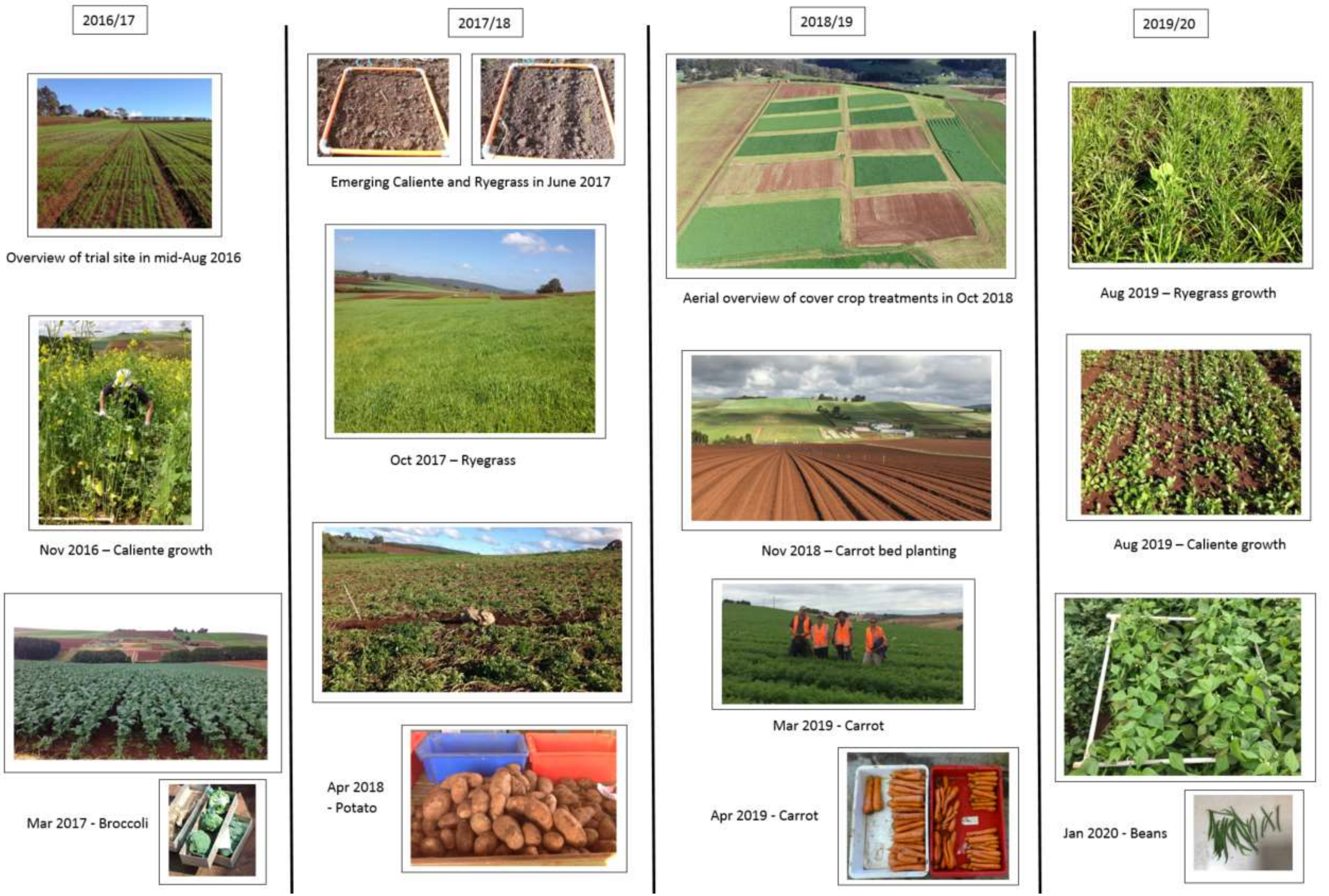

Figure 1. Pictorial overview of rotation from 2016-2020.

Results and Discussion

Soil chemistry properties

Key chemistry properties, specifically the major nutrients, NPK, pH and eC were generally consistent across the cover crop treatment types with no significant treatment differences recorded (Table 2). The pH varied between the southern and northern side of the trial site with the southern side approximately 0.4 units more acidic than the Northern side.

Table 2. Summary of key soil characteristics at trial initiation in 2016.

	Organic matter (%)	Total C (%)	Total N (%)	pH	K (mg/kg)	P (mg/kg)	S (mg/kg)	Fe (mg/kg)
Control (under fenceline)	8.2	5.36	0.38	6.23	614	12	23	62
Fallow	6.2	4.02	0.27	6.61	379	31	9	61
Biofumigant	6.95	4.52	0.32	6.55	374	35	10	63
Ryegrass	6.42	4.17	0.29	6.57	256	36	8	67

Soil C levels, and the related surrogate measure, organic matter content showed distinct treatment differences (Fig 2), with both Caliente and ryegrass treatments leading to an increase of 0.2-0.4%C (0.4-0.8% OM) compared with the fallow treatment across all 4 years the measurements were made. Additionally, measures of labile carbon made in 2019 were 669, 734 and 761 mg C/kg in the fallow, ryegrass and caliente treatments respectively supporting the trends seen in the other carbon measurements made. Increases in organic matter content are a key known positive response to biofumigant and cover cropping usage in general (Larkin, 2015, Murphy, 2015). Ferrosols, by their nature have relatively high C levels typically and increasing C levels significantly is difficult as they inherently tend to return to their equilibrium C levels. The positive impacts reported here are positive outcomes although the results would potentially be greater if the soil was a poorer quality one with less organic matter as a starting point (sandy loam etc.) or was severely degraded. In these cases, there is generally greater scope for improving soil C contents.

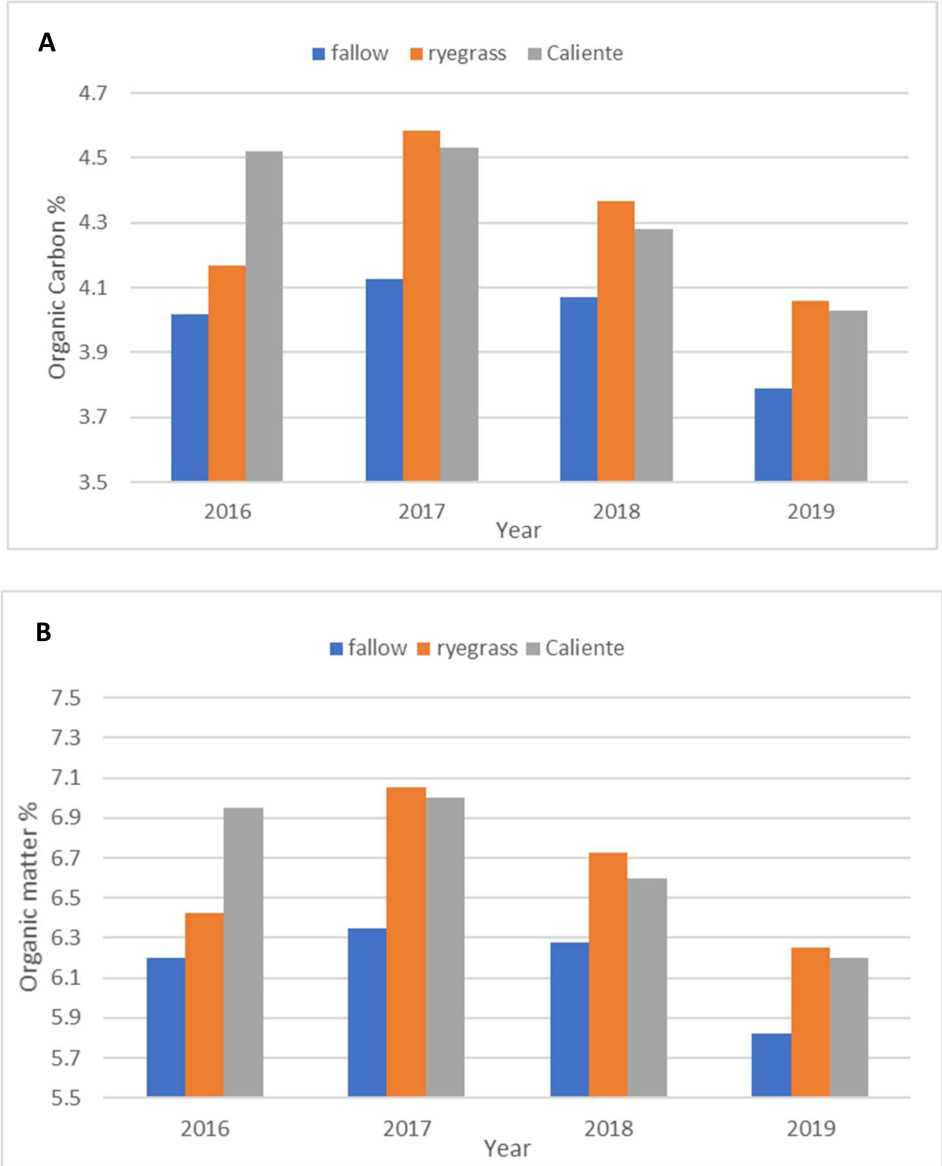

Figure 2. Impacts of winter treatments that included fallow, ryegrass and Caliente over the trial duration on A) organic carbon % and B) organic matter %.

Soil physical properties

Aggregate stability

The aggregate stabilities, using the wet sieving technique, were assessed eight times over the duration of this trial with the trends observed in assessments over four years in late October (just prior to cover crop incorporation – Fig 3) typical of the responses also seen when measurements were made within the commercial crop period (February – April - results not presented). Both ryegrass and Caliente increased proportions of aggregates in the larger more stable category size (specifically the >2mm fraction) compared to the fallow treatment, this impact was significant on 3 of the 4 annual samplings. Ryegrass tended to be slightly more effective than Caliente, although the results were not significantly different between these two cover crop treatments. Associated with this, the fallow treatment also showed a greater proportion of aggregates in the least stable category size, <0.25mm. The addition of organic matter through cover cropping is recognised as an important component of improving soil and associated physical structure (Larkin, 2015, Murphy, 2015) with the work presented here strongly supporting these positive outcomes.

Additionally, some annual variation was observed, and this is likely related to environmental, commercial crops grown and other associated cultural practices. The most significant response observed was between the 2018 and 2019 measurements, whereby there was a 50% decrease in the larger >2mm aggregate fraction. This was most likely attributed to a wet carrot harvest in May 2019 which may have partly destroyed soil structure. This highlights the importance of careful management in cropping activities as the impacts of machinery and harvesting operations on wetter soils can have significant negative impacts on soil physical properties (Keller et al. 2019).

Penetration resistance

The penetrometer resistance data over the duration of this experimental data showed that in 6 of the 7 assessment dates presented there was no significant differences between the treatments (fallow, ryegrass, caliente) over all the depths examined (Fig 4). The only significant difference recorded was in October 2017 (Fig 4E) (during the later stages of cover crop growth) where in the upper profile depth range 25-230mm the fallow treatment had significantly less resistance ($P < 0.05$) to penetration than both the Caliente and ryegrass treatments. Although not presented here, a similar but more significant trend was recorded on the 25th October 2018, although due to data variability and the sub-optimal drier conditions that the measurements were taken under, the data has been excluded, although partly supports the results of October 2017. The impact of soil moisture on penetrometer reading is well defined (Cotching and Belbin 2007) on ferrosols with larger impacts noted when the soils are assessed under drier conditions, hence the need to sample at consistent soil moisture levels.

Of considerable interest is the transition through the seasons and how crop type and cultural practices impact the penetration readings. The biggest change in penetration resistance patterns occurred between early 2020 (Fig 4F) and June 2020 (Fig 4G) during which time a subsoil ripping remediation event was required to remediate the soil from a wet carrot harvest in 2019. The change between these two graphs shows an alleviation of compaction impacts as the curve dramatically shifts to the left.

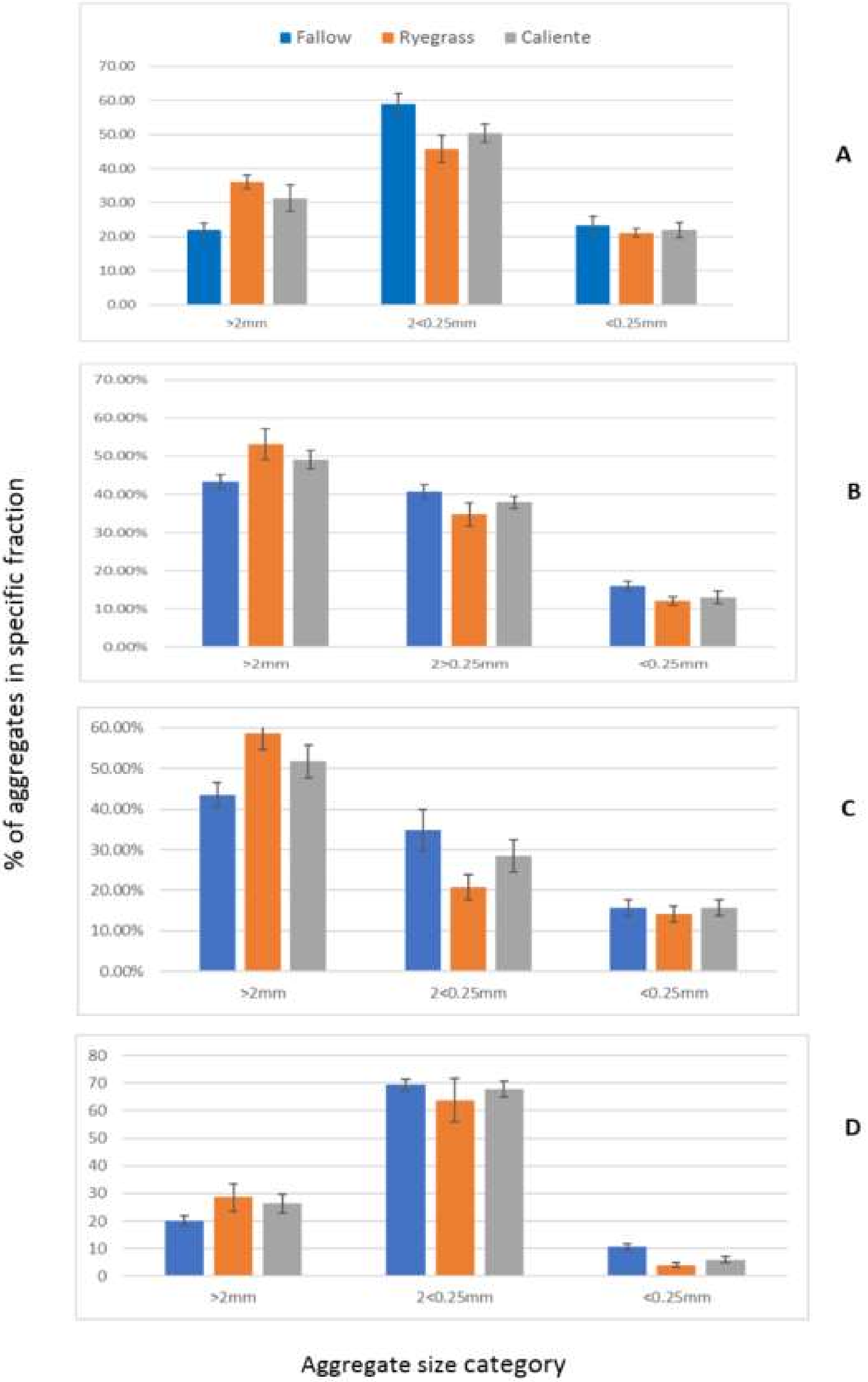

Figure 3. Aggregate stability fractions using the wet sieving technique taken just prior to cover crop incorporation in October-November over four consecutive seasons. Treatments are a winter fallow, ryegrass or Caliente crop with soil sampled at a depth of 0-15 cm on A) Oct 20 2016, B) Oct 18 2017, C) Oct 25 2018, and D) Oct 12 2019. Shown are means ± standard error.

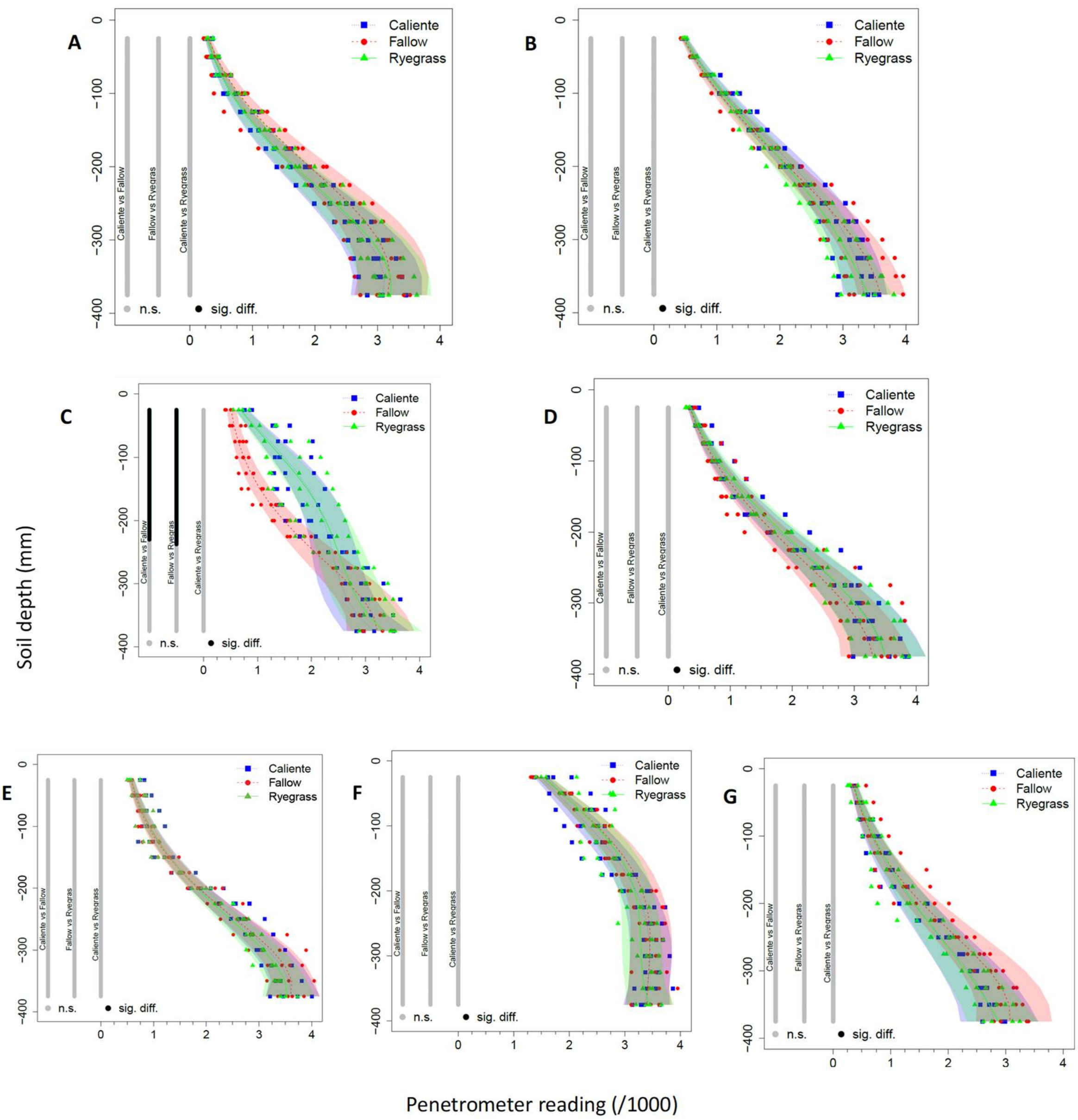

Figure 4. Penetration Resistance readings at 25mm intervals taken at soil depths from 0 to 400 mm at various sample dates A) Oct 20 2016, B) Apr 28 2017, C) Oct 18 2017, D) Mar 7 2019, E) Aug 29 2019, F) 22 Jan 2020, and G) Jun 10 2020. Shown are the fitted mean trends by treatment versus depth. Also shown are 95% CIs for the mean. On the left significances of differences are indicated.

Soil Biology measurements – soil communities and pathogens

Amplicon sequencing of biological communities

Biological community diversity

The biological communities were very diverse with several thousand Amplicon Sequence Variants (ASV) detected in all samples. These could be classified into 28 phyla (over 200 genera) of bacteria, 34 of eukaryotes and 15 phyla of fungi. The main groups observed in the soil are presented in Figure 5. At the phylum level these are all typical soil groups. The Proteobacteria in the bacterial communities contain mainly Alphaproteobacteria and Gammaproteobacteria which are generally metabolically versatile heterotrophic bacteria. The Bacteroidetes are often anaerobic or facultatively anaerobic organisms. The Gemmatimonadetes are ubiquitous in soil environments but little is known about them as they have only recently been identified and have been difficult to study. The other large bacterial group are the Actinobacteria which includes organisms responsible for the production of geosimin or the “wet earth” smell. Many of the fungal sequences detected could not be classified with any degree of certainty. This reflects limitations of the current databases available for fungi for the ITS gene. The main phyla detected are the Ascomycota and Basidiomycota the two largest groups of fungi. The Glomeromycota, important because they associated with plants as arbuscular mycorrhizal fungi, are also present as a significant proportion of the community. The eukaryotes groups that were detected are also very diverse and include terrestrial algae, a range of protozoa and amoeba as well as slime moulds, arthropods, platyhelminthes and nematodes.

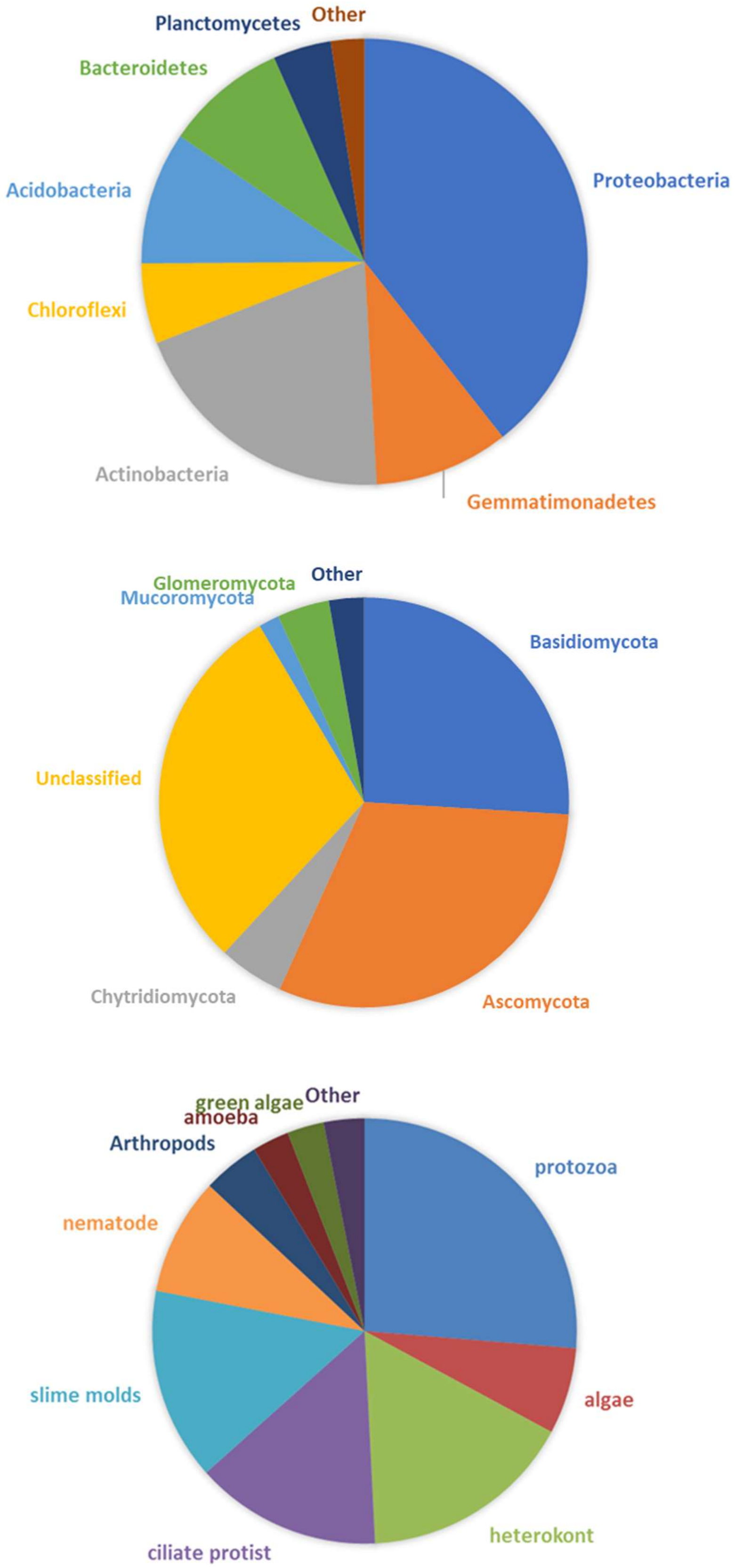

Figure 5. Average percentage composition of the main groups (phyla) of the bacterial (A), fungal (B) and eukaryote (C) communities at the Forthside site.

Effect of cultivation and soil characteristics

In the 2016 sample collection, a set of soil samples were collected from under the fence line to act as a 'long-term pasture' control. In all three communities analysed, these samples contained distinctly different communities compared to the communities in any of the samples from the paddock (see Figures 6a, b, c). The ANOSIM test produced a significant result ($p < 0.05$).

A summary of the soil analysis tests from this time also shows some differences in these samples when compared to those from the blocks that were either fallow or had cover crops of ryegrass or biofumigant mix (Table 2). It is likely that those differences, particularly organic matter, pH, nitrogen and phosphorus, have influenced the organisms that are living in the soil.

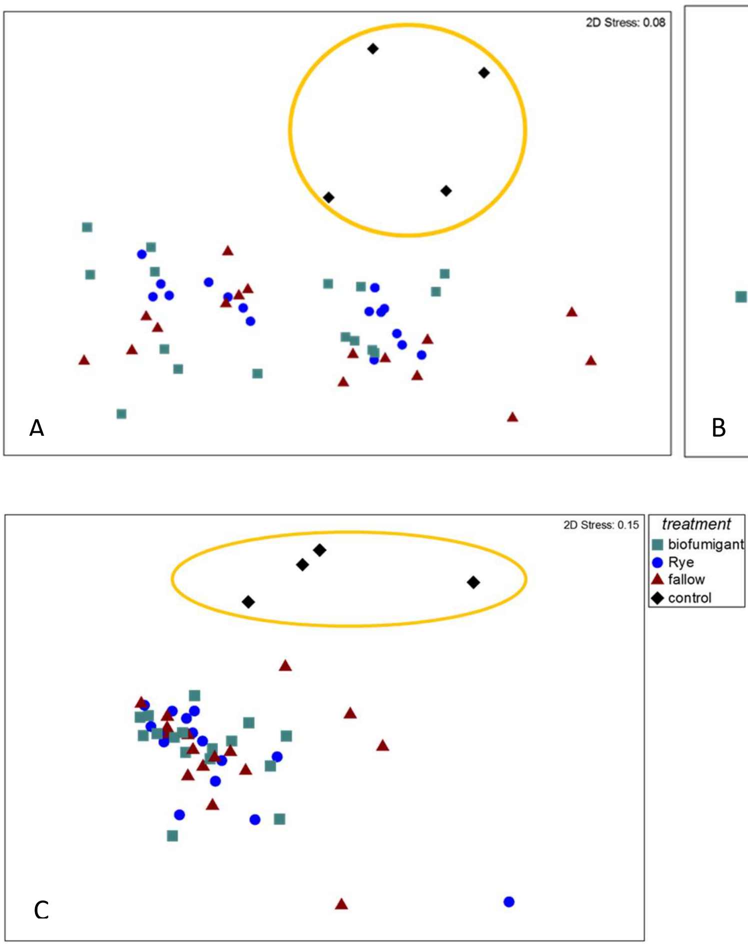

Figure 6. Plots showing the similarity in the composition of the bacterial (A), fungal(B) and eukaryote (C) communities found in the control samples of long-term pasture (circled) compared to the samples from cultivated sites.

Further investigation of the soil communities and their relationship to the soil characteristics showed a strong effect of within site location. Communities from the north or south of the site clustered together more strongly than samples from fallow, ryegrass or biofumigant plots (for example see Fig 7). This effect can be observed in all years in the bacterial, eukaryote and fungal communities although it seems more pronounced in the fungal communities but was less noticeable in 2019. A multivariate correlation with soil characteristics suggests that a combination of pH and total N are the factors most strongly correlated to the biological community structures although there are other factors, such as the preceding crop that will also be influencing the soil biological communities.

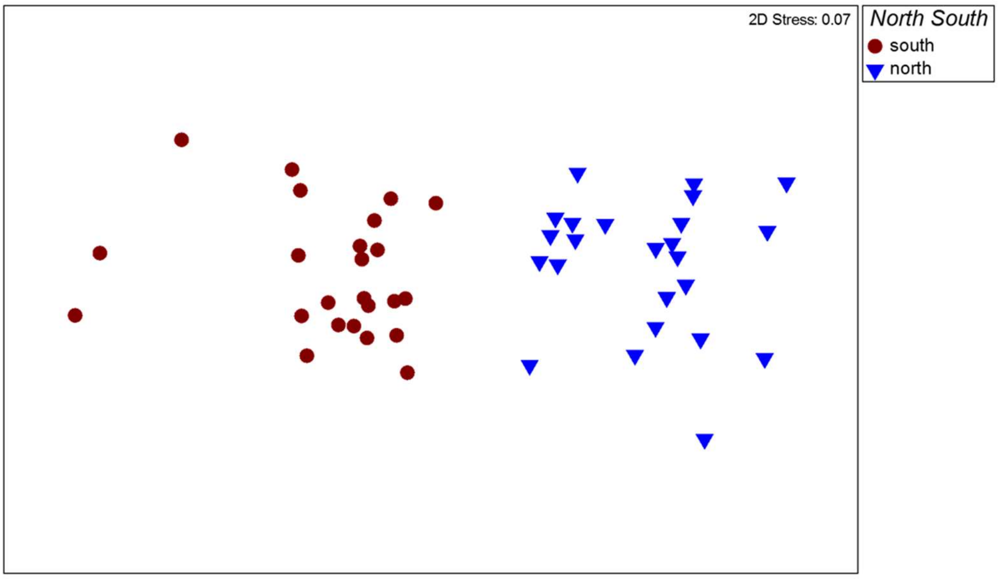

Figure 7. Similarity of bacterial communities in the three treatments in 2016 showing the difference between communities from the south (brown) and north (blue) sides of the site. ANOSIM R value = 0.926 ($p < 0.001$).

Effect of cover crop on soil biological communities

To examine the long-term effect of the two cover crops compared to the fallow, communities from all three treatments in three years were plotted on the same figure. The data for the fungal communities is presented in Figure 8 but the same trend was observed also for the bacterial and eukaryote communities. This shows that for all three community types (bacterial, eukaryote and fungal) the most obvious effect is the year in which the samples were collected, followed by the north/south paddock effect and then within these groups, the cover crop treatment.

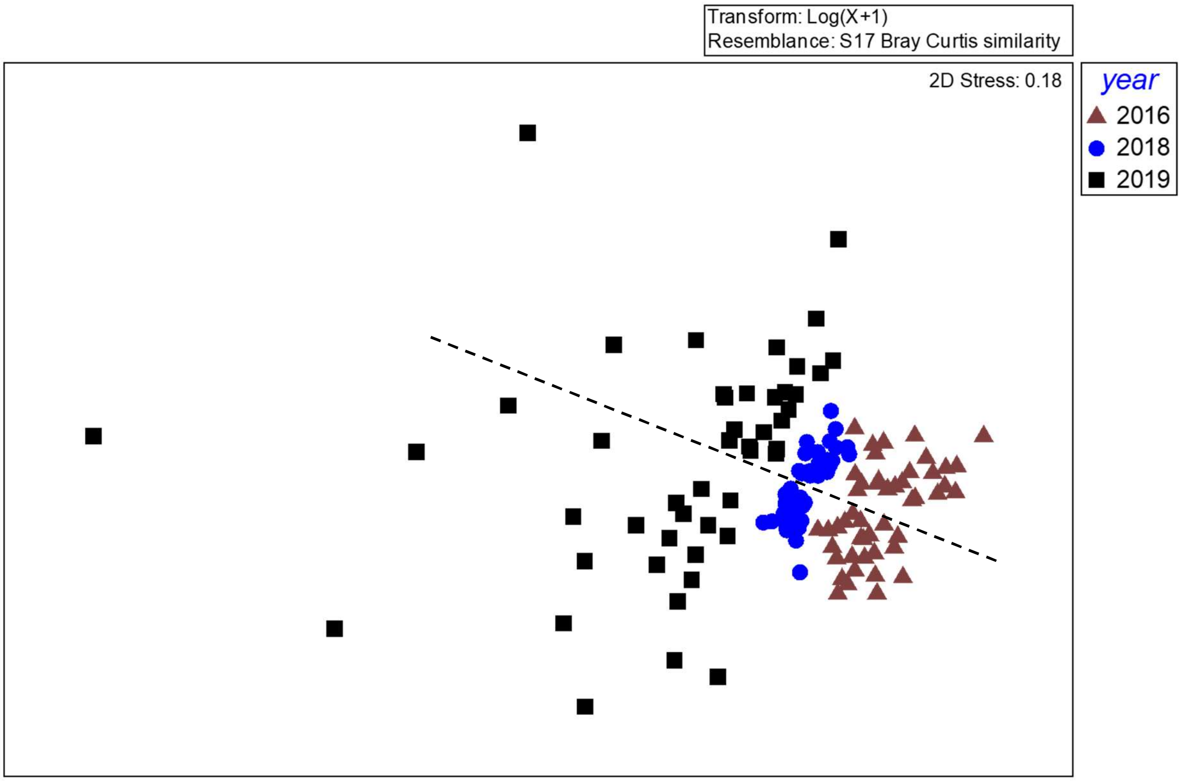

Figure 8. The similarity of fungal communities in soil samples from all three treatments (fallow, ryegrass and biofumigant) collected in 2016, 2018 and 2019. The years are significantly ($p < 0.01$) different to each other with ANOSIM R values of 0.40 – 0.67. The dashed line indicates the north-south divide.

Each year, for each type of biological community, there were differences between the communities observed in the fallow, ryegrass and biofumigant plots (Figs 9 – 11). These differences were significant (p <0.05) although small as measured by the ANOSIM test. In this test the R-value has a maximum value of 1 which indicates that the groups cluster completely separately. In Table 3, the differences between the treatment groups is less than 0.5 in nearly all cases.

Table 3. Global ANOSIM tests (R) for differences between treatment groups within each year. R is a measure of the dissimilarity of groups with a maximum value of 1.

	Bacteria	Fungi	Eukaryotes
2016	0.337 (p=0.001)	0.495 (p=0.001)	0.444 (p=0.001)
2018		0.518 (p=0.001)	0.787 (p=0.001)
2019	0.144 (p=0.001)	0.242 (P=0.001)	0.126 (p=0.002)

In the bacterial communities (see Fig 12), differences between the treatments are not clear at higher taxonomic levels such as the class level. The trends seen in Figure 9 are due to changes in the proportions of different bacterial genera and species (ASV). This suggests that the functioning of these communities will be similar throughout the site regardless of the cover crop planted. Bacterial communities are very dynamic and respond quickly to changes in their environment. It may be that the effect of the cover crops is greater in the days or weeks immediately after incorporation. The similarity between the communities later in the year, when these annual samples were collected, suggests a degree of resilience in the system. The same is true of the fungal and eukaryote communities. In Figure 13 for example, differences in the proportions of the fungal phyla present can be observed amongst the years but not among the treatments within each year. The differences between treatments is again due to changes in the proportions of different genera and species.

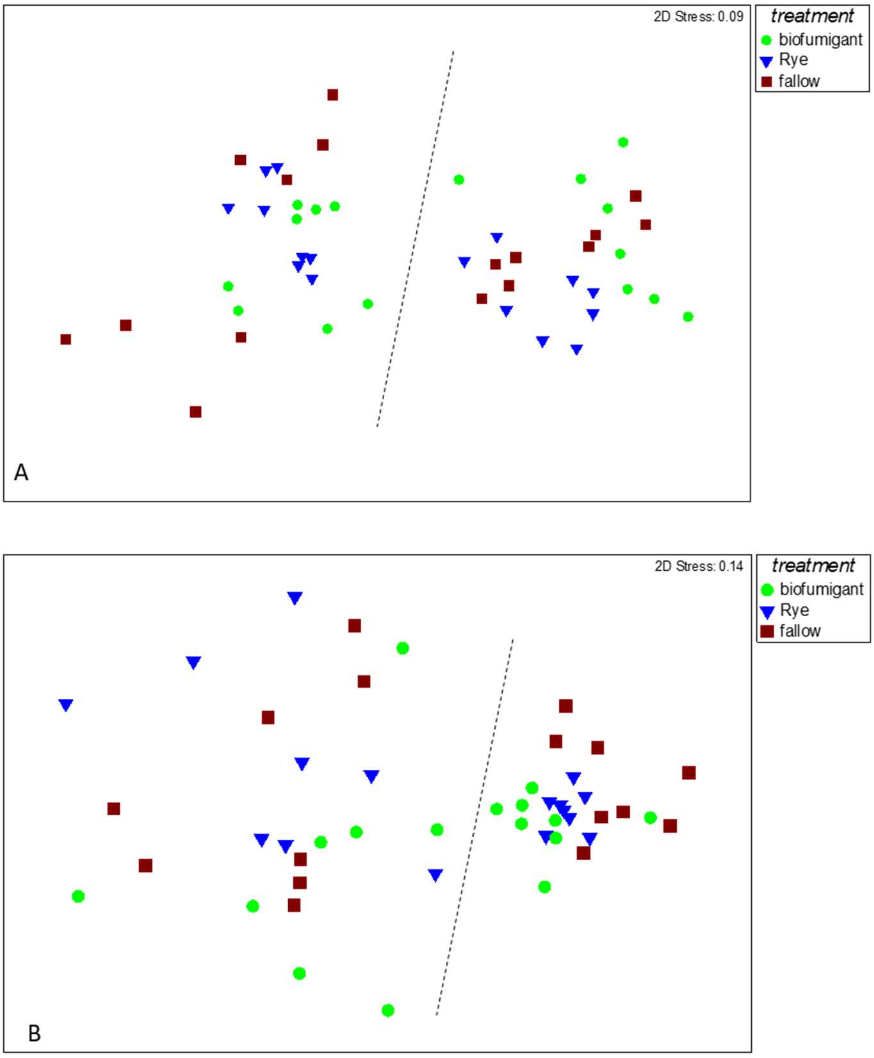

Figure 9. Similarity of bacterial communities in the three treatments (green = biofumigant, blue = ryegrass, brown = fallow) in 2016 (A) and 2019 (B). In these plots the dashed line indicates the north – south separation

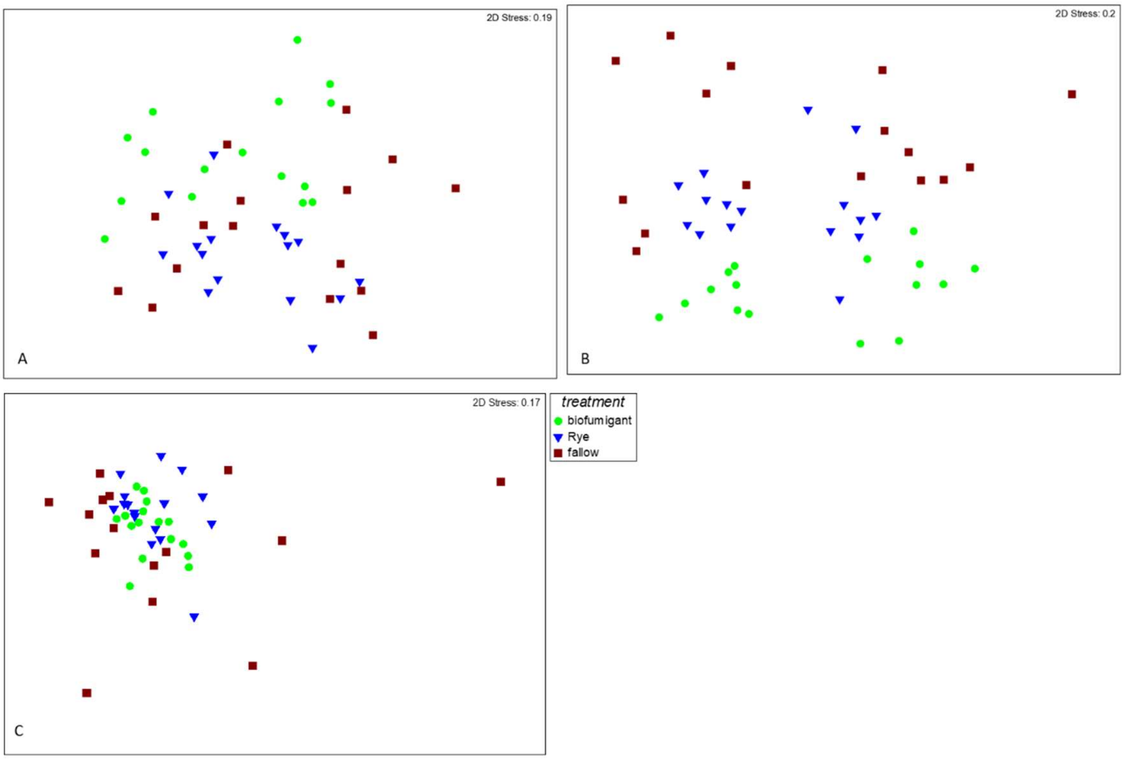

Figure 10. Similarity of fungal communities in the three treatments (green = biofumigant, blue = ryegrass, brown = fallow) in 2016 (A), 2018 (B) and 2019 (C).

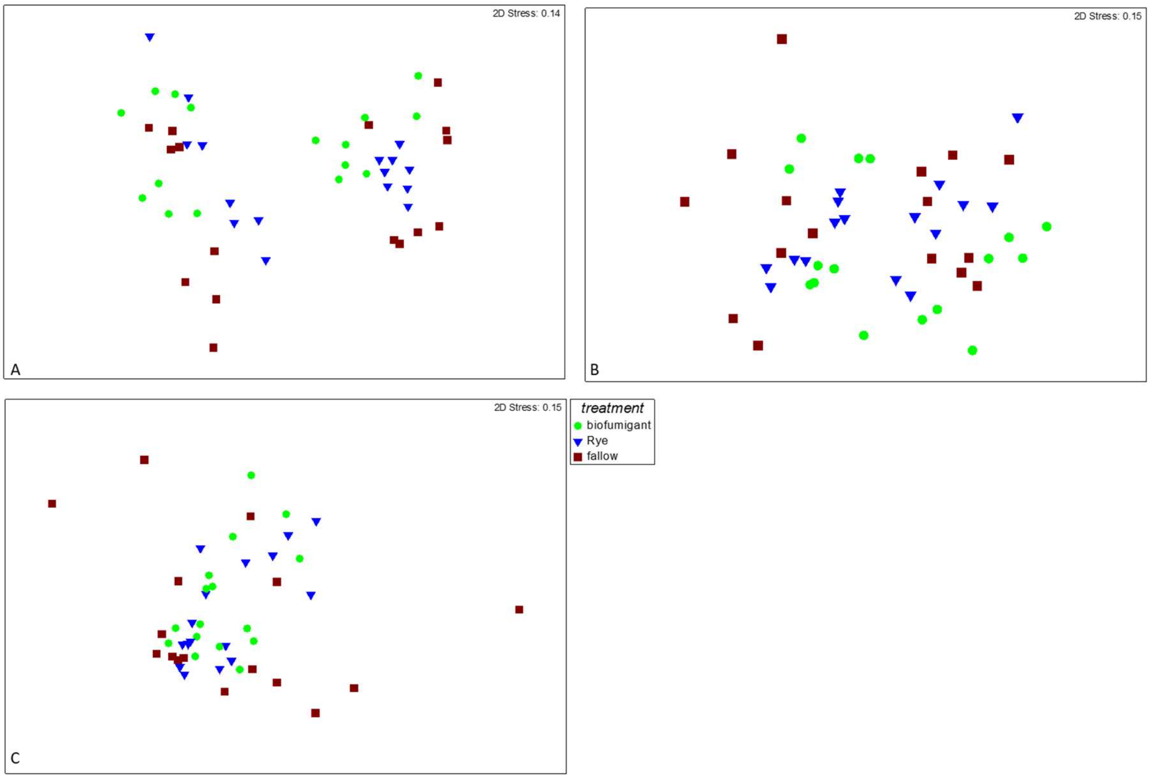

Figure 11. Similarity of eukaryote communities in the three treatments (green = biofumigant, blue = ryegrass, brown = fallow) in 2016 (A), 2018 (B) and 2019 (C).

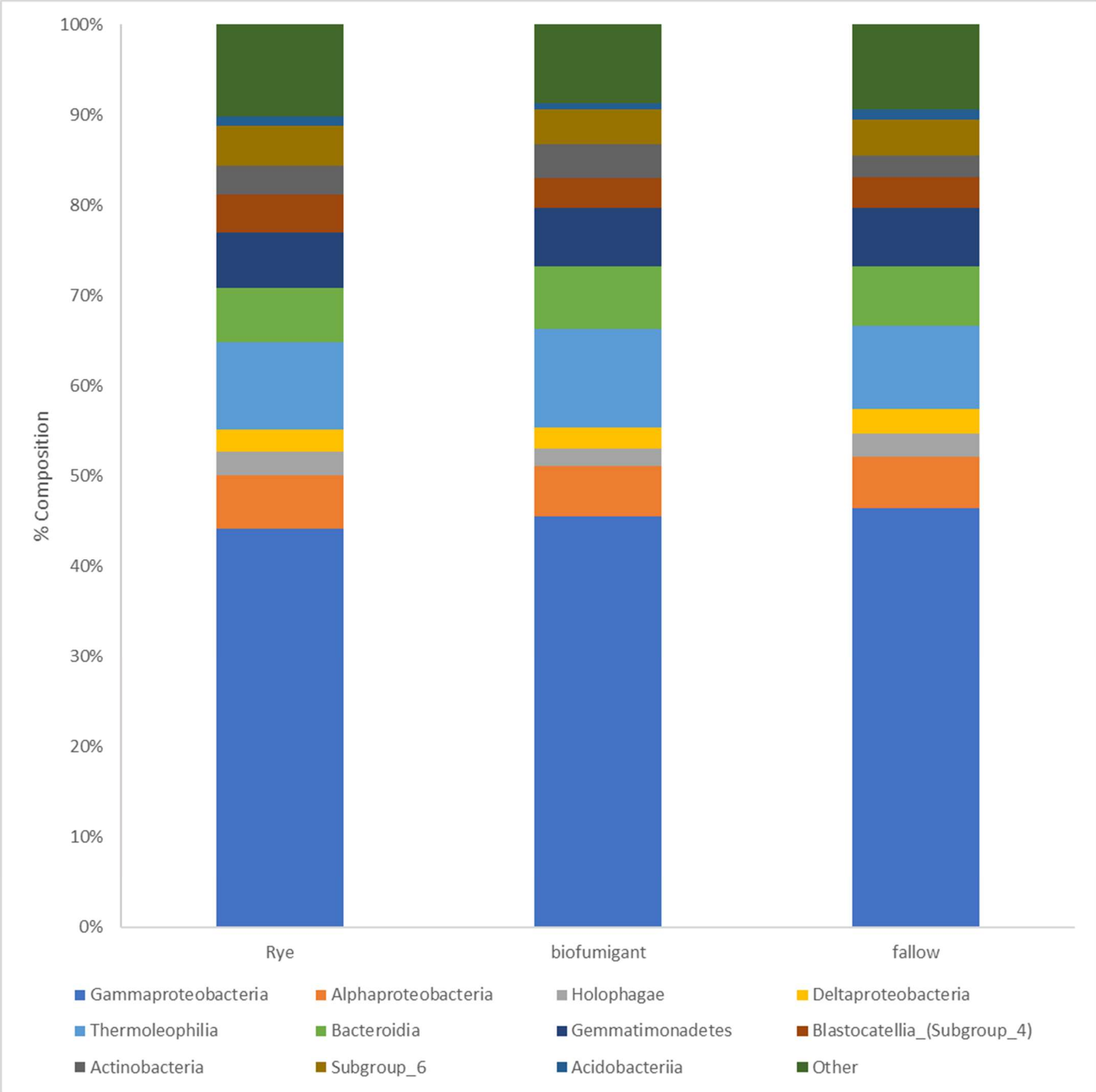

Figure 12. Percentage composition of bacterial communities in 2019 at the class level

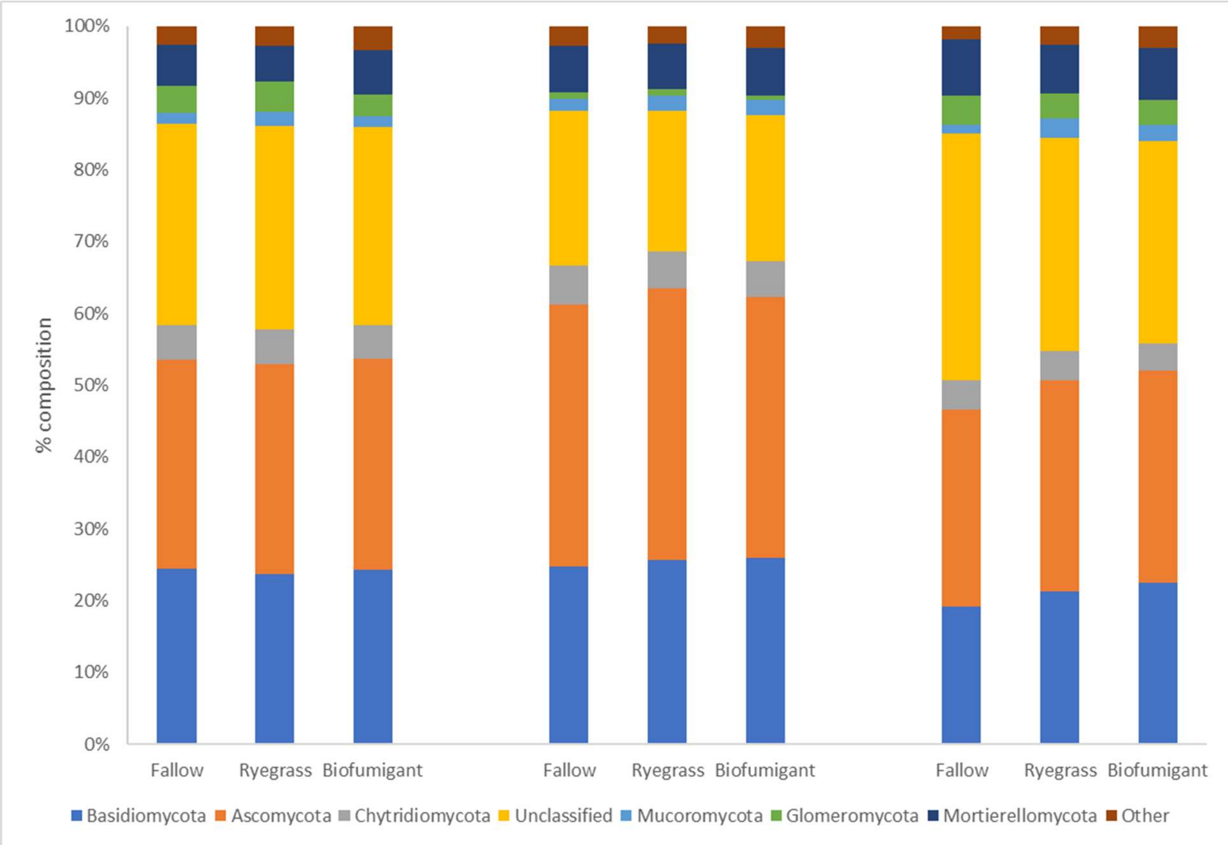

Figure 13. Percentage composition of fungal communities at the phylum level for the years 2016, 2018 and 2019 (left to right)

Concluding remarks on biological communities

The biological communities in the soil at Forthside are very diverse and appear to be strongly influenced by the characteristics of the soil. It can clearly be seen that the nutrients in the soil in the 'control' or undisturbed samples are different to the nutrients in the cultivated soil and so are the biological communities. Differences in the relative proportions of organisms were observed year to year, between locations within the site, and between treatments within each year. However, the large diversity and presence of the same major groups in each treatment suggests that the ecosystem services provided by the biological communities will still be present.

The timing of sample collection is likely to be important. Samples were collected each year two to three weeks prior to the planting of the cover crop at the time when the soil was expected to be the most stable. This is also the time of year that the influence of the preceding cover crop is likely to be the least as a cash crop will have been grown in the intervening time. As the same cash crop is grown in all plots, this will have had a similar effect on all the treatment plots.

Pathogen quantification using PreDicta

Key potato pathogens, *S. subterranea*, *C. cocodes* and *V. dahliae* that cause the diseases powdery scab, black dot and verticillium wilt respectively increased substantially in 2018 which was immediately after the potato crop in the rotation (Fig 14). The impacts of the cover crop grown were negligible for *V. dahliae* pathogen levels while for *S. subterranea* and *C. coccodes* levels were increased by both the cover crop treatments, especially ryegrass, compared to the winter fallow treatment. Both the *Rhizoctonia* pathogens studied AG3 and AG2.1 were not increased when potato was grown in the rotation, unlike the other three pathogens. Both *Rhizoctonia solani* AG3 and AG2.1 were highest in the fallow in 2016 before declining to relatively low levels throughout the trial period. *Rhizoctonia solani* AG2.1 was recorded at higher levels in 4 of the 5 years from the Caliente treatment. Other potato pathogens tested for but either not detected or only recorded at very low levels included various nematode species; *Meloidogyne hapla*, *Meloidogyne fallax* and *Pratylenchus neglectus*, the common scab pathogen, *Streptomyces scabies*, and the pink rot pathogen, *Phytophthora erythroseptica*.

Of note, general potato pathogen levels and related disease incidences are very low to low at this research site compared to other commercial farms on the NW coast of Tasmania. Whilst it is therefore difficult to identify specific pathogen trends although the increase in *R. solani* AG2.1 level under the Caliente cover crop has been recorded elsewhere within Tasmania (pers. comm., F. Mulcahy, Simplot Tasmania).

Key vegetable soil pathogen tests are more in their infancy of development compared to potato pathogen soil tests, with many of the tests just becoming available in the later stages of this study (2019 onwards). Those that were recorded over the whole trial duration included *Plasmodiophora brassicae*, *Pythium violae*, and *Phoma terrestris* that cause the diseases club root, cavity spot and pink root rot, respectively. Levels of *Pythium* and *Phoma* did not vary significantly as a result of the winter cover crop treatment (Fig 15). Levels of *Pythium violae* did increase in both 2016 and 2019, both measurements taken directly after a carrot crop. Caliente, a brassica biofumigant caused significantly higher levels of *P. brassicae* across all years of the study, this was expected as it is a know host of this pathogen. Levels were also significantly enhanced in 2017 after the growing of a commercial broccoli crop. While the test for *S. sclerotiorum* is under development, levels recorded in 2019 and 2020 showed that it was increased approximately 2-fold under both cover crop treatments compared to the fallow treatment, although this was not a significant difference.

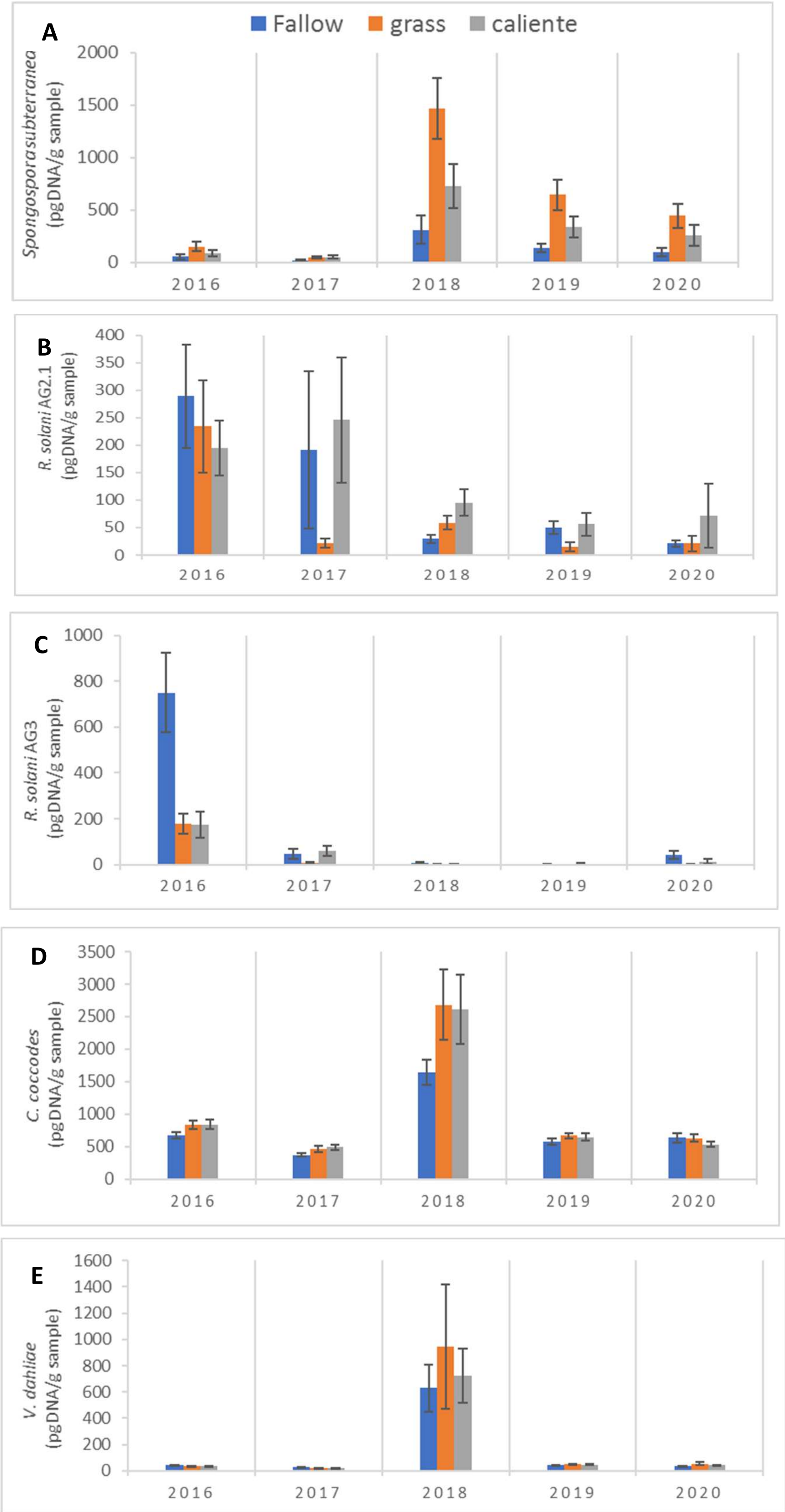

Figure 14. Potato pathogen levels tracked annually through the trial duration from 2016-2020 showing winter fallow, ryegrass and caliente treatments. Shown are A) *Spongospora subterranea*, B) *Rhizoctonia solani* AG2.1, C) *Rhizoctonia solani* AG3, D) *Colletotrichum coccodes*, and E) *Verticillium dahliae*. Note that a potato crop was planted in the 2017/18 season. Shown are the means ± standard error (n = 16).

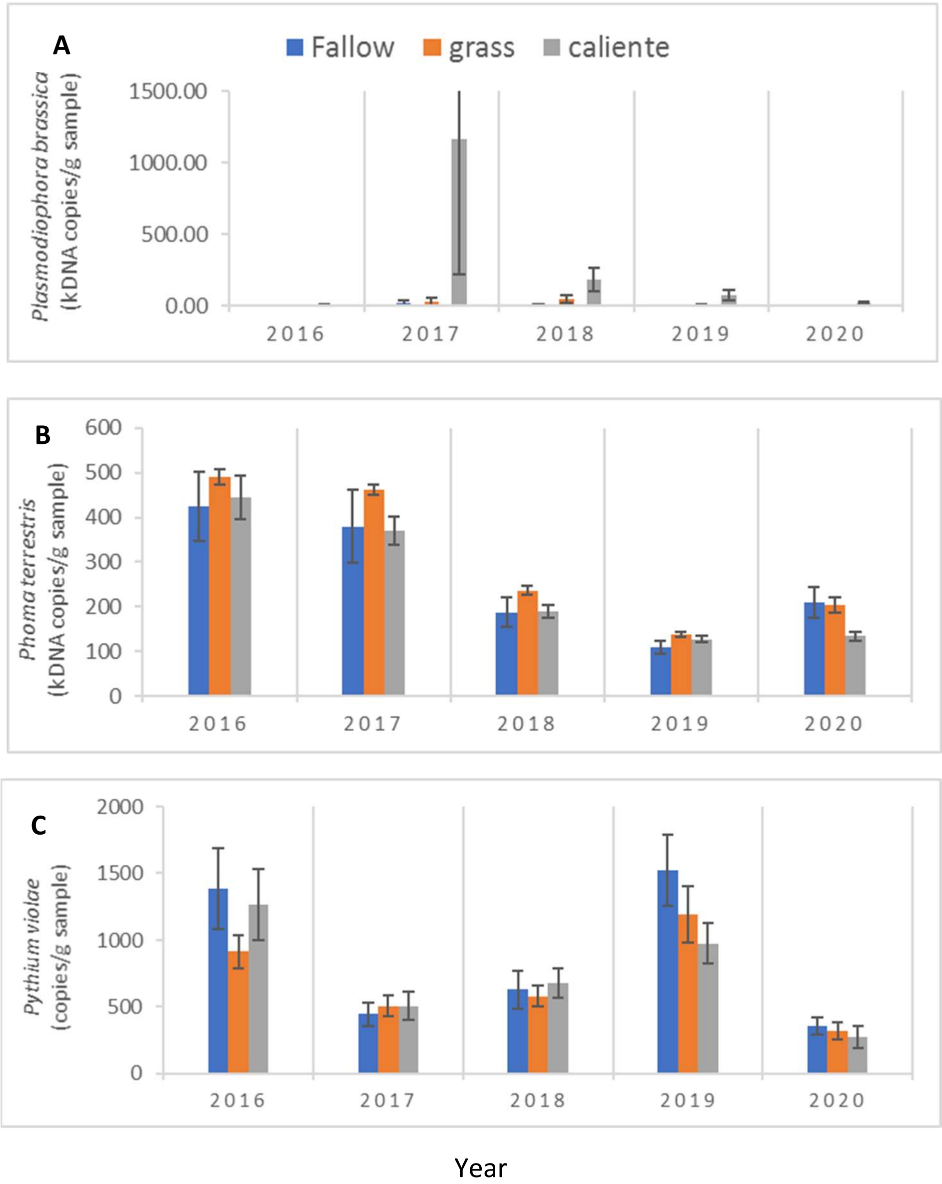

Figure 15. Vegetable pathogen levels tracked annually through the trial duration from 2016-2020 showing winter fallow, ryegrass and caliente treatments. Shown are A) *Plasmodiophora brassicae*, B) *Phoma terrestris*, C) *Pythium violae*. Note that a broccoli, potato, carrot and bean were planted in the 2016/17, 2017/18, 2018/19 and 2019/20 seasons respectively. Shown are the means ± standard error (n = 16).

Case study – *Spongospora subterranea* levels under a 3-yr vs a 6-yr rotation potato crop

Based on prior rotational differences imposed on the trial site in 2009, an extra potato crop was grown within the typical 6 year rotation in the year 2009 to determine the impact of rotation length on *S. subterranea* levels. The standard rotation included a potato crop in the seasons 2006/07, 2012/13, 2017/18 while select sub-plots received an extra potato crop in the season 2009/10. Levels of *S. subterranea* were significantly increased following the additional potato crop in 2009 (Fig 16) and the residual impact of this is evident in 2018 following another potato crop which elevated *S. subterranea* levels again, but to a greater extent where an additional potato crop had been grown 9 years prior. This indicates the significance of rotation length on key soil borne pathogens. Further discussion of this experimental work is presented in Appendix X.

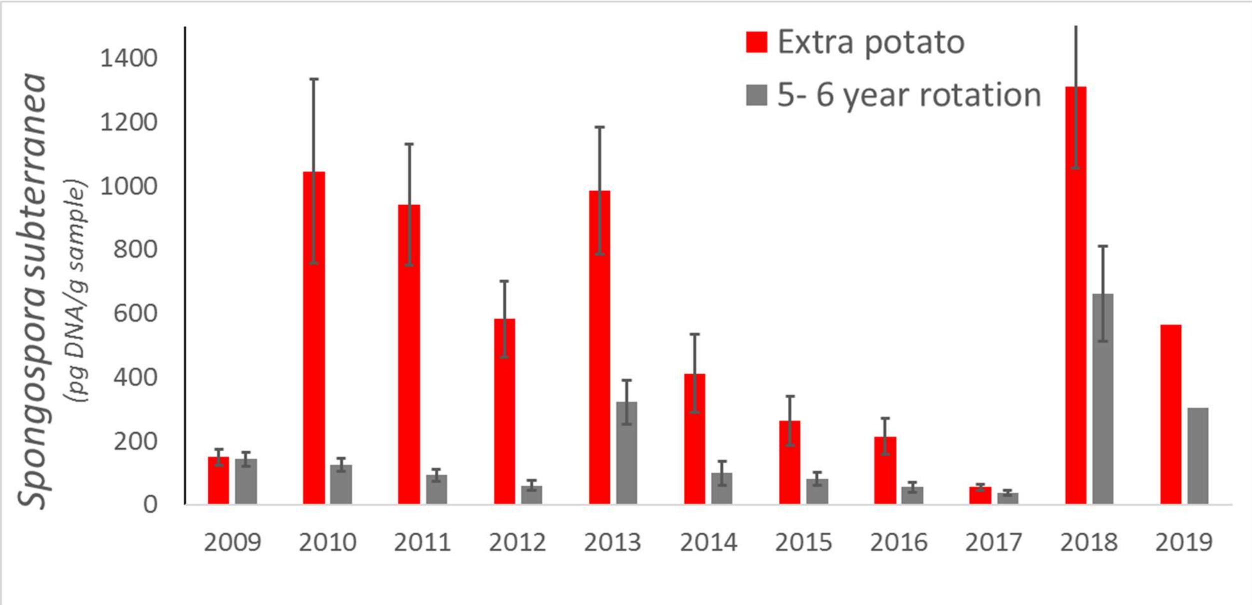

Figure 16. Impact of potato rotation length on levels of *S. subterranea*. Potato was grown in a standard 5-6 year rotation (grey bars) compared to select plots which received an extra potato crop within the rotation in 2009 (red bars).

Weed assessment

Weed levels varied across the whole duration of the trial and was related to cultural management practices across the site and the specific winter cover crop treatments imposed. In the first 2016/17 season, while the cover crops were growing, weed densities were variable; chickweed densities were significantly higher where green manure crops were grown (Table 4). Possibly the young chickweed plants were protected during early development by the slowly growing cover crops. Broadleaf weeds and other crop species (as weeds), although quite low, were significantly higher in the fallow plots compared to those planted with either Caliente or ryegrass. Six months later, in the commercial brocolli crop weed levels were low across the plots so a single combined total weed count was made. Although the annual ryegrass treatment had significantly greater weed levels than the fallow treatments all levels were very low.

Table 4. Density of Broadleaf weeds, chickweed and other weed crops (per m^2 from cover crop, per 2 m of broccoli row) from various treatment plots in 2016/17 season (n =12)

Treatment	Cover crop period (Sep 2016)			Broccoli crop (Mar 2017)
	Broadleaf weeds	Chickweed	Other crops (carrot, onion, poppy)	Weeds
Fallow	2.4 a	3.2 c	2.4 a	0.25 b
Ryegrass	1.6 b	13.1 b	0.9 b	1.13 a
Caliente	1.4 b	17.6 a	0.8 b	0.75 ab
F prob.	0.03	0.001	0.01	0.01

A separate assessment of volunteer potatoes in the September period showed that the fallow plots had significantly greater numbers compared to where ryegrass and Caliente were planted (Table 5).

Table 5. Potato volunteer density on September 23rd, 2016 (n =4) from site planted with Caliente, ryegrass or fallow

Treatment	Total per plot (576 m^2)	Average per m^2
Fallow	157 a	0.27 a
Ryegrass	9 b	0.015 b
Caliente	7 b	0.012 b
F prob.	0.001	0.001

Post cover crop emergence in the 2017/18 season a weed assessment occurred on the 5th of June across all plots; fat hen was the dominant weed observed across all treatment plots with no significant treatment differences (Table 6). However wild radish was generally only recorded at low levels in the fallow treatment plots, significantly higher than the cover crop treatments.

Table 6. Density of the key weeds, fat hen and wild radish (per m^2) just after cover crop emergence (June 5 2018) from various treatment plots in 2017/18 season (n =12)

Treatment	Fat hen	Wild radish
Fallow	11.0	1.63 a
Ryegrass	11.4	0.13 b
Caliente	9.5	0 b
F prob.	0.34	0.01

A detailed weed assessment was carried out by UNE weed scientists on October 9 2018. They found that the fallow plots were the least weedy due to herbicide application (weed counts and weed biomass) (Table 7). Italian ryegrass suppressed weeds more effectively than Caliente, most likely due to its thick biomass cover allowing less light in, with a significant number less weeds per sqm, which equated to about half the weed biomass. Chickweed, the major weed on the site just prior to cover crop incorporation, was the best example of this. Comparable results, greater chickweed densities, under the cover crop treatments just prior to crop termination was also recorded in the 2019 and 2020 season just prior to incorporation (data not provided) supporting the UNE findings of 2018.

Table 7. Density and biomass of key weeds (per m^2) just prior to cover crop incorporation (Oct 2018) from various treatment plots in 2017/18 season. Data 'was obtained from the University of New England, Hort Innovation-funded project VG15070 – A strategic approach to weed management for the Australian Vegetable Industry'

une University of New England

Cover crop trial – TIA Forthside Tas

Weed density and weed biomass, October 2018

Hort Innovation

Cover Crop	Weeds Density 48DAS (plants per sqm)	Weeds Density 48DAS (plants per hectare)	Weeds Density 145DAS (plants per sqm)	Weeds Density 145DAS (plants per hectare)
Fallow (weeds)	87.3	872,500	22.3	222,500
Italian Ryegrass	236.5	2,365,000	189.8	1,897,500
Caliente (mustard)	212.0	2,120,000	262.3	2,622,500

Cover Crop	Weeds Biomass N/A (grams per sqm)	Ground Cover 20DAS (%)	34DAS (%)	48DAS (%)	145DAS (%)
Fallow (weeds)	12	2	3	11	5
Italian Ryegrass	24	2	12	21	100
Caliente (mustard)	48	4	19	48	100

Cover Crop	Chickweed (plants per sqm)	Shepherds purse (plants per sqm)	Wild radish (plants per sqm)	Blackberry Nighshade (plants per sqm)
Fallow (weeds)	3.8	2	0.8	9
Italian Ryegrass	166.8	20	0.8	0
Caliente (mustard)	259.0	1	0.3	0

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Planting date 16/5/18
Harvest date 10/10/18

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Biofumigant and cover crop outcomes

Dry matter production

The biomass production of the cover crop varied significantly between treatments and over different years (Table 8). In 2018 and 2019 Caliente produced significantly ($P<0.05$) more dry mass than the ryegrass treatment (Fig 16), whilst over the other years there was no significant difference between cover crop treatments. Overall yield altered between seasons with the highest yield occurring in 2018 which corresponded with an earlier planting date in 2018 compared to the lowest yielding year (2019) where cover crop planting was delayed until June due to a late wet carrot harvest in May 2019.

Table 8. Mean DM yields (t/ha) from the winter cover crop treatments, Caliente and Ryegrass from 2016-2020 (n = 8-16).

Treatment	Cover crop dry matter yield (t/ha)				
	Sept 2016	Oct 2017	2018	2019	2020
Caliente	6.30	5.92	12.59 a	4.45 a	4.58
Ryegrass	6.80	5.69	8.48 b	3.28 b	4.50
LSD (0.05)	ns	ns	2.56	1.00	ns
F value	0.34	0.37	<0.01	0.02	0.45

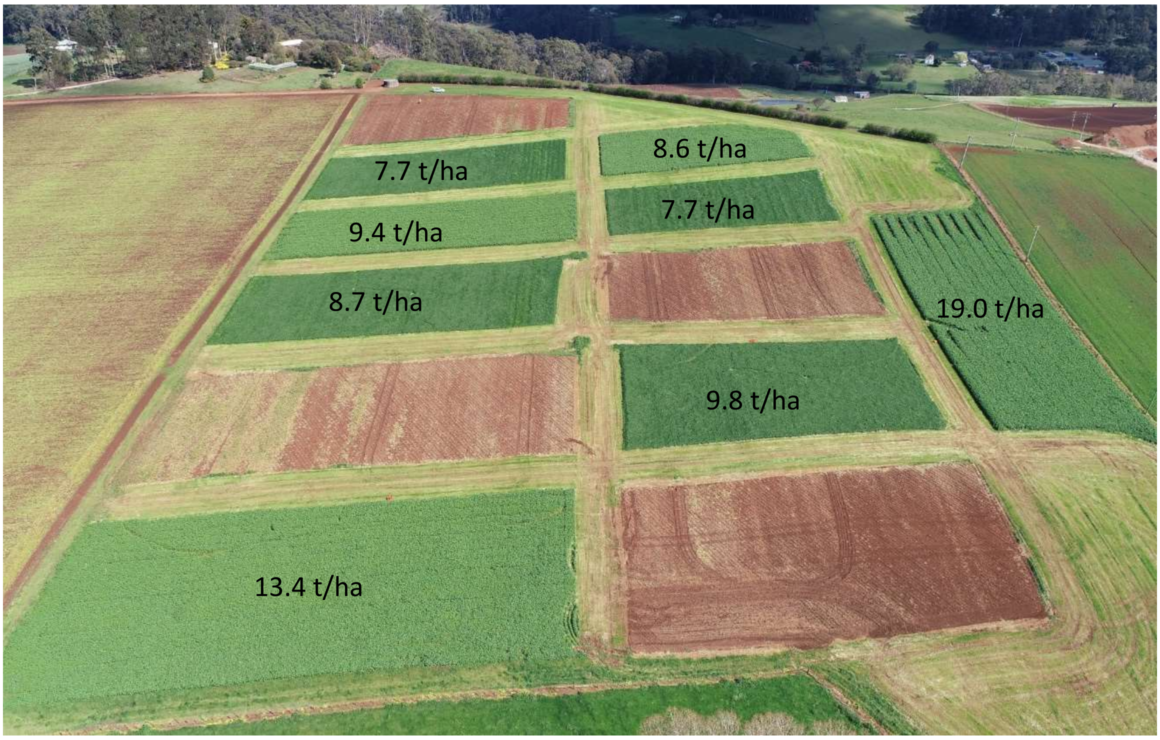

Figure 16. Aerial overview of the trial site in winter 2018 showing cover crop plot biomass production from separate cover crop plots (light green – Caliente; darker green – ryegrass).

Observations of root growth indicated that both ryegrass and Caliente roots were penetrating to approximately 35cm upon which they were halted by a heavier B clay horizon (Fig 17). There was minor penetration into this horizon by the Caliente crop roots. Ryegrass root mass tended to be more prolific in the upper horizons and bound the soil together a little more effectively than the Caliente crop.

Figure 17. Caliente root penetration to 30-35cm just prior to harvest.

Glucosinolate production

Total glucosinolate levels and the proportions of different glucosinolate components varied significantly between the different years of assessment (Table 9). Sinigrin was identified as the major active glucosinolate component and was responsible for greater than 90% of the total glucosinolates identified. Levels of sinigrin and total glucosinolates were both significantly higher (P<0.05) in 2018 compared to the other years while the levels produced in 2017 were significantly lower than the other two years.

Table 9. Average amounts of glucosinolate components produced from the Caliente crop over 2017-2019. Whole plant samples were taken just prior to incorporation for analysis. Each sample consisted of five pooled plants per replicate (n=4).

Year	Glucoiberin (µmole/g) DW	Progoitrin (µmole/g) DW	Sinigrin (µmole/g)DW	Glucoraphanin (µmole/g)DW	Gluconapin (µmole/g) DW	Total Glucosinolates (µmole/g) DW
2017	0.00 b	0.23 a	9.2 c	0.18 b	0.43 a	10.00 c
2018	0.00 b	0.00 b	25.4 a	1.24 a	0.31 ab	26.93 a
2019	0.11 a	0.05 b	18.5 b	0.00 b	0.20 b	18.85 b
	0.078	0.054	6.77	0.43	0.156	6.70
F value	0.026	<0.001	0.004	<0.001	0.033	0.003

Commercial crop outcomes – Yield and Disease

2016/17 (Broccoli)

Two key growth and disease assessments were made in this short season crop, one at ~6 weeks after transplanting (Fig. 18) into the field and another just prior to commercial crop harvest. The initial mid-crop assessment showed that shoot weights were not significantly different between the treatments although Caliente showed the lowest weights (Table 10). At this initial crop stage club root disease was also recorded in two of the twelve large plots assessed, with infection highest in Caliente plot F where 5 of the 6 plants assessed were infected, one of the six plants assessed from Ryegrass plot D was also infected (Fig 19).

Figure 18. Overview of Broccoli plots (March 9 2017)

Table 10. Dry weights of broccoli plants from paddocks that had a winter sown treatment of fallow, annual ryegrass or Caliente at 6 weeks after transplanting and at harvest.

Treatment	6-week assessment (kg)	Final harvest (kg)			
	Shoot DW	Total plant DW	Leaf DW	Head DW	Root DW
Fallow	0.128	531.7	364.3	84.6	82.8
Ryegrass	0.129	541.3	370.2	80.0	91.0
Caliente	0.120	544.8	370.4	87.3	87.1
LSD (0.05)	ns	ns	ns	ns	ns
F prob	0.407	0.958	0.986	0.221	0.279

Each mean measurement is from 16 plots (48 plants in total)

At final harvest (Fig 20), while there was no significant difference between in field yields (Table 10) across all treatments but the overall packout quality was reduced in the Caliente treatment. This was due to the impact of *P. brassicae* and club root disease in the Caliente plots where significant infection was recorded compared to the fallow and ryegrass treatments (Table 11). This was expected as Caliente is a host of club root and needs to be considered in context, as a normal rotation would not include multiple brassica biofumigant plantings followed by a brassica crop.

Figure 19. Images of broccoli at 6 weeks: F1 (biofumigant plot - left) shows club root symptoms while E1 (fallow plot - right) shows no symptoms

Figure 20. Separating plants into root and commercial head components for disease assessment and weighing at final harvest.

Table 11. Broccoli club root presence and severity from paddocks that had a winter sown treatment of fallow, annual ryegrass or Caliente, at final harvest

Treatment	Presence of clubroot^		Clubroot severity
	Score	Plants Infected	
Fallow	0.00 b	0/80	0.00 b
Grass	0.013 b	1/80	0.013 b
Caliente	0.200 a	16/80	0.438 a
LSD (0.05)	0.07		0.169
F prob	<0.001		<0.001

^Each mean measurement is from 80 individual plants

2017/18 (Potato)

A commercial processing potato crop 'Ranger Russet' was planted at the site in the 2017/18 season and key yield parameters were assessed (Table 12) from typical sample plots, which consisted of 20 potato plants (Fig 21). There was no significant impact (P>0.05) of the winter cover crop treatment on tuber number, average tuber weight and Graded tuber yield. The highest yielding plots were the Caliente treatment followed by the fallow, with the lowest yields recorded from the ryegrass treatment. Disease level across the site was extremely low with only minimal superficial common scab lesions recorded on a couple of tubers across the whole site, which was insufficient to analyse any treatment effects.

Table 12. Tuber yield components in a commercially grown 'Ranger Russet' potato crop that had a winter sown treatment of fallow, annual ryegrass or Caliente (n = 16)

Treatment	Average Tuber number per 20 plants	Average weight per tuber (g)	Graded Total Tuber Yield (t/ha)
Fallow	155	210	75.0
Ryegrass	144	219	72.8
Caliente	152	218	76.5
LSD (0.05)	ns	ns	ns
F prob	0.263	0.484	0.265

Figure 21. Overview of typical 20 plant plot at potato harvest.

2018/19 (Carrot)

A commercial carrot crop 'Stefano' was planted at the site in the last week of November 2018 with harvest in early May 2019. The carrots were graded according to size criteria as shown in Figure 22 with these size criteria used to determine total marketable yield (Table 13) and economic outcomes . From a whole yield perspective, the total yield was slightly higher, but not significantly so, in the Caliente and Ryegrass treatment, compared to the fallow. The proportion of Premium grade carrots was higher in the Caliente, compared to Ryegrass and fallow treatments, although this was not statistically significant.

Table 13. Carrot yield components in a commercially grown 'Stefano' carrot crop that had a winter sown treatment of fallow, annual ryegrass or Caliente (n = 16)

Treatment	Premium grade categories (includes Premium and baby) (t/ha)	Total Carrot Yield (t/ha)
Fallow	98.3	128.2
Ryegrass	97.3	131.5
Caliente	102.5	132.8
LSD (0.05)	ns	ns
F prob	0.25	0.34

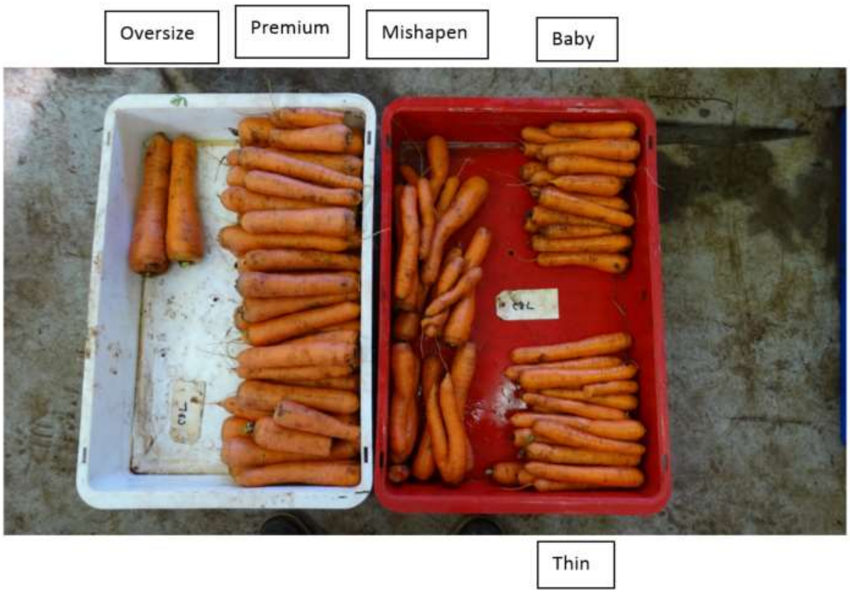

Figure 22. Typical size categorization of a single carrot plot. The categories are broken down into, **Oversize:** Length >250mm and/or diameter >40mm, **Premium:** Length 150-250mm and diameter 25-40mm, **Baby:** Length 80-150mm and diameter 15-28mm, **Thin:** Length >150mm and diameter <25mm, **Mishapen:** those with visual deformities including twisted, forked, root protrusions and stumping.

Very low disease incidence was recorded at harvest across the site with some of the 48 plots showing no disease at all. On average, there were minor incidences (2-5%) of very low level (generally only 1 minor lesion per carrot) disease (see Figure 23). It was hard to confirm the specific diseases, but it visually appeared there was some cavity spot and carrot scab. However, there was no trend associating disease with any specific treatment (fallow, ryegrass, Caliente).

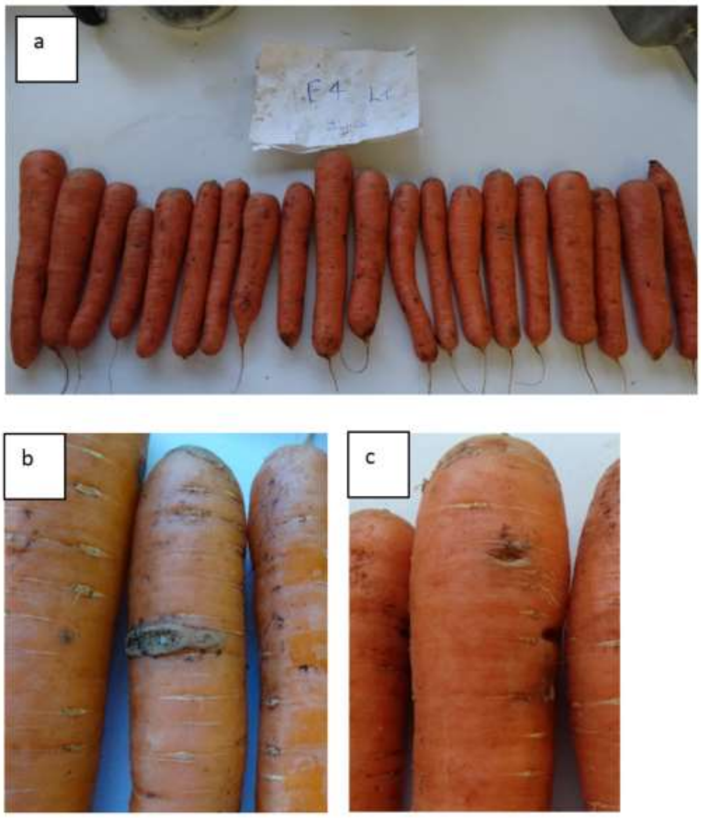

Figure 23. Carrot harvest from Forthside in May 2018 showing **a)** typical twenty carrot sample from a research plot, and **b)** putative carrot scab lesion, and **c)** putative cavity spot.

2019/20 (Bean)

A commercial bean crop was planted at the site in the 2019/20 season and a number of yield and disease parameters were assessed (Table 14) from 1m^2 quadrats (Fig 24). Although the winter sown ryegrass treatment yielded the greatest amount and quantity of marketable pods, this was not significantly higher (P>0.05) than the other treatments, Caliente and fallow. A small amount of Sclerotinia was observed across the site on the plants and the pods. Although levels were highest under the Caliente crop this was not significantly higher than the other treatments, ryegrass and fallow.

Table 14. Yield and disease components in a commercial summer grown bean crop that had a winter sown treatment of fallow, annual ryegrass or Caliente (n = 16)

Treatment	Yield components				Sclerotinia disease	
	Marketable pods FW per m^2	Marketable pods FW (t/ha)	Number of marketable pods per m^2	Average weight of pods (g)	% plants infected	% pods infected
Fallow	0.85	6.65	298	2.84	0.67%	0.07%
Grass	0.85	7.28	320	2.89	1.56%	0.24%
Calientae	0.93	6.68	314	2.73	3.57%	0.51%
LSD (0.05)	ns	ns	ns	ns	ns	ns
F prob	0.126	0.126	0.344	0.08	0.222	0.184

Figure 24. Typical 1m^2 sample plot that was assessed for bean yield and disease.

Economics

Economic analysis of the commercial crop outcomes was undertaken on the basis that all costs incurred within the commercial crop are constant and fixed across the site and treatments, so were not accounted for. The variation to cost basis is through the variable costs associated with managing the cover crops and fallow treatments. Essentially differences in input costs varied between treatments based on seed costs, ground preparation, herbicide treatments and incorporation procedures. The input costs for managing a fallow ($575/ha) were significantly less than ryegrass ($1345/ha) and Caliente ($1280-$1408/ha). Caliente costs varied depending on whether herbicide was used for crop termination and whether soil moisture levels accommodated the rolling of plots.

Table 15. Gross and estimated nett values (per ha) of commercial crops grown over three consecutive seasons that had a winter sown treatment of fallow, annual ryegrass, or Caliente. Shown in brackets is the change in % compared to the fallow treatment. These costs consider variable cover crop input costs only and not the fixed costs of managing the commercial crop.

Treatment	Potato (2017/18)		Carrot (2018/19)		Bean (2019/20)	
	gross	nett	gross	nett	gross	nett
Fallow	$26,250	$25,675	$17,867	$17,292	$6,482	$5,907
Ryegrass	$25,480 (-2.9%)	$24,135 (-6.0%)	$18,133 (1.5%)	$16,788 (-2.9%)	$7,099 (9.5%)	$5,754 (-2.6%)
Caliente	$26,775 (2.0%)	$25,495 (-0.7%)	$18,756 (5.0%)	$17,476 (1.1%)	$6,877 (6.1%)	$5,597 (-5.2%)
LSD (0.05)	ns	ns	ns	ns	ns	ns
F prob	0.27	0.20	0.34	0.45	0.13	0.18

Gross value of the commercial crop was improved by Caliente over all three years compared to the fallow by an average of 4.4% (Table 15). Ryegrass gross value was greater than the fallow in two of the three years and worked out on average 2.7% better than the fallow treatment. When the variable input costs of cover crop management were considered these trends were reversed. Ryegrass treatments resulted in a lesser nett value compared to the fallow across all three commercial crops with an average reduction of 3.8%. For Caliente there was a lesser nett value in two of the three commercial crops compared to the fallow, which resulted in an average reduction of 1.6%. All comparative results were not significantly different (P>0.05). The accounting does not consider the potential financial benefits associated with improved soil structure and soil C, that were increased under the ryegrass and Caliente treatments. It is difficult to put a financial benefit on such traits.

It is also worth noting that a full financial analysis could not be conducted on the broccoli crop, but such a crop rotation, broccoli following a brassica biofumigant would not be common commercial practice, so excluding this is wise. It was noted that the broccoli crop showed no in field yield differences between treatments but the pack out from the Caliente plots was reduced due to club root within that treatment.

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In vitro studies to determine the biofumigant effectiveness of Brassica cover crops on mortality of soil microorganisms

Aim

In order to more accurately quantify the suppressive or fatal effect of biofumigant crops on soil microorganisms, *in vitro* studies were undertaken. The aim of this work was to assess the impact of biofumigant vapours from a range of cover crop varieties on a range of common soil pathogens and beneficial microorganisms in relatively consistent doses in the absence of soil.

Methods

Source and preparation of the Brassica tissues

Field grown plants were sampled from experimental plots at Gatton Research Facility, QLD at 25% flowering at 2-monthly intervals throughout the year (2017). In addition, plants were sampled from plots at Bundaberg Research Facility, QLD in three seasons in 2019. Whole plants were removed from the soil so that the main taproot and laterals were also sampled. The soil was washed from the roots and the intact plants oven dried at 70^{0}C. After drying, the plant tissues were ground using a Wiley mill with 2 mm screen. The dried ground material was stored in large plastic vials at -18^{0}C.

Experimental procedure for in vitro *tests*

Methods were based on early work by Kirkegaard *et al.* (1996) which provided baseline concentrations and water ratios. Immediately prior to each experiment using fungal isolates, plugs (5mm diameter) of actively growing mycelium were taken from the margins of fungal colonies growing on quarter-strength potato dextrose agar (1/4 SPDA) and transferred to the centre of freshly poured sterile plates (85mm diameter) containing 15mL of 1/4 PDA+streptomycin. For the bacterial isolate, a loop was scraped through growing colonies and then streaked in a cross pattern on nutrient agar (NA) plates. The plates were kept for no longer than 1h at 25^{0}C prior to the introduction of Brassica tissues.

Brassica dry matter (DM) tissue subsamples were placed into clear plastic bags, thinly and evenly distributed and placed under UV light in the laminar flow cabinet for 15 mins to minimise contamination of plates. Bags were turned over for a further 15 mins.

Dry matter tissue was added to each petri plate at a rate of 250mg and 500mg. Sterile distilled water (SDW) was added at a rate of 6uL/mg of dried material (DM) (i.e. 1.5mL for 250mg DM and 3mL for 500mg DM) to start the hydrolysis process. This was replicated six times. The inverted bottom plate with the fungal plug on agar was replaced to become the lid and the plates were sealed with Parafilm. Control plates containing only SDW were included. Plates were incubated at 20^{0}C for 10 days, after which they were assessed for inhibition/growth and the diameter of any colonies were measured.

For treatments where no mycelial growth occurred, preliminary tests were carried out to establish if the effect was inhibitory/fungistatic (slowed/halted growth temporarily) or biocidal/fungicidal (no regrowth/death). The fungal plug was transferred from the fumigated plate to a new SPDA plate and assessed for growth after one week.

Experimental variables

For Bundaberg, crops were grown and assessed for their agronomic performance in field trials at the Bundaberg Research Facility QLD. Three soil pathogens were assessed in vitro, *Sclerotium cepivorum*, *Fusarium oxysporum*, and *Verticillium dahliae* using dried plant material from Bundaberg. In addition, beneficial microorganisms, which are used as biocontrol agents, *Trichoderma viride* (Trich-A-Soil™) and *Bacillus amyloliquefaciens* (Serenade® Prime), were assessed to determine impacts of the biofumigants on their survival. Plant material from Plantings 1, 2, and 4 were assessed to correspond to summer, autumn, and spring with three replicates of each field crop and six replicates of each microorganism (N.B. Planting 3, a June winter planting, was not tested due to inconsistent crop management). Cultures were incubated at 20^0C for 10 days and diameter of mycelial growth recorded. After 10 days, *F. oxysporum*, *S. cepivorum*, and *T. viride* control cultures had grown to the edge of the petri plate (i.e. 85mm). However, *V. dahliae* grows more slowly, and after 10 days was at approximately 55mm. Plates were not assessed beyond 10 days as contamination from the plant material causes degradation of plates. For the bacterial assessment of *Bacillus amyloliquefaciens* (Serenade® Prime), a loop of culture was streaked in a cross pattern on each plate and growth was compared with the control plates and rated as a percentage. In some instances, growth of test cultures exceeded the control plate growth and, hence, achieved a rating over 100%.

The following summarises the products that were grown and the planting times, as well as the microorganisms assessed:

Biofumigant products:

- Caliente™ (*Brassica juncea*)
- BQ Mulch® (*Brassica nigra* + *B. carinata*)
- Nemat™ (*Eruca sativa*)
- Cappucchino (*Brassica carinata*)
- Terranova Radish (*Raphanus sativus*)

Soil microorganisms tested *in vitro*:

- *Sclerotium cepivorum*
- *Fusarium oxysporum*
- *Verticillium dahliae*
- *Trichoderma viride*
- *Bacillus amyloliquefaciens*
- Planting times (3 replicates):

1. January summer
2. March autumn
3. nil
4. September spring

For Gatton, eight crops were assessed for their activity against three fungi *Macrophomina phaseolina, Sclerotium rolfsii,* and *Sclerotinia sclerotiorum.* There were six plantings across the seasons. Only *S. rolfsii* was tested against Fumig8tor™ and both *S. rolfsii* and *S. sclerotiorum* were tested against Mustclean™.

The following summarises the products that were grown and the planting times, as well as the microorganisms assessed:

- Caliente™ (*Brassica juncea*)
- BQ Mulch® (*Brassica napus + B. campestris*)
- Nemat™ (*Eruca sativa*)
- Biofum® (*Raphanus sativus + Sinapis alba*)
- Nemfix™ (*Brassica juncea*)
- Tillage Radish® (*Raphanus sativus*)
- Mustclean™ (*Brassica juncea*)
- Fumig8tor™ (*Sorghum*)

Soil microorganisms tested:

- *Sclerotium rolfsii*
- *Sclerotinia sclerotiorum*
- *Macrophomina phaseolina*

Planting times (3 replicates):

1. Late spring
2. Mid-summer
3. Mid-autumn
4. Late autumn
5. Mid-winter
6. Early spring

Data for the Bundaberg trial were analysed using GENSTAT edition 18.2 (VSN International, Hemel Hempstead, UK. Web page: Genstat.co.uk). Analyses used ANOVA in randomised blocks incorporating Fisher's pairwise comparison tests. Due to insufficient replicates for the Gatton trial, data was not analysed statistically.

Results

Bundaberg trials

Results at the lower concentration of 250mg dry matter (Table 1) show that for *F. oxysporum*, treatment with biofumigants Caliente and Nemat are most effective at Planting 1 time (summer), along with Cappucchino reducing fungal growth *in vitro* by more than 60%. All treatments provide some control. Similarly, for *V. dahliae*, all biofumigants provide control by at least 60% with Caliente and BQ Mulch being most effective at Plantings 1 and 2 respectively. Control of *S. cepivorum* was a lot more variable, with no growth of the fungus against Caliente and Nemat at Planting 1 and only slight growth in the presence of Caliente and BQ Mulch at Plantings 4 and 2 respectively.

For the beneficial organisms (Table 2), sensitivity levels were variable, ranging from nil growth for *T. viride* for Nemat Planting 1, and BQ Mulch and Terranova's Planting 4. Spring plantings seemed to have most effect on *B. amyloliquefaciens*, however, in some instances, growth of the bacterium was increased to levels greater than the control.

Total glucosinolate levels suggest that early autumn is the optimal planting time for pathogen suppression with most products producing their highest levels of GSL, with the highest levels from Caliente, Nemfix, Mustclean, and Biofum. It was found that Nemat does not produce a high level of

GSL, although it peaked in autumn BRF. Caliente GSL levels were low in spring but were nonetheless sufficient to suppress *S. cepivorum*.

Where biofumigants were further assessed for the extent of their suppressive ability i.e. whether the effect is halting growth temporarily or permanently, results were variable. At the lower concentration (250mg), 21 out of 57 isolates were killed by the biofumigant, while 36 isolates started to grow again, once exposed to fresh air. At the higher concentration (500mg), it was shown that Caliente killed *S. cepivorum* and *V. dahliae*, while *F. oxysporum* was 50% killed and 50% suppressed. Nemat killed virtually all *S. cepivorum,* while most of *V. dahliae* and *F. oxysporum* were suppressed and growth was reactivated once removed from the biofumigant plate. BQ Mulch killed most of the *M. phaseolina* isolates tested while all the *V. dahliae* and *F. oxysporum* commenced regrowth. Cappucchino and Terranova appeared to suppress *S. cepivorum* which recommenced growing.

Table 1: Pathogen tests at 250mg dry matter, Bundaberg. Mean growth of fungus after 10 days (Means with same subscript are not significantly different at the P = 0.05 level)

Fusarium oxysporum							
	TREATMENT (Dry Matter) mg	**Biofumigant**					
PLANTING		**Caliente**	**Nemat**	**BQ Mulch**	**Terranova**	**Cappucchino**	**Control**
Planting 1	250	18.3 f	10.6 f	47.3 bcd	63 a	33.8 e	85
Planting 2	250	57.6 ab	38.4 de	61.8 a	46.3 cd	58.1 ab	85
Planting 4	250	49.1 bcd	58.7 ab	55.6 abc	63 a	66.7 a	85
Verticillium dahliae							
	TREATMENT (Dry Matter) mg	**Biofumigant**					
PLANTING		**Caliente**	**Nemat**	**BQ Mulch**	**Terranova**	**Cappucchino**	**Control**
Planting 1	250	9.2 e	19.2bcde	23 abc	22.3abcd	24.4 abc	55
Planting 2	250	30.2 a	15.2 cde	11.8 de	22.6 abc	29.2 ab	55
Planting 4	250	26.5 ab	20.1abcd	22.7 abc	14 cde	29.4 ab	55
Sclerotium cepivorum							
	TREATMENT (Dry Matter) mg	**Biofumigant**					
PLANTING		**Caliente**	**Nemat**	**BQ Mulch**	**Terranova**	**Cappucchino**	**Control**
Planting 1	250	0 h	0 h	23.7defgh	28.4 defg	45.7 adcd	85
Planting 2	250	42.3abcde	17.4 egh	5.6 gh	54.6 ab	52.6 abc	85
Planting 4	250	5.4 gh	31.4bcdef	17.8 fgh	28.5cdefg	61.1 a	85

Table 2: Beneficial organism tests at 250mg dry matter, Bundaberg. Mean growth of fungus and bacterium after 10 days (Means with same subscript are not significantly different at the P = 0.05 level)

Trichoderma viride							
	TREATMENT (Dry Matter) mg	**Biofumigant**					
PLANTING		**Caliente**	**Nemat**	**BQ Mulch**	**Terranova**	**Cappucchino**	**Control**
Planting 1	250	63.1 abcd	0 h	28.1 fg	80.6 a	17.8 gh	85
Planting 2	250	76.6 ab	45.3 def	30.3 efg	73.7 abc	51.9 cde	85
Planting 4	250	11.3 gh	47.5 def	0 h	79.5ab	58.9 bcd	85
Bacillus amyloliquefaciens							
	TREATMENT (Dry Matter) mg	**Biofumigant**					
PLANTING		**Caliente**	**Nemat**	**BQ Mulch**	**Terranova**	**Cappucchino**	**Control**
Planting 1	250	102.8	44.2	61.1	70.8	108.3	100
Planting 2	250	75	65.3	13.9	40.3	63.9	100
Planting 4	250	10.6	68.1	6.9	55.6	29.2	100

Results at the higher concentration of 500mg dry matter (Table 3) show that for *F. oxysporum* control, Nemat and Caliente had the most impact at Planting 1, along with Caliente at Planting 4. For *V. dahliae*, Caliente, Nemat and BQ Mulch were most effective at Planting 1. For *S. cepivorum*, Caliente prevented all growth at Planting 1 and Planting 4, as did Nemat and BQ Mulch at Planting 1. In general, most treatments, reduced most fungal growth by over 70% at this concentration, except for *F. oxysporum* which appears to be less sensitive to all products.

For the beneficial organisms (Table 3), Caliente and BQ Mulch restricted growth of *T. viride*. Terranova appeared to have the least impact on *T. viride*. Planting 4 (spring) appeared to have the most impact on *B. amyloliquefaciens*, as did the product Nemat over all planting times.

Table 3: Pathogen tests at 500mg dry matter, Bundaberg. Mean growth of fungus after 10 days (Means with same subscript are not significantly different at the P = 0.05 level)

Fusarium oxysporum							
	TREATMENT (Dry Matter) mg	**Biofumigant**					
PLANTING		**Caliente**	**Nemat**	**BQ Mulch**	**Terranova**	**Cappucchino**	**Control**
Planting 1	500	2.6 ef	0 f	7.6 ef	50.7 bcd	16.7 e	85
Planting 2	500	37.5 d	44.1 cd	61.8 ab	40.1 cd	38.6 d	85
Planting 4	500	9.9 ef	56.2abc	54.1 abcd	62.3 ab	67.5 a	85
Verticillium dahliae							
	TREATMENT (Dry Matter) mg	**Biofumigant**					
PLANTING		**Caliente**	**Nemat**	**BQ Mulch**	**Terranova**	**Cappucchino**	**Control**
Planting 1	500	0 i	6.7 hi	5.1 hi	19.1 bcde	19.1 bcde	55
Planting 2	500	26.2 ab	12 efgh	11.7 fgh	22 abc	27.1 a	55
Planting 4	500	15.2cdefg	14.1defg	18.5 cdef	11.1 gh	19.6 bcd	55

Sclerotium cepivorum							
	TREATMENT (Dry Matter) mg	**Biofumigant**					
PLANTING		**Caliente**	**Nemat**	**BQ Mulch**	**Terranova**	**Cappucchino**	**Control**
Planting 1	500	0	0	0	7.2	25.5	85
Planting 2	500	19.3	9.4	1.5	13.2	52.6	85
Planting 4	500	0	12.6	5.9	10.9	5.8	85

Table 4: Beneficial organism tests at 500mg dry matter, Bundaberg. Mean growth of fungus and bacterium after 10 days (Means with same subscript are not significantly different at the P = 0.05 level)

Trichoderma viride								
	TREATMENT (Dry Matter) mg	**Biofumigant**						
PLANTING		**Caliente**	**Nemat**	**BQ Mulch**	**Terranova**	**Cappucchino**	**Control**	
Planting 1	500	0 e	0 e	5.5 e	73.9 a	0 e	85	
Planting 2	500	0 e	35 d	3.7 e	52.9 b	31.1 bc	85	
Planting 4	500	0 e	30.5 cd	0 e	74.7 a	45.6 d	85	
Bacillus amyloliquefaciens								
	TREATMENT (Dry Matter) mg	**Biofumigant**						
PLANTING		**Caliente**	**Nemat**	**BQ Mulch**	**Terranova**	**Cappucchino**	**Control**	
Planting 1	500	66.7	8.3	55.6	59.7	75	100	
Planting 2	500	25	12.5	13.9	23.6	25	100	
Planting 4	500	18.1	18.1	0	11.1	20.8	100	

Gatton Trials

All the biofumigants tested suppressed growth of *Sclerotium rolfsii in vitro* compared with the controls which grew to 85mm after one week (Tables 5, 6, 7 and 8). Early and late autumn crop plantings were shown to be the most effective for suppressing pathogen growth. Mid-winter to early spring appeared generally to be the least effective planting times for suppressing *S. rolfsii in vitro*.

Caliente, Nemfix and Nemat were the most effective biofumigants. At the higher concentration (500mg dry matter/plate), *S. rolfsii* was killed at all times of the year by biofumigant crop Caliente. Even at the lower concentration (250mg), all *S. rolfsii* was killed except for minimal survival during mid-winter. In the field, assessments of survival of sclerotia indicated that Caliente was less effective, with mortality ranging from 40% in mid-autumn to 70% in mid-winter. At the higher rate of 500mg, Nemfix and Nemat suppressed all growth except for the mid-winter Planting 5 where fungal growth was reduced to about 15%. Tillage Radish limited mycelial growth to 15-30% throughout the year reducing growth to only 10% in late autumn and mid-winter at the higher concentration (500mg) *in vitro*. In the field, control of sclerotia germination was not as effective, except for mid-autumn where 70% mortality was achieved. Biofum and Fumig8tor suppressed all growth throughout autumn. For BQ Mulch, growth was reasonably well-suppressed except for the mid-winter Planting 5.

Where biofumigants were further assessed for the extent of their suppressive ability, results were variable. For Caliente, it was established that this biofumigant kills the fungus even at the lower concentration (250mg) i.e. it is fungicidal. For Tillage Radish, tests for Planting 2 showed a mixture of fungicidal and inhibitory results while Planting 5 was inhibitory only. For Nemfix, Planting 5 had an inhibitory effect while all other planting times were fungicidal. Mustclean and Biofum were variable. Biofum killed at the higher concentration (500mg), but only suppressed at 250mg concentration.

Sclerotinia sclerotiorum was slightly more difficult to control. Caliente and Nemfix were most effective at the higher concentration, followed by Nemat. Again, mid-winter was the least effective time period for control. Field studies revealed a 100% mortality in late spring plantings for Nemfix and BQ Mulch, followed closely by Nemat and Tillage Radish. At other times of the year, Nemat and BQ Mulch suppressed the pathogen by 40%.

In tests to determine if the fungus was killed or suppressed, Caliente killed the fungus for the most part although some plantings showed suppression only. The other biofumigants mostly only suppressed the fungus with some death occurring for Nemat.

Control of *Macrophomina phaseolina* was more variable depending on time of year. Mid-winter saw less control than the rest of the year for most of the biofumigants but there was still some suppression compared with the control. In the field, mid-winter saw higher mortality of sclerotia which may have also been due to environmental factors.

In tests to determine if the fungus was killed or suppressed, it was found that all biofumigants only suppressed the fungus at 250mg concentration with only the occasional death. At 500mg, Caliente and Nemfix killed the fungus but for the most part the other products only suppressed the growth.

Table 5: Pathogen tests at 250 dry matter, Gatton. Mean growth of fungus after 10 days

Macrophomina phaseolina								
	TREATMENT	**Biofumigant**						
PLANTING	**(Dry Matter) mg**	**Caliente**	**Nemat**	**BQ Mulch**	**Tillage Radish**	**Biofum**	**Nemfix**	**Control**
Planting 1	250	0	0	12.2	50.7	41.3	22	85
Planting 2	250	1.2	14.3	0	67	23.3	0	85
Planting 3	250	9.7	13.2	17.8	66	65	0	85
Planting 4	250	3.3	0	10.5	69.2	42.5	0	85
Planting 5	250	37.3	57.8	50	69.8	23.7	42.7	85
Planting 6	250	0	0	28.8	63.8	64.2	3.3	85
Sclerotinia sclerotiorum								
	TREATMENT	**Biofumigant**						
PLANTING	**(Dry Matter) mg**	**Caliente**	**Nemat**	**BQ Mulch**	**Tillage Radish**	**Biofum**	**Nemfix**	**Control**
Planting 1	250	0	0	16.3	62.5	45.3	21.2	85
Planting 2	250	19.5	13.8	9.2	57.8	57.8	0	85
Planting 4	250	42.5	27.3	60.6	57.5	59.2	2.2	85
Planting 4	250	1.2	0	25.8	49.5	48.2	0	85
Planting 5	250	49.7	37.5	85.0	44.8	42.5	48.5	85
Planting 6	250	0	24.0	66.3	59.5	50.5	0	85

Sclerotium rolfsii								
PLANTING	TREATMENT (Dry Matter) mg	Biofumigant						
		Caliente	Nemat	BQ Mulch	Tillage Radish	Biofum	Nemfix	Control
Planting 1	250	0	0	17.5	18.3	53.8	6.8	85
Planting 2	250	0	1.8	4.7	30.2	22	0	85
Planting 4	250	0	0	14.5	33.5	29.7	0	85
Planting 4	250	0	0	4.2	25.8	0	0	85
Planting 5	250	4	20.7	60.2	14.2	10.8	24	85
Planting 6	250	0	2.8	8.7	22.3	53.8	0	85

Table 6: Pathogen tests at 500 dry matter, Gatton. Mean growth of fungus after 10 days

Macrophomina phaseolina								
PLANTING	TREATMENT (Dry Matter) mg	Biofumigant						
		Caliente	Nemat	BQ Mulch	Tillage Radish	Biofum	Nemfix	Control
Planting 1	500	0	0	0	5.2	23.8	0	85
Planting 2	500	0	0	0	25.2	0	0	85
Planting 3	500	0	0	0	63.8	54.8	0	85
Planting 4	500	0	0	0	41.3	5.8	0	85
Planting 5	500	0	55.5	53	50.5	23.7	16.3	85
Planting 6	500	0	0	0	21.8	52.8	0	85
Sclerotinia sclerotiorum								
PLANTING	TREATMENT (Dry Matter) mg	Biofumigant						
		Caliente	Nemat	BQ Mulch	Tillage Radish	Biofum	Nemfix	Control
Planting 1	500	2.3	6	4	14.8	28.5	0	85
Planting 2	500	2.3	13.3	0	40.3	52.7	0	85
Planting 4	500	2.3	28.8	52.7	43.2	57.5	0	85
Planting 4	500	1.2	7.5	0	27.7	18.5	0	85
Planting 5	500	0	34.7	60.2	24.7	49.8	8.3	85
Planting 6	500	0	6.3	0	39.3	35	0	85
Sclerotium rolfsii								
PLANTING	TREATMENT (Dry Matter) mg	Biofumigant						
		Caliente	Nemat	BQ Mulch	Tillage Radish	Biofum	Nemfix	Control
Planting 1	500	0	0	0	32	8.7	0	85
Planting 2	500	0	0	0	29.2	0	0	85
Planting 4	500	0	0	29.3	21.5	24.8	0	85
Planting 4	500	0	0	0	9.3	0	0	85
Planting 5	500	0	12.8	40.2	11.7	0	11.8	85
Planting 6	500	0	0	0	20.7	40.3	0	85

Table 7: Additional biofumigant tests for *S. sclerotiorum*

Sclerotinia sclerotiorum			
	TREATMENT (Dry Matter) mg	**Biofumigant**	
PLANTING		**Mustclean**	**Control**
Planting 1	250	10.7	85
Planting 2	250	3	85
Planting 3	250	12.2	85
Planting 4	250	27.3	85
Planting 5	250	85	85
Planting 6	250	79.7	85
Sclerotinia sclerotiorum			
	TREATMENT (Dry Matter) mg	**Biofumigant**	
PLANTING		**Mustclean**	**Control**
Planting 1	500	4.2	85
Planting 2	500	3.3	85
Planting 3	500	2.5	85
Planting 4	500	3.7	85
Planting 5	500	55.5	85
Planting 6	500	66.7	85

Table 8: Additional biofumigant tests for *S. rolfsii* ('na' denotes unable to assess due to high levels of contamination)

Sclerotium rolfsii				
	TREATMENT (Dry Matter) mg	**Biofumigant**		
PLANTING		**Mustclean**	**Fumig8tor**	**Control**
Planting 1	250	14.2	47.8	85
Planting 2	250	21	46.5	85
Planting 4	250	0	na	85
Planting 4	250	30.8	na	85
Planting 5	250	60.7	36.7	85
Planting 6	250	43.8	62.8	85
Sclerotium rolfsii				
	TREATMENT (Dry Matter) mg	**Biofumigant**		
PLANTING		**Mustclean**	**Fumig8tor**	**Control**
Planting 1	500	na	47	85
Planting 2	500	0	33.7	85
Planting 4	500	0	na	85
Planting 4	500	0	na	85
Planting 5	500	45	40.7	85

Planting 6	500	30.8	43.2	85

Overall Conclusions

1. Results are variable, however, there are significant differences between treatments.
2. Most of the treatments reduced pathogen growth, even at the lower concentration.
3. For *F. oxysporum, S. cepivorum* and *V. dahliae*, Caliente and Nemat were most effective treatments, especially in summer plantings.
4. For *S. cepivorum* and *V. dahliae*, BQ Mulch was also effective.
5. For *M. phaseolina*, Caliente, Nemat, Nemfix and BQ Mulch were all effective at most times of the year.
6. For *S. rolfsii*, Caliente, Nemfix and Nemat were most effective in autumn plantings.
7. For S. sclerotiorum, Caliente, Nemfix and Nemat were most effective in spring plantings.
8. Most of the treatments had an impact on the beneficial organisms, therefore, care must be taken when using these two approaches in a crop management system.
9. Some of the treatments killed the pathogens *in vitro* and some suppressed their growth, whereby they were capable of resuming growth once removed from the fumigation environment.
10. The impact of fumigation on the suppressed organisms is unknown. It is possible that, while the fungus may be able to continue growth, it may have reduced aggressiveness and pathogenicity.
11. Glucosinolate levels did not seem to correlate with pathogen impact.
12. Correlation of *in vitro* effects versus field effects was variable.

COVER CROPS

FOR AUSTRALIAN VEGETABLE GROWERS

INTRODUCTION

This table provides a starting point for helping you choose a cover crop for your farm. Adapt the information to suit your farming operations, climate and cover crop objective. Also look for local guidance on suitable varieties for your conditions.

SPECIES

The cover crops are grouped into 1) Cereals & Grasses, 2) Legumes, and 3) Broadleaves. In choosing your cover crop you should also consider your crop rotation to minimise potential pest and disease issues. Use the **Cover Crops and Soilborne Disease** table for additional guidance.

The most common cover crop species are listed at the top of the groupings, with some less used options at the bottom.

RATINGS

The table provides the user with a summary of cover crops benefits and tolerance of growing conditions, relative to each other. Varietal differences and growth stage at the time of any environmental stress will influence the relative rating. Specific local information should be sought on varieties. This is particularly important for biofumigants.

A 5-star rating system is used in the table:

★★★★★ EXCELLENT

★★★★ VERY GOOD

★★★ GOOD

★★ FAIR

★ POOR

COOL AND WARM SEASONS

The cover crop groups are divided into cool and warm season. Use the map to help guide your choice of cover crops for your season. Growing cover crops in their optimal time of year will typically maximise the benefits and reduce potential insect and disease issues.

COOL SEASON

Cool season cover crops can be grown in most areas over winter. Germination and early growth will be affected by soil temperatures in autumn. Early sowings will establish quicker and lower sowing rates can be used. As the soil temperature declines, increase sowing rates to get good establishment and cover.

WARM SEASON

In the warm to hot summer areas (see map), warm season cover crops can be grown to produce high levels of biomass. Look for greater heat tolerance for growing hot areas in the north and inland regions.

In the mild/warm summer areas, warm season cover crops will grow, once the minimum soil temperature is reached, but will produce biomass at the bottom end of the range. Most cool season cover crops will produce more biomass than warm season cover crops during the summer in this area. Look for cool season cover crops with greater heat tolerance for growing over summer in these areas. Also, choose cover crops which aren't affected by daylength. Daylength sensitive cover crops, e.g. radish, cereal rye, will bolt and produce less biomass if sown in early summer.

1. WHAT BENEFITS?

PROTECT SOIL AND ADD BIOMASS

A key role of cover crops is to protect the soil from water and wind erosion, as well as adding biomass to help maintain and build soil organic matter. Only the above ground biomass is considered in this table - add another 20-25% for root biomass. Active growing roots also add microbe stimulating exudates, especially in the early stages of growth.

The biomass range (t/ha above ground dry weight) will be influenced by conditions and management. Low biomass will be produced when a cover crop is stressed due to a poor match to growing conditions, is not well supplied with water and nutrients or sown at low rates. Early terminated cover crops will also result in low biomass. Use the **Cover Crops and Termination** table for guidance on cover crop termination methods and impact on biomass quantity and quality.

SUPPRESS WEEDS

The most successful cover crops for weed suppression typically establish quickly and/or form a dense canopy. The rating assumes that the cover crop is sown in the right season and is well supplied with fertiliser and water to ensure a competitive stand.

Cover crops that germinate and grow quickly tend to be more effective in suppressing early-germinating weeds. Canopy density can be influenced by sowing rate, and fertiliser and water supply. Dense canopies allow less light to penetrate to the soil surface, reducing the number of weeds that germinate, grow and set seed.

All cover crop choices will benefit from effective weed management in the period leading up to sowing, by reducing the impact of early weed germination and competition during cover crop establishment. Use the **Cover Crops and Herbicides** table for guidance on herbicides.

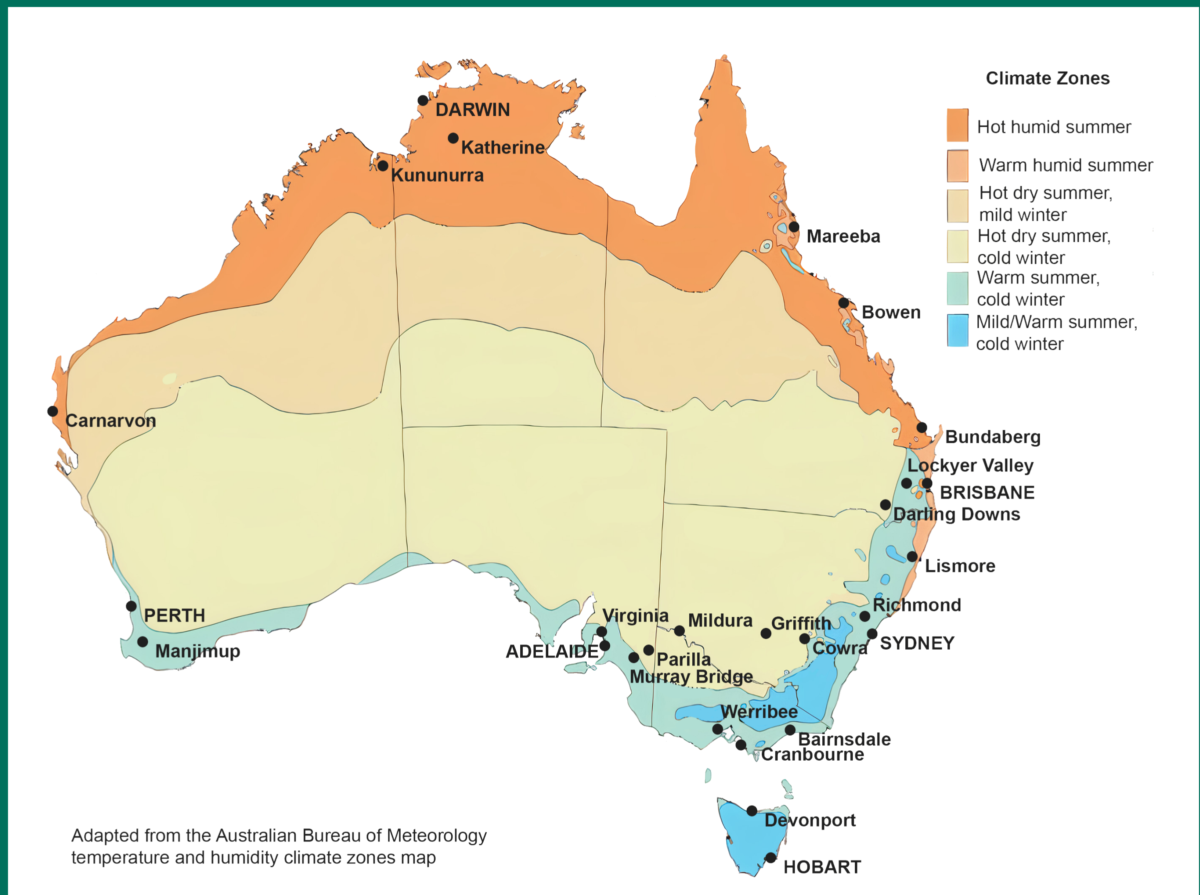
Use the **Integrated Weed Management for the Australian Vegetable Industry** manual, due for publication in 2021, for detailed guidance.

ADD NITROGEN

Legume cover crops can add up to 150-200 kg/ha of nitrogen when grown well with the right rhizobium.

The ratings for the legumes are based on above ground biomass produced and assume a nitrogen fixation rate of 20 kg nitrogen per tonne of biomass.

★ indicates that the cover crop does not add nitrogen.



Adapted from the Australian Bureau of Meteorology temperature and humidity climate zones map

RECOVER NUTRIENTS

Cover crops can play an important role in recovering and storing nutrients remaining in the soil after a vegetable crop. The ratings summarise a cover crop's ability to scavenge for nutrients in the soil and to access nutrients below the root zone of vegetable crops through deep rooting. The nutrients recovered and stored in the cover crop biomass are released to benefit the following vegetable crops and help reduce the off-farm environmental impacts.

BIOFUMIGANTS

Biofumigation is the use of specialised cover crops which are grown, mulched and incorporated into the soil prior to cropping. High biomass can provide the traditional benefits of cover crops and, if done right, naturally occurring compounds from the biofumigant plants can suppress soilborne pests, diseases and weeds. The table only summarises the biofumigant cover crops at the species level. Varieties vary considerably. For performance of biofumigant varieties see the **Guide to Brassica Biofumigant Cover Crops: Managing soilborne diseases in vegetable production systems.**

★ indicates no biofumigant activity.

2. GROWTH TOLERANCES

Choosing cover crops well suited to the conditions is important, but remember to get the most out of your cover crops your need to treat them like a crop by sowing at the right time, avoiding main pest and disease periods, and giving them adequate nutrition and water.

The table summarises the relative tolerances of the cover crops to heat, drought, waterlogging and frost. Use these ratings to identify cover crops which will cope with the growing conditions expected in your region.

3. SOIL CONDITIONS

Use the soil conditions to make sure the cover crop is suited to your soil's pH. The minimum soil temperature for germination is provided and for best results the temperature should be rising for early sowing of warm season cover crops.

4. SOWING

Practical information on sowing cover crops is summarised.

Possible sowing rates (kg/ha) are provided as a guide. The lower rate would be suitable for drilled cover crops at the optimum sowing time. Use higher rates when broadcasting, sowing late in the season, or for improved weed suppression.

Seed size and sowing depth information is provided to help match with sowing machinery.

If the legume is not regularly grown, then adding the right rhizobium inoculant is very important.

The specific rhizobium inoculant for each legume is provided. For the best result, coat seed and sow on same day.

5. ESTABLISHMENT

The establishment time provides a ranking of the relative speed to achieve ground cover. This will be important for outcompeting weeds and providing protection against wind and water erosion. Sowing rates and soil temperatures will have a big influence on establishment time.

Root depth is important in stabilising subsoil structure, e.g. after deep ripping, scavenging for nutrients below crop roots, and for drought tolerance. Three classes for root depth are used: Shallow – majority of roots 0-50 cm; Medium – majority of roots 0-100cm; and Deep – roots can grow deeper than 100cm.

COVER CROPS FOR VEGETABLE GROWERS

Cover Crop Quick Reference table for picking a cover crop.

Pick your season, your main purpose (1), and expected growth (2) and soil conditions (3). The suggested sowing practices are provided in 4, with 5 providing an indication of establishment.

More information on how to use the Quick Reference table is on the back. For other cover crop resources **visit www.soilwealth.com.au**

SPECIES	1. WHAT BENEFITS?					2. GROWTH TOLERANCES				3. SOIL CONDITIONS		4. SOWING				5. ESTABLISHMENT	
	PROTECT SOIL & ADD BIOMASS (t/ha)	SUPPRESS WEEDS	ADD NITROGEN	RECOVER NUTRIENTS	BIOFUMI-GANT	HEAT	DROUGHT	WATER-LOGGING	FROST	pH (water)	LOWEST GERMINATION TEMP (°C)	RATE (kg/ha)	SEED SIZE	DEPTH (cm)	RHIZOBIUM INOCULANT	TIME	ROOTING DEPTH
CEREALS & GRASSES																	
COOL SEASON																	
Cereal rye (*Secale cereale*)	3 - 10	★★★★	★	★★★★★	★	★★	★★★	★★★	★★★	4.9 - 7.9	3	60 - 120	M	1 - 3	NA	quick	deep
Oat (*Avena sativa*)	2 - 10	★★	★	★★★★	★	★★	★★★	★★★	★★★	4.5 - 7.5	8	80 - 110	M	3 - 6	NA	quick	deep
Black/Saia oat (*A. strigosa*)	4 - 10	★★	★	★★★★	★	★★	★★★	★★★	★★	4.5 - 7.5	8	50 - 70	S - M	3 - 6	NA	quick	deep
Annual ryegrass (*Lolium multiflorum/rigidum*)	2 - 9	★★★★	★	★★★★	★	★	★★	★★★	★★★	5.5 - 7.5	13	15 - 20	S	1 - 2	NA	slow	medium
Barley (*Hordeum vulgare*)	2 - 10	★★★	★	★★★★	★	★	★★	★★	★★★	6.0 - 7.9	8	50 - 100	M	3 - 5	NA	quick	deep
Wheat (*Triticum aestivum*)	3 - 8	★★	★	★★★★	★	★	★★	★	★★★	5.5 - 7.9	5	60 - 120	M	2 - 4	NA	medium	deep
WARM SEASON																	
Sorghum (*Sorghum bicolor*)	4 - 14	★★★★	★	★★★★★	★★★	★★★★	★★★	★★	★	>4.8	16	15 - 30	M	3 - 5	NA	medium	deep
Sorghum x Sudan grass (*S. bicolor x S. sudanense*)	4 - 10	★★★★	★	★★★★★	★★	★★★★★	★★★★★	★★★	★	>4.8	18	20 - 30	M	2 - 4	NA	medium	deep
Sudan grass (*Sorghum sudanense*)	4 - 10	★★★★	★	★★★★★	★	★★★★	★★★★	★★	★	>4.8	18	15 - 30	M	1 - 2	NA	medium	deep
Millet - French or Proso (*Panicum miliaceum*)	2 - 8	★★★	★	★★★★	★	★★★★★	★★★	★	★	4.5 - 9.0	14	8 - 15	S	1 - 2	NA	medium	medium
Millet - Japanese (*Echinochloa esculenta*)	2 - 6	★★★	★	★★★★	★	★★★★	★★	★★	★	4.6 - 7.4	15	10 - 30	S	1 - 3	NA	medium	medium
Teff (*Eragrostis tef*)	3 - 8	★★	★	★★★	★	★★	★★★★	★★★★★	★	>4.8	18	6 - 12	VS	0.3 - 1	NA	medium	shallow
LEGUMES																	
COOL SEASON																	
Faba bean (*Vicia faba*)	6 - 8	★★	★★★★★	★★	★	★★	★★	★★★	★★★	6.0 - 7.2	4	100 - 200	L	5 - 8	F	slow	shallow
Vetch, Woollypod "hairy" (*V. villosa*)	4 - 7	★★	★★★★	★★	★	★	★★	★★	★★★★	5.0 - 7.5	9	25 - 40	M	2 - 4	E	slow	medium
Vetch, common (*V. sativa*)	2 - 5	★★	★★★	★★	★	★	★★	★★	★★★★	5.0 - 7.5	6	50 - 60	M	1	E	medium	medium
Field pea (*Pisum sativum*)	3 - 8	★★	★★★★	★★	★	★★	★★	★★	★★★	6.0 - 7.0	6	80 - 120	M	3 - 7	E or F	medium	shallow
Clover, white (*Trifolium repens*) - perennial	2 - 6	★★	★★★★	★★	★	★★★	★★	★★★★	★★	6.0 - 7.0	5	4 - 12	S	1	B	medium	shallow
Clover, berseem (*T. alexandrinum*)	3 - 7	★★★	★★★★	★★	★	★★★	★★	★★	★	7.0 - 7.5	6	10 - 20	S	1	B	medium	shallow
Clover, balansa (*T. michelianum*)	3 - 6	★★	★★★★	★★	★	★	★★★	★★★	★★★	5.0 - 7.0	6	4 - 8	S	1	C	medium	medium
Clover, crimson (*T. incarnatum*)	3 - 6	★★	★★★	★★★	★	★	★	★	★★★	5.5 - 7.0	6	10 - 20	S	1	C	medium	deep
Clover, red (*T. pratense*)	2 - 5	★★	★★★	★★★	★	★★	★★	★★	★★	5.5 - 7.0	5	5 - 10	S	1	B	medium	deep
Lentil (*Lens culinaris*)	2 - 5	★	★★★	★★	★	★★★	★★★	★	★★★	6.0 - 7.5	5	50 - 60	M	5 - 10	F	slow	shallow
Lupin (*Lupinus* spp.)	2 - 8	★	★★★	★★★	★	★★	★★★	★★	★★★	4.5 - 7.0	5	70 - 100	M	3 - 5	G or S	slow	medium
Medic (*Medicago* spp.)	1 - 4	★	★★	★★	★	★★★★	★★★	★★	★★★	6.0 - 7.5	10	10 - 20	S	1	AL or AM	slow	shallow
Serradella (*Ornithopus* spp.)	3 - 8	★	★★★★	★★	★	★★★	★★	★★	★★	4.5 - 7.0	5	2 - 5	S		S or G	slow	medium
Biserrula (*Biserrula pelecinus*)	3 - 8	★★★	★★★★	★★★	★	★★	★★★★	★	★★★	4.0 - 7.5	5	10 - 20	M	3 - 5	WSM1497	medium	deep
WARM SEASON																	
Lablab (*Lablab purpureus*)	4 - 12	★★★	★★★★★	★★★	★	★★★★★	★★★★★	★	★	5.0 - 7.5	18	20 - 40	L	4 - 6	J	medium	deep
Soybean (*Glycine max*)	2 - 8	★	★★★★	★★	★	★★★	★★★	★★★	★	5.5 - 7.5	15	40 - 60	M	2 - 5	H	medium	medium
Cowpea (*Vigna unguiculata*)	2 - 6	★★★	★★★	★★	★	★★★★★	★★★★	★	★	4.5 - 6.5	18	35 - 90	M	3 - 6	I	medium	deep
Mung bean (*V. radiata*)	1 - 6	★★	★★★	★★	★	★★★★★	★★★★★	★★	★	5.5 - 7.5	18	20 - 30	M	2 - 4	I	medium	medium
Sunn hemp (*Crotalaria juncea*)	4 - 8	★★★★	★★★★	★★★	★	★★★★★	★★★★	★	★	6.0 - 7.5	14	10 - 20	M	.5 - 3	I	medium	medium
Lucerne (*Medicago sativa*) - perennial	4 - 10	★★	★★★★★	★★★	★	★★★★★	★★★★★	★★★	★★★	6.5 - 8.0	4	15 - 25	S	1	AL	slow	deep
Sulla (*Hedysarum coronarium*) - perennial	3 - 10	★	★★★★	★★★	★	★★	★★★	★★	★★	6.5 - 8.5	15	6 - 12	S	1 - 2	WSM1592	slow	deep
BROADLEAF (NON-LEGUME)																	
COOL SEASON																	
Fodder mustard (*Brassica napus*)	8 - 16	★★★	★	★★★★	★★★	★★★	★★	★★★	★★★	6.0 - 7.5	6	6 - 12	S	1 - 2	NA	medium	medium
Indian mustard (*Brassica juncea*)	4 - 15	★★★★	★	★★★★	★★★★★	★★★	★★	★★	★★★	6.0 - 7.5	5	6 - 14	S	1 - 2	NA	medium	medium
Oilseed radish (*Raphanus sativus var. oleiformis*)	5 - 12	★★★	★	★★★★★	★★★★	★★★	★★	★★	★★★	6.0 - 7.5	7	9 - 15	M	1 - 2	NA	medium	deep
Turnip (*Brassica rapa*)	2 - 6	★★★	★	★★★	★★★	★★★	★★	★★	★★	6.0 - 7.5	5	5 - 8	S	1 - 2	NA	medium	deep
White mustard (*Sinapis alba*)	4 - 12	★★	★	★★★★	★★★	★★★	★★	★★	★★	6.0 - 7.5	4	10 - 20	S	1 - 2	NA	medium	medium
Rocket (*Eruca sativa*)	2 - 8	★★★★	★	★★★	★★★	★★★	★★★	★★	★★★	6.0 - 7.5	6	8 - 16	S	1 - 2	NA	medium	medium
Chicory (*Cichorium intybus*) - perennial	3 - 6	★★	★	★★★★	★	★★★	★★★	★	★★★★	5.5 - 7.0	12	4 - 7	S	1 - 3	NA	medium	deep
Linseed (*Linoideae & Hugonioideae*)	2 - 5	★	★	★★	★	★★	★★★	★★	★★★	6.0 - 7.5	9	30 - 50	S	1 - 3	NA	slow	medium
Phacelia (*Phacelia tanacetifolia*)	3 - 6	★★★	★	★★★	★	★★	★★★	★	★★★	6.5 - 8.5	10	8 - 10	S	1	NA	slow	medium
WARM SEASON																	
Buckwheat (*Fagopyrum esculentum*)	2 - 6	★★★★	★	★★★★	★	★★★	★	★	★★	5.0 - 7.0	10	30 - 70	M	1 - 2	NA	quick	shallow
Tillage Radish (*Raphanus sativus*)	6 - 12	★★★★	★	★★★★★	★★★	★★★★	★★	★★	★★★	6.0 - 7.5	7	3 - 10	M	1 - 3	NA	medium	deep
Ethiopian mustard (*Brassica carinata*)	6 - 14	★★★	★	★★★★	★★★★★	★★★★	★★★	★★	★★	5.5 - 7.5	7	5 - 15	S	1 - 2	NA	medium	medium
Safflower (*Carthamus tinctorius*)	3 - 8	★	★	★★★★★	★	★★★★★	★★★★	★	★★	6.0 - 8.0	5	15 - 25	M	2 - 3	NA	slow	deep
Sunflower (*Heliantus annuus*)	3 - 8	★	★	★★★	★	★★★★	★★★	★	★★	5.5 - 8.0	10	5 - 10	L	2 - 5	NA	medium	medium
Marigold (*Tagetes* spp.)	1 - 3	★★★	★	★★	★	★★★★	★★	★	★	6.0 - 7.5	18	1 - 2	M	2	NA	medium	shallow

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