Final Report

Optimising the benefits of vermiculture in commercial-scale vegetable farms

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Delivery partner:

Blue Environment

Project code:

VG15037

Project:

Optimising the benefits of vermiculture in commercial-scale vegetable farms VG15037

Disclaimer:

Funding statement:

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.

Publishing details:

ISBN 978 0 7341 4583 3

Published and distributed by: Hort Innovation

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Contents

Summary

This report details work undertaken between June 2016 and September 2019 researching and promoting the potential productivity benefits of increased earthworm activity on commercial vegetable farms.

Work undertaken included the following activities:

- Produced a detailed research report including a literature research into factors affecting the levels of activity and agronomic benefits of earthworms in commercial vegetable growing and the results of field research and stakeholder consultation (Appendix A).
- Developed field methodologies for surveying earthworms and identifying species.
- Established two detailed research sites: one at Maffra, Victoria and the other at Moriarty, Tasmania.
- Identified and undertaken field research at a further 16 commercial vegetable farms in New South Wales, Queensland, South Australia, Tasmania, Victoria and Western Australia, and identified additional properties with practices beneficial to soil health and earthworm activity. Properties have been selected on the basis of growers adopting practices that are recognised as beneficial to soil health.
- Consulted suppliers of vermiculture products, including potential suppliers of 'agronomic' earthworms that could be used to 'seed' populations of beneficial earthworms on properties with historically low earthworm numbers but soil management practices conducive to beneficial earthworm activity.
- Interviewed growers about historic and current practices and barriers and opportunities for practice changes that would increase beneficial earthworm activity.
- Undertook an assessment of the likely productivity implications of practice changes that promote greater earthworm activity.
- Developed information sheets about the project, the trial sites, the benefits of earthworms and practices to increase earthworm activity (see Appendix B).

Key outcomes of the project are:

- A review of literature regarding earthworms in Australian cropping areas, potential benefits of earthworms on soil function, plants health and productivity, and the impacts of different farm practices on earthworm activities.
- A survey of earthworm types and numbers under different commercial vegetable farms in different parts of Australia.
- Field research of the impacts of different farm practices on earthworm activity and soil health.
- Development of information sheets on the productivity benefits of greater earthworm activity and the practices that promote greater earthworm activity.
- Field days and events used to promote earthworm-friendly practices in commercial vegetable growing.
- Economic and risk assessment of farm practices that promote earthworm activity and the potential productivity gains achievable through greater earthworm activity.

Key findings of the work include:

- Earthworm activity levels (as indicated by the average number of earthworms per square metre) were generally low on most of the surveyed properties. This is despite most of the properties having adopted one or more practices to improve soil health. The most likely reason for low earthworm numbers observed is tillage practices. Earthworms are sensitive to intensive tillage.
- There was limited diversity in the species of earthworms observed under cultivated areas. With the exception of an unidentified Epigeic (surface dwelling) earthworm species found under a pasture phase on one property, the earthworms found in cultivated areas were all from a small number of introduced species. This seems surprising given that Australia reportedly has over 700 identified native species of earthworms, but is consistent with previous research that has found the same small number of 'agronomic' introduced earthworms are predominant under cultivated and improved pasture areas. In other words, native earthworms do not seem to survive under conventional agricultural systems. This is most likely due to cultivation, vegetation/habitat change and changes to soil ecosystems. Fertiliser and other farm chemical use may also affect soil ecosystems and native earthworm activity.

- Earthworm numbers were generally higher where there was a history of less intensive cultivation, higher labile soil carbon and higher soil nitrogen.
- In the more detailed field trials, earthworm numbers were higher under the cover crop/green manure treatment, with lower positive responses under treatment using composts and vermi-casts. Unsurprisingly, bio-fumigation treatments reduced levels of earthworm activity.

Keywords

Earthworms, soil health, green manure, cover crop, compost, vermiculture, cultivation, vegetable production.

Introduction

Earthworms are known to be an indicator of healthy soil function. However, prior to this project, there has been limited research into how farm practices in commercial vegetable growing impact on levels of earthworm activity and how earthworms can potentially contribute to farm productivity.

A review of relevant literature has found that although there was research into the agronomic benefits of earthworm activity in Australia up until the late 1980s, most of this was related to pasture and broadacre cropping. Little work has previously been undertaken into the potential productivity benefits of increased levels of earthworm activity in commercial vegetable production.

The potential benefits of greater earthworm activity are:

- Improved soil aeration, drainage and structure in the upper 300-500mm of soil due to earthworm burrowing and cast (excrement) production. In addition to the physical creation of burrows, earthworm casts and exudates ('slime' excreted through the skin to lubricate movement through soil) contain compounds that promote formation of soil aggregates or peds, reduce bulk density and improve soil structure. Sufficiently high levels of earthworm activity could reduce the need for deeper soil cultivation, resulting in reduced fuel, equipment and labour costs associated with cultivation.
- Improved plant nutrient availability. Earthworm casts contain concentrated nutrients and organic compounds that improve soil cation exchange capacity. Earthworm activity can improve the availability of immobilized nutrients in the soil because ingested minerals and organic mineralised nutrients are released in more plant available forms. This results in increased nutrient cycling and nutrient availability in the root zone.
- Improved soil function. Earthworm wastes contain nutrients and compounds that promote beneficial soil bacteria, fungi and other microorganisms.
- Increase root and plant growth. Earthworm casts contain nutrients and compounds that stimulate root growth. Improved and deep soil aeration also promote deeper root growth. Healthier root growth stimulates beneficial soil microbial activity and contributes to soil carbon.
- Some earthworms can reduce microbial pathogens by feeding on microorganisms.

Methodology

The project had multiple components. There were:

1. Information review

A review was conducted of secondary data and information regarding the use of vermiculture in horticulture and agriculture. This work involved detailed and on-going review of journal and other literature, and focused on the potential benefits of earthworms and vermiculture products and the practices that affect levels of earthworm activities. This review also included a preliminary assessment of the potential financial and environmental benefits of increased earthworm activity and vermiculture and the practice change required to increase earthworm activity.

2. Stakeholder consultation and engagement

Stakeholder consultation was undertaken to determine levels of awareness of vermiculture in commercial vegetable growers and potential best practice examples of growers working to benefit from vermiculture and earthworm activity. The work also focused in finding potential field sites and project partners. The project involved on-going engagement with participating growers about practices that could promote earthworm activity. A survey sheet used in stakeholder consultation is provided in Appendix C.

3. Development of a field-based research and demonstration program

This work involved development and trial of a method for assessing levels of earthworm numbers on properties. A range of techniques were considered and trialed. The testing method used was based on previous earthworm surveys and practicality in the field.

Two main field research and 18 other field and demonstration sites were identified and established. These were selected on the basis of state (minimum of three sites in each of NSW, Qld, Tas, Vic SA and WA), practices to promote soil health (e.g. one or more of the following: cover cropping, green manuring, reduced tillage intensity, application of compost or other organic soil amendment, and/or use of vermiculture products.

Preliminary survey work and review of previous research suggested that field identification would be possible for the most likely and common earthworm varieties, with laboratory taxonomy work using a dissecting microscope to confirm identifications and for any earthworms where there was uncertainty about their species. This method was adopted successfully for the project. Soil samples and field conditions records were taken for all sampling periods.

4. Field days and promotions and industry adoption program

A field day and promotions program was developed and delivered to promote the benefits of earthworms, vermiculture products and practices that promote earthworm activity. This included media articles, factsheet development, field days, industry events and radio media interviews.

A Facebook page has been developed and is maintained by Blue Environment, and presentations on the project and benefits of earthworms are available online.

Outputs

Project outputs include:

- A project report detailing research and field work and an assessment of how earthworms and 'earthworm friendly' practices can improve productivity on commercial vegetable farms (see Appendix A).
- Information sheets about earthworms, earthworm friendly practices and the project (see Appendix B).
- The following field days and stakeholder events were held to promote the project and benefits of earthworms in commercial vegetable growing:
  - May 2017, Adelaide, SA
  - September 2017, Manjimup, WA
  - May 2018, Brisbane, Qld
  - November 2018, Hillier, SA
  - May 2019, Perth, WA
  - June 2019, Richmond, NSW
  - June 2019, Melbourne, Vic
  - August 2019, Maffra, Vic
  - August 2019, Forthside, Tas.

  See examples of presentations in Appendix D.
- Media and promotions via industry publications, stakeholder networks, radio interviews and a Facebook page. A presentation on the project and the benefits of earthworms is available online via Hort Connections 2019. The presentation used for this and other similar presentations have been distributed to participants at events who requested copies and are available via the Blue Environment website.
- Stakeholder engagement and communications plan for on-going promotion of the use of Earthworms and vermiculture in commercial vegetable production (see Appendix E).

Outcomes

The main project outcomes are:

1. Improved understanding of the distribution and levels of activity of earthworms under different commercial vegetable farm practices in different parts of Australia. The project found:

    - Levels of earthworm activity are generally low, even on farms adopting practices to promote soil health.
    - A healthy and agronomically useful population of earthworms is at least 100-200 earthworms per square metre, or at least two to four earthworms per a spade full/sod of approximately 150mm x 150mm cut to depth of 300mm. Growers have been encouraged to assess earthworm populations when conditions are favourable.
    - Historic and current tillage practices, as well as levels of soil carbon are key factors in determining levels of earthworm activity.
    - There is limited bio-diversity in the range of earthworm species present on commercial vegetable farms, with only a small number of earthworm species found on the surveyed premises. Native earthworm species do not appear to have a potential role to provide agronomic services on commercial vegetable farms and are not adapted to western farming systems used in Australia.
    - Surface-dwelling (epigeic) and deeper-dwelling (anecic) species that feed on organic matter at the soil surface appear to have no or limited capacity to provide key agronomic services to most commercial vegetable growers. This leaves endogeic species that are most active in the upper 100-400mm of soil to provide agronomic services.
    - Endogeic earthworm populations require soil organic carbon levels of at least 2% by dry weight and healthy soil bacterial and fungal populations. They are highly sensitive to tillage below 100mm, bio-,r chemical or thermal soil fumigation, extended periods of dry fallow, and some farm chemicals (many fungicides, some insecticides and, to a lesser extent, herbicides can have direct a direct impact).
    - There may be potential for earthworms harvested by vermiculture (worm farm) businesses or deliberately raised on farms to be used by growers to re-populate areas that have conditions favourable to earthworm activity but have had tillage, drought or soil fumigation events that have reduced numbers. However, the epigeic 'composting' earthworm species used by most commercial vermiculture operations do not survive in significant numbers when applied to farming land, so cannot be used to re-populate farms. Some vermiculture operations have healthy populations of useful endogeic species present under their main in-ground vermiculture beds and some claim that that these species can be present in populations of earthworms sold commercially, but most Australian vermiculture businesses are focused on the sale of vermi-casts and liquid extracts rather than live worms or earthworm egg-containing casts. International examples of vermiculture businesses selling useful endogeic species have been identified, but quarantine restriction would likely make it impossible to import such vermi-products. Two vermiculture businesses interested in developing methods for harvesting endogeic species in Australia have been identified.
    - There are low levels of grower awareness of the benefits of earthworms, earthworm-friendly farming practices, and vermiculture products. Many of the growers consulted have indicated that they would see an increased population of earthworms as an indication of good soil health, but are uncertain of the specific benefits of earthworm activity and expressed reservations about reducing the intensity of tillage – this is a key requirement to build an agronomically useful population of earthworms on most soils.
    - Many growers employing other practices to improve soil health remain dependent on tillage practices that are antagonistic to maintenance of healthy earthworm populations and were not convinced that earthworm activity could reduce the need for tillage. Most growers are busy and focused on maintaining yield and quality using modifications to existing practices, and the move to reduced tillage is perceived as too high risk and the potential benefits of earthworms are insufficiently proven.
    - Some growers that felt they had high earthworm populations were found to have lower than the minimum of 100-200 earthworms per square metre considered to represent a healthy and agronomically useful earthworm population.

2. Improved understanding of the farm management practices that promote or hinder earthworm activity on commercial vegetable farms. Key findings are:

- Reduced intensity and depth of tillage allows viable populations to thrive and provide agronomically beneficial soil 'tillage' and fertility enhancement services in the upper 250-400mm of soil (and deeper in some circumstances).

Monitoring and evaluation

The main project outputs have been:

Performance benchmark	Outcomes
Number of trial sites established and data quality from sites	The two main research sites were established and maintained.
Number of field demonstration sites established	A further 18 field sites were visited and sampled as part of the project.
Number of earthworm surveys conducted	A total of 44 earthworm surveys were conducted across the 20 participating sites. Data and observations from the surveys was used in the preparation of the research report and information sheets.
Factsheets prepared	Three final factsheets were prepared and a number of interim draft factsheets were prepared and used during the project.
Field days held, attendance at these and feedback from attendees	Blue Environment and SESL presented on the project at nine events. This included five field days and four industry events. Growers at field day events were surveyed about levels of awareness of earthworms and earth-worm friendly practices (see Appendix C) and discussions were held about barriers to adopting such practices. Survey responses were only useful for qualitative rather than quantitative information. This found that even with audiences interested enough to attend field days there was low understanding of earthworms and earthworm friendly practices, and often reservations about reducing the intensity of tillage.
Economic assessment of productivity of using earthworms in vegetable production	Completed and included in project research report (Appendix A).
Media articles and coverage	Articles, news items and media releases have been circulated during the project, with print and online publication of these in AusVeg and industry publications. Radio interviews were held on regional ABC in Western Australia, Tasmania and Victoria, with the Tasmanian interview preserved as an online resource.
Establishment of project Facebook	A site has been established and will be maintained. It has attracted few followers.
Preparation of review and maintenance of up-to-date reference library of relevant literature as e-library	Completed.
Benchmark and annual surveys of growers	Survey responses were poor and resources were directed to more detailed interviews with participating growers and surveys of those attending field days.
Establishment and activity of Communities of Interest (CoI)	We were not successful in this. Stakeholder engagement found limited grower awareness and interest in using earthworm activity as a soil management tool. This hampered the ability for the project team to establish communities of interest of commercial/levy paying growers to build and share knowledge about vermiculture in vegetable productions. Levels of grower interest and available time to participate was low. Field day attendance suggests interest agronomists and growers operating in less mainstream farm production such as Certified Organic, Biodynamic and regenerative agriculture, as well as more 'conventional' growers interested in building and maintaining soil health.

Performance benchmark	Outcomes
Inquiries received regarding earthworms in commercial vegetable growers	Most inquiries received followed from field day events, articles and media appearances. In total around 25-30 such inquiries have been received and replied to. It is expected inquiries will be ongoing.
Communications with growers through industry channels such as AusVeg and National Extension Program	Articles and news items promoting events have been communicated through these channels.
Communications with commercial vegetable agronomists and suppliers of complementary products, and the feedback from these	Our team has contacted suppliers of vermiculture products in Australia and New Zealand regarding products and the potential for harvesting and selling viable earthworms and cocoons/eggs in casts to boost earthworm numbers on areas with favourable soil organic matter levels and tillage practices. We have also consulted agronomists about grower awareness about earthworms and the viability of earthworm-friendly practices.
Other	
Development of a farm based and low tech method for assessing earthworm numbers and a benchmark for a healthy earthworm population	Method developed and promoted.
Survey of earthworm biodiversity on commercial vegetable farms around Australia	Surveys conducted with the conclusion that earthworm numbers and species biodiversity are low. Native earthworms appear to not have potential to be useful agronomically under cropping systems.
Investigation of opportunities to use vermicast products and live/viable earthworms from commercial vermicultralist (worm-farmers) in commercial vegetable growing	Completed, with the conclusion that although vermi-products can have positive effect, there are insufficient national standards to give growers confidence in products other than developing relationships with individual Vermiculturalists (i.e. supply of products are not interchangeable). The potential to introduce earthworms via viable live earthworms or cocoons may require further research.

Recommendations

Key findings from the work are:

- The most significant factors influencing the earthworm activity appear to be:
  - The use of green manures and crop rotations that build levels of labile carbon. On the studied soils, the farms that had green manures or pasture phases in their rotations have high levels of earthworms and the effect of burrows and casts on sub-soil structure was apparent.
  - Reduced intensity and depth of tillage. On most, but not all, of the studied soils, rotary hoe tillage to greater than 300mm greatly reduced earthworm numbers. This was more marked at sites where tillage was to the depth of clay pans or gravel layers. Two sites with intensive tillage were found to have healthy earthworm numbers but these both had sub-soils deeper than the tillage depth, allowing some earthworms to survive and recolonise areas.
  - Soil moisture. Soils that experienced significant and prolonged drying down the soil profile had low earthworm numbers despite good soil management practices.
  - Sensitive chemical use. Sites using integrated soil management and biological agents for disease control and soil health enhancement had higher earthworm numbers. However, some sites with scheduled regular use of insecticides and fungicides, but with high levels of labile soil carbon and reduced intensity tillage, had healthy earthworm numbers.
- The economic benefits of soil management practices that promote earthworm activity include reduced input costs and potential increase or maintained yields. The main economic values of earthworm activity are likely to be:
  - Reduced soil compaction and reduced need for tillage.
  - Reduced need for fertilisers due to ‘manuring’ with earthworm casts.
  - Deeper and healthier plant root growth.
  - Increased yields per unit of input. Little work has been done on the impacts of earthworm activity on vegetable crops, but on pasture and cropping systems yield increases in excess of 10% have been reported. Trials of soil management practices that improve soil organic matter levels and soil structure in vegetable farms have reported yield increases of 5-10%. This cannot all be attributed to earthworm activity, although they can make a significant contribution to soil structure and fertility.
- Earthworm numbers on most of the surveyed farms were below a healthy minimum population of 100-200 earthworms per square metre. This is despite many of these farmers having adopted practices to build soil organic matter.
- The biodiversity of earthworms present on the surveyed farms was low, with a small number of introduced earthworm species being found on cropped areas. This suggests native earthworms are not well adapted to European agricultural practices and the literature suggests native species are uncommon on any cropping land and even under areas of improved permanent pasture.

The project has found generally low levels of grower knowledge and interest in working with earthworms to promote soil health and productivity. A key barrier to greater use of earthworms in commercial vegetable farming is the reliance on many growers on tillage practices that can decimate earthworm numbers. Although healthy earthworm populations can potentially take over sub-soil tillage functions, many growers feel that they face a ‘chicken and egg’ dilemma in that heavy and deep tillage is needed to maintain soil porosity and crop yields and this prevents the establishment of earthworm populations that could take over this function. However, many of the soil and crop management practices being promoted by the Soilwealth program, AusVeg and National Extension Program will also promote beneficial and agronomic useful earthworm activity.

The main practice changes required to promote earthworm activity are:

- Building and maintaining levels of labile and other soil organic matter.
- Reducing the intensity of tillage below 100mm.
- Reconsidering soil-borne disease management practices to avoid the need for soil fumigation. Thermal and bio-

fumigation methods can devastate earthworm populations and their microbial food chain as effectively as chemical fumigants.

- Providing 'earthworm refuges' of uncultivated strips or patches in cropped areas where earthworms can survive and recolonise cropped areas following fumigation or deep and heavy cultivation. Permanent buried irrigation lines can provide such refuges in some situations and could be sown to cover crop species or mulched to aid earthworm survival.
- Potentially reintroducing earthworms to areas with low earthworm numbers or after cultivation or fumigation using 'sods' with viable endogeic earthworms of cocoons/eggs.

It is recommended Hort Innovations and industry partners continue to promote the benefits of earthworms and earthworm friendly practices as part of wider promotion of soil health.

It is recommended that growers are advised to adopt the following approach to transition from conventional cropping to practices that favour earthworms. Throughout this transition growers should be encouraged to monitor soil compaction/porosity and earthworm populations.

1. Build soil organic matter down the soil profile through a combination of cover crops, green manures and application of composts. Labile soil carbon from plant matter and roots will feed soil microbiology and earthworms. Composts can provide humic carbon compounds that improve soil structure and help to retain other particulate organic matter.
2. If needed, amend soil pH down the soil profile to within a 5.5-8.0 range.
3. Use deep-rooted cover crops in rotations to 'break up' heavy soils and increase organic matter down the profile. This should improve soil porosity and structure and allow less intense tillage over time. This transition will depend on how heavy soils are and their tendency to be become compacted. Growers will need to monitor levels of soil compaction and porosity to assess the level of cultivation required.
4. Transition to the use of less disturbing narrow tynes rather than deep rotary hoeing for any needed sub-surface tillage. Heavier use of hoes, scarifiers and/or power hoes might be used on the upper 100mm of surface soil to prepare seed or seedling beds, but over time the objective would be to move to more minimal tillage and strip sowing for at least some crops.
5. Where heavier tillage is required, aim to cultivate to a depth less than 300mm and consider leaving uncultivated strips or patches every 30m to allow earthworms to survive and recolonise cultivated areas. Permanent irrigation lines can be sown with cover crop species or covered with mulch to better act as refuges for earthworms that can recolonise other areas. If possible, undertake heavy tillage when upper layers of soil are dry so that more earthworms are further down the soil profile.
6. Reconsider the types and timing of application of chemicals used that are likely to impact on earthworms and their microbial food chain. In particular, methods of soil fumigation and fungal pathogen control need to be reconsidered. Integrated Crop management practices such as use of disease breaks and biological disease control agents should be considered to reduce the need for soil fumigation or scheduled applications of fungicide.
7. Where possible, maintain soil moisture under crops and cover crops, and avoid period where soil at depths of 200-400mm become very dry for periods greater than three months.
8. Where farm practices or climatic conditions result in devastation of earthworm populations, consider re-introducing earthworms from areas with earthworm-rich soil. This should only be considered if the land with low earthworm populations has high SOM and will not undergo heavy cultivation, disruptive harvesting (e.g. potato harvesting) or fumigation within the following two to three years.

Further work could be undertaken to work with commercial vermiculture (worm farm) businesses to develop:

- Industry standards for the quality assurance of processes and products. Until this is done, it will be difficult to promote generic vermicast and liquid extracts. Advice for vegetable growers about what Vermiculturalists should be able to demonstrate about their products could be developed.
- Ways to cost-effectively harvest and distribute viable endogeic earthworms and cocoons to allow growers to repopulate areas with low earthworm numbers.

Further work could be undertaken to better establish yield and other productivity benefits associated with maintaining healthy earthworm populations. These are likely to relate mainly to soil porosity and plant nutrient availability, but may also involve earthworms excreting compounds that promote healthier root growth.

Refereed scientific publications

Nil.

References

Please see research report (Appendix A) for references used in the delivery of this project.

Intellectual property, commercialisation and confidentiality

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

Acknowledgements

Blue Environment and SESL wish to acknowledge the following project participants:

- James Addision
- Geoff Baker
- Rob Blakemore
- Mark Boersma
- Peter Conasch
- John Cranwell
- Leanne Dimasi
- David East
- Greg Gibson
- Paul Grech
- Karen Guymer
- Steven Hodges
- Leonie Inger
- David Keller
- Brett Kirkpatrick
- Kevin Le
- Valentine Micallef
- David Murphy
- Ian Neuendorf
- Hugh Reardon
- Scott Samwell
- Adam Schreurs
- Graeme Stevenson
- Stan Velisha
- Peter Visage

Appendices

Appendix A: Project research report

Appendix B: Information sheets (B1, B2, B3)

Appendix C: Stakeholder survey sheet

Appendix D: Examples of field day and event presentations

Appendix E: Stakeholder engagement and communications plan

Final report

Earthworm field research report

7 JANUARY 2020

PREPARED FOR

Horticulture Innovations Australia

PREPARED IN ASSOCIATION WITH

SESL Australia

Report title	Earthworm field research report
Client	Horticulture Innovations Australia
Status	Final report
Author(s)	Bill Grant, Declan McDonald
Reviewer(s)	Christine Wardle
Project number	P708
Report date	7 January 2020
Contract date	1 June 2016
Information current to	1 May 2019
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Summary

Earthworms can have beneficial effects on surface and sub-soil structure and fertility. However, many common practices in commercial vegetable growing have negative impacts on earthworm populations and levels of activity. Practices that improve soil health such as increasing soil organic carbon levels, reducing intensity and depth of tillage and more sensitive use of farm chemicals can result in increases in earthworm numbers and activity and have significant benefits for soil structure and fertility.

This report details outcomes of field research undertaken as part of the Hort Innovations Australia funded project *VG15037 – Optimising the benefits of vermiculture in commercial-scale vegetable farms* in between July 2016 and September 2019.

Blue Environment and SESL Australia:

- Conducted a literature review of the potential benefits of earthworm activity in commercial vegetable growing and the factors that affect earthworm populations and activity. This considered farm practice as well as soil and climate effects.
- Established two detailed research trials at sites in Victoria and Tasmania. These were sampled in 2016, 2017 and 2018.
- Secured access to a further 16 demonstration and observational sites in NSW, Queensland, South Australia, Tasmania, Victoria and Western Australia. Earthworm surveys were conducted at these sites in 2016 and 2017. Observations about the impacts of different farm practices on earthworm numbers have been used to develop case studies.
- Undertook an economic assessment of the possible productivity benefits of farm practice changes that increase earthworm activity. These practices have wider productivity and farm sustainability benefits and the assessment focused on the additional benefits that are likely to result from increased earthworm activity.

Analysis of the results has sought to determine the significance of different land management practices on levels of earthworm activity and the impact of earthworm activity on soil health and productivity.

All sites were selected on the basis of growers adopting some practices to improve soil health and levels of soil carbon.

Interviews were conducted with growers about current and historic practices, and attitudes toward the adoption of practices that would increase earthworm activity.

Key findings include:

- There are multiple variables impacting on earthworm numbers and activities. Key factors are:
  - intensity of tillage practice
  - soil moisture
  - soil organic carbon levels, and particularly levels of labile carbon
  - levels of soil biological activity
  - cover crops/green manures
  - chemical regimes
  - site history/historical land management.
- The variability between and within sites made it impossible to obtain strong statistical evidence of correlation between earthworm numbers of different soil attributes. Two sites with 'good'

soil conditions were found to have inexplicably low earthworm numbers, and one site with less favourable soil conditions had 'hot spots' of surface dwelling, pasture worm varieties; the site had been under pasture for two years. These results as well as other variability across sites has prevented statistical validation of observed trends.

- Variability across the two detailed research sites, as well as favourable soil conditions under the 'control' treatments, has also reduced the statistical significance of observed trends, with only a weak to moderate statistical correlation between green manure crops, labile soil carbon and higher earthworm activity being observed.
- The most significant factors influencing the earthworm activity appear to be:
  - The use of green manures and crop rotations that build levels of labile carbon. The farms that had green manures or pasture phases in their rotations had high levels of earthworms and the effect of burrows and casts on sub-soil structure was apparent.
  - Reduced intensity and depth of tillage. On most, but not all, of the studied soils, rotary hoe tillage to greater than 300mm greatly reduced earthworm numbers. This was more marked at sites where tillage was to the depth of clay pans or gravel layers. Two sites with intensive tillage were found to have healthy earthworm numbers but these both had sub-soils deeper than the tillage depth, allowing some earthworms to survive and recolonise areas.
  - Soil moisture. Soils that had experienced significant and prolonged drying down the soil profile had low earthworm numbers despite good soil management practices.
  - Sensitive chemical use. Sites using integrated soil management and biological agents for disease control and soil health enhancement had higher earthworm numbers. However, some sites with scheduled regular use of insecticides and fungicides, but with high levels of labile soil carbon and reduced intensity tillage, had healthy earthworm numbers.
- The economic benefits of soil management practices that promote earthworm activity include reduced input costs and increased yields. The main economic values of earthworm activity are likely to be:
  - reduced soil compaction and reduced need for tillage
  - reduced need for fertilisers due to 'manuring' with earthworm casts
  - deeper and healthier plant root growth
  - increased yields per unit of input. Little work has been done on the impacts of earthworm activity on vegetable crops, but on pasture and cropping systems, yield increases in excess of 10% have been reported. Trials of soil management practices that improve soil organic matter levels and soil structure in vegetable farms have reported yield increases of 5-10%. This cannot all be attributed to earthworm activity, although they can make a significant contribution to soil structure and fertility.
- With appropriate soil management, earthworm activity can provide soil health and productivity benefits in intensive commercial vegetable production. Favourable soil management practices include: reduced and less intensive and deep tillage; maintenance of high labile soil carbon through the use of cover crop, green manure and/or pasture phases in rotations; management of soil moisture to prevent drying of soil in the upper 300 mm.
- Historic soil management, and particularly heavy tillage practices have resulted in low earthworm numbers on many farms, and even the adoption of some practices to improve soil health such as increasing soil organic carbon and reduced tillage may not be sufficient for earthworm numbers to recover. Properties with good soil health management but continued low earthworm numbers may need to artificially increase earthworm numbers by introducing them from other areas. Our surveys generally, but not always, found higher and healthy earthworm numbers on adjacent land that had not been disturbed.

1 Introduction

This report details outcomes from the Hort Innovations funded project, *VG15037 – Optimising the benefits of vermiculture in commercial-scale vegetable farms.*

Although earthworms are known to be an indicator of soil health, and contribute to soil and plant health, these effects are not well understood in commercial vegetable growing. Little previous research has been undertaken that is specific to commercial vegetable production.

The project has used two main field research sites in Victoria and Tasmania (as well as 16 other observational sites around Australia) and a review of relevant literature to investigate the key factors influencing earthworm numbers and any ensuing productivity benefits.

This report has the following sections:

- Review of literature
- Reporting of field research between 2016 and 2019
- An economic comparison of practices that promote earthworm activity
- Conclusions section summarising key findings.

2 Review of literature

Blue Environment has completed a review of literature regarding the land management practices that promote or harm earthworm activity, and the productivity gains arising from increased earthworm activity under cropping systems.

2.1 Introduction

Although earthworms are recognised as both an indicator of and contributor to soil health, there is limited research into the agronomic and productivity benefits of increased earthworm activity or the application of 'vermi-products' (such as casts, vermi-composts, liquid extracts or live earthworm or eggs/cocoons) in commercial vegetable production.

This review considers literature and other sources of information regarding the potential to use earthworms and other vermicultural practices to improve the sustainability of commercial vegetable growing. Key literature reviewed is listed in the references section and reflected within the text. The review has the following parts:

1. Earthworms and soil health. This discusses the different types of earthworms, their requirements for healthy growth, and their potential role in promoting soil health within agronomic systems including vegetable production.
2. Other vermicultural practices. This section considers the use of vermi-products from dedicated worm farms.
3. Productivity gains from earthworm activity and vermiculture products.
4. Practice change to promote beneficial earthworm activity. This considers how growers can modify practices to build and maintain earthworm activity at levels that have agronomic benefit. This also considered other agronomic benefits and potential risk of such practice change.
5. Systems for monitoring earthworm activity. This section details methods for monitoring earthworm numbers and activity with a view to developing cost-effective methods growers can use to determine current levels of earthworms and monitor changes in activity levels attributable to practice change.

2.2 Earthworms and soil health

Types of earthworms

Earthworms are a diverse grouping of macro-invertebrates of the taxonomic order *Megadrilacea*, with over 20 taxonomic families and over 1,000 distinct species. In Australia, there are over 700 recorded species of native and introduced earthworms. Despite this diversity of species, multiple studies have found that only a relatively small number of mostly introduced earthworms and very few native species persist or thrive under 'improved'/disturbed agronomic systems where tillage, introduced crop and pasture plant species, chemical fertilisers and other farm chemicals are or have been used. The reasons for this are considered in the following discussion, but key factors appear to be tillage, soil organic matter and nutrients and moisture. Only a small number (fewer than fifteen) introduced species are typically present where tillage is or has been used and introduced plant species are dominant. These 'agronomic' species are better adapted to European agriculture than native species which are rarely found under such conditions.

Earthworms can be broadly classed according to where in the soil profile they are most active, and are generally classed into one of the following three groupings:

- **Epigeic** species are 'litter dwelling' and are typically found on the surface and upper few centimetres of the soil. They can also be found in organic- and nutrient-rich upper 5-10cm of soils; for example, where manures have been heavily applied. These earthworms are relatively heavy feeders and are more rapidly reproducing than earthworms inhabiting deeper soil levels. Although these earthworms can burrow into the soil, they do not form permanent burrows and are mainly active on the surface. These species feed on decomposing surface organic matter such as leaf litter, hayed off grasses, manures and dead roots near the soil surface. They include species used as 'compost' earthworms that thrive in decaying organic matter but do not persist in great numbers when added to the soil. Epigeic species have a role in more rapidly converting surface organic matter into casts. However, they are generally only found where there is a heavy A-horizon or 'mulch' of organic material and high soil moisture at the soil surface, such as in pastures, in grassed orchards or on forest floors. These species struggle to survive under most vegetable cropping system due to tillage and lack of an organic 'mulch' on the soil surface. Some species that can also survive at greater depth in the soil may be present and increase in numbers during pasture or cover crop phases in cropping rotations.
- **Endogeic** species are most active in the upper 5-30 centimetres of soil, feeding on decaying plant matter and soil micro-organisms including bacteria, fungi, protozoa and nematodes. In order to thrive such species need soils with higher soil carbon (>1-2% by weight and ideally 4-5% or more), active soil biology and moisture. Depending on soil type and conditions, these earthworms can be present to greater depths down to 50cm. These earthworms mainly produce temporary burrows and 'work' the soil, consuming and passing their bodyweight of organic and mineral material each day during active periods. This activity improves the porosity of soil and moves organic matter from the surface down the soil profile. During hot and drier periods these earthworms can migrate further down the soil profile, but will generally go into hibernation (aestivation) at about 15-50centimetres' depth depending on soil moisture down the profile, with most at the 20-30cm level. This makes them susceptible to conventional tillage which can reduce earthworm populations by 80-90%.
- **Anecic** species live at depths of greater than 20-30 centimetres, but require undisturbed soils in order to dig permanent burrows to the surface. They feed on organic matter at the surface. For these reasons they are found in pastures but are not common in cropped areas or on vegetable farms. These earthworms help soil porosity and move organic material and nutrients down the soil profile, as well as moving soil from lower levels to the surface.

Although some Epigeic species of earthworms can reproduce rapidly under the right conditions and are referred to as 'compost earthworms', these species do not thrive on soils with low organic matter and nutrient levels. Buckerfield (1994) usefully divides earthworms into 'compost earthworms' that live in organic matter at the soil surface but do not work the soil and 'earthworkers' or 'workers' that work the soil. Some species that can act as both 'composters' and 'workers' - but these are mainly found in pasture rather than cropping systems. This may be to do with the generally low level of organic matter in soils under conventional cropping systems.

The relatively common and widely distributed *Lumbricus rubellus* (red earthworm) is one of the few earthworms that can work as both a composter and earthworker although it only thrives in organic- and nutrient-rich soils, commonly being found in higher numbers under dung pads in pasture. It could potentially be 'bred up' in an on-farm earthworm farm or dedicated earthworm bed and introduced to soils around a farm to artificially increase earthworm numbers, but this would only be effective of there were high levels of soil organic matter (SOM) and under such conditions populations of already present earthworms could be expected to increase.

Common 'agronomic' endogeic and anecic earthworm species are not such prolific breeders. Most of these species take over 150-200 days to become sexually mature. Because they are hermaphrodites, both earthworms in a mating are fertilised and then produce cocoons/eggs every 7 to 14 days for a period of months after mating. In most instances, the cocoons contain only one or two juveniles. This means it can take an earthworm from a hatching egg over 12 months to initially double the population of mature earthworms, but once fertilised will increase numbers at a rate of about 1 per week until the soil dries out and the earthworms go into aestivation/hibernation. If soil has higher organic matter and moisture and are not disturbed for a year, earthworm populations can recover to 'healthy' levels of 100-400 earthworms from relatively few adults.

Non-epigeic earthworms can live for four to ten years under undisrupted conditions and earthworms are capable of 'hibernation' during dry periods. In Australia, earthworms are generally not found in abundance in climates with less than 400 mm per year, and are more common in areas with rainfall of 600mm or more. Drying during a typical Australian summer in the 400-600 mm zone found about 60% of earthworms in aestivation 'cocoons' died off, and close to 100% died off during extended periods of drought, leaving surviving eggs to repopulate the areas when rains returned. Vegetable growers can use irrigation to promote and maintain earthworm numbers.

2.3 Benefits

The benefits of earthworm activity on soil health are well recognised but not always well quantified, and this is particularly true of cropping systems and vegetable production. Benefits of earthworms include:

- Improved soil porosity, aeration and root penetration. Earthworm burrows and improved soil ped formation associated with cast production improve the porosity of soils, helping air flow to greater depth, improving water infiltration, and in some instances allowing better root growth to depth or along horizontal burrows (Elton, 2006). Larger earthworms create larger burrows, so having a higher population of older mature earthworms will have greater positive impact on soil porosity than an earthworm population of smaller and less mature earthworms. This will require non-disturbance of active and aestivating earthworms through shallower and reduced intensity tillage.
- Conversion of readily degradable 'labile' organic matter into more stable 'humic/humified' forms. These can increase the amounts of soil organic carbon (SOC) persisting in the soil, and have benefits related to cation exchange capacity (CEC) and soil structure /ped formation. In some instances, casts and mucus excreted to lubricate earthworm movement through soil contains higher levels of calcium carbonate. This is a highly stable and persistent form of carbon and has a liming effect in acid soils.
- Production of 'casts' (droppings) rich in nutrients and stimulants for root growth and some beneficial soil microbiology. The nutrient composition of earthworm casts varies, but typically has 2.5-3 % dry weight (dwt) nitrogen, 1.8-2.9% dwt phosphorous, and 1.4-2.0% dwt potassium, as well micronutrients and plant growth stimulants. This NPK is largely plant available and about 3 to 4 times greater than typical composts. Casts are typically pH neutral and can have a 'buffering' effect and burrows containing casts can provide 'thoroughfares' for root growth in acid and alkaline soils. However, it is worth noting that earthworms are generally intolerant of pH conditions falling outside of the 5.5 to 8.0 range.
- Disease suppression. There is some evidence that earthworms can supress plant diseases by eating bacteria, fungi, and the eggs and juveniles of nematodes and insects, as well excreting compounds that feed and stimulate beneficial bacteria that 'crowd out' disease-causing microbes. The evidence for this in vegetable production systems is limited and may reflect benefits associated with application of compost products that have also been found to suppress pathogenic bacteria and fungi.

Factors influencing earthworm number and activity are:

- **Soil organic matter (SOM).** Common earthworm species feed on dead organic matter as well as fungi, bacteria and other soil microbes that feed on organic matter. Numerous studies show a strong positive correlation between SOM and earthworm activity (measured as number and/or biomass per square metre). A SOM level of at least 3-5% by dry weight appears to be desirable to sustain earthworm populations.
- **Tillage.** Heavy tillage reduces earthworm populations by as much as 80-90%, and rotary hoeing and multiple workings per crop can decimate earthworm numbers. It can take over six months to double the population of sexually mature individuals, and it may take over twelve months for earthworm numbers to recover after heavy tillage under typical seasonal conditions. On vegetable farms producing multiple crops per year, beds are often heavily tilled at least two or three times a year at three to six-month intervals. This does not allow time for earthworm number to recover, and in fact reduces numbers further with each tillage. Tillage, along with low soil organic matter is likely to be the reason for low earthworm numbers observed under cropping systems. No till and reduced intensive tillage results in higher earthworm numbers.
- **Moisture and waterlogging.** Earthworms need soil moisture to function. As soils dry, earthworms migrate down the soil profile and 'hibernate' (estivate).
- **Temperature.** Earthworms are most active when soil temperatures are 10-20^{o}C and will become inactive and dormant below this. Temperatures greater than 25^{o}C will reduce activity and result in some deaths, and temperatures greater than 35^{o}C will kill them.
- **Soil pH**. Earthworms prefer neutral to alkaline soils and cannot function for extended periods outside the pH range 5.5-8.0.
- **Available nitrogen.** Earthworm numbers have been observed to respond positively to higher rates of available nitrogen and organic nitrogen. Moderate fertiliser use may therefore benefit earthworm activity.
- **Chemical use.** Some herbicides and nearly all insecticides and fungicides will negatively impact earthworm numbers in the form of deaths, and/or reduced activity and biomass. Studies using pot tests typically record greater negative effects in earthworm numbers and health than field testing, and reviews of the toxicity of chemicals in crops have found that if chemicals are used according to label advice then earthworm activity is generally not greatly impacted. Herbicide use that increases the availability of higher nutrient organic matter can increase earthworm activity and numbers. Herbicide use on weeds and cover crops can temporarily increase labile organic matter to the soil and improve earthworm levels. Nitrogen fertilisers can also feed soil microbiology and earthworm activity. Fungicides, nematicides and some insecticides, including 'natural' products such as copper sprays and pyrethrin, can negatively impact on earthworm activity. Pyrethrin has been found to have greater toxic effect on earthworms than many synthetic chemicals. Earthworms have been recorded to migrate from chemical treated areas to untreated areas.
- **Soil fumigation.** Any effective form of soil fumigation, whether chemical, biological or thermal, will have drastic negative effects on earthworm numbers to the depth of soil treated. Chemical and some bio-fumigant methods create an environment toxic to earthworms and the soil microbes they feed on for several days or weeks, and therefore have greatest impact on populations.
- **Soil texture and structure.** Highly sandy soils or heavy/unstructured clays are not as conducive to earthworm activity as loams and lighter clay soils.

2.4 Other vermi-cultural products and practices

Vermicasts

Litter-dwelling epigeic or ‘compost’ earthworms can be used to convert high concentrations of organic material and manures into earthworm casts. Casts contain concentrated plant available nutrients (and a range of beneficial microbes, plant growth promoting chemicals and stable/ humified organic carbon and carbon calcium products). Casts are disease-free and pH neutral. Although casts can contain eggs and juvenile earthworms, the epigeic species typically do not thrive under cropped systems unless very high levels of organic matter are available in the upper 5cm of soil. Commercially purchased compost earthworms and casts are generally expensive and are not likely to persist in significant numbers under most vegetable production systems. It may be possible to raise some endogeic species within on-farm ‘worm farms’ or dedicated ‘worm beds’ with the purpose of producing casts and introducing higher earthworm populations around a farm. Earthworm beds could be managed by applying high levels of organics (manure, crop residues, clean food waste, and/or straw/hay) and maintaining soil moisture levels to promote earthworm activity. Casts from such areas could be excavated and either directly applied to land when soil moisture is high, or can be used to make liquid extracts.

Australian Standard 4454 Composts, Soil Conditioners and Mulches can cover vermicasts that have or have not been subject to pasteurization or composting, provided it passes provisions related to contamination, nutrient, pathogen, plant propagule and maturity levels, as well as provisions related to process and product quality management. However, there are no other or widely used Australian or industry standards for vermicast or liquid extract products (see below) and claims by some commercial vermiculturalists about the presence of beneficial biological and growth promoting hormones in products are not verified by standard tests. This means products can vary, and could make it difficult for agronomists to promote the use of products as soil health and root growth stimulants.

Liquid extracts

Liquid extracts from either exudate / leachate from earthworm farms or adding vermi-casts to water to make a ‘tea’ are sold commercially and have been shown to have a range of benefits including providing nutrients, beneficial microbes, disease suppression and plant growth hormones. However, some suppliers of earthworm cast teas suggested liquid exudates/leachate draining from earthworm-farms are inferior and potentially only provide nutrient benefits.

There is no Australian or international standard for the production of liquid extracts, so it is difficult to verify claimed attributes of extracts. Testing of a range of products from various suppliers by SESL has shown that product quality varies enormously in terms of nutrient status and microbial biomass. Vegetable farmers could produce vermi-casts using dedicate earthworm beds, and then produce vermi-teas from these. Guides for the production of vermi-teas are available, but the veracity of claims made regarding the attributes and benefits of compost teas is uncertain and will be influenced by a range of factors including inputs into earthworm farms, the management of the inputs and the ways in which vermi-teas are ‘brewed’. Although benefits from vermi-teas have been observed it is difficult to strongly recommend particular products or practices in vegetable growing systems based on current levels of knowledge.

2.5 Productivity gains from vermiculture

Little work has been undertaken that empirically measures direct productivity gains from increased earthworm activity or use of vermi-products in commercial vegetable production. Field trials in pasture and broadacre cropping systems have consistently shown growth responses of 30-40% by biomass yield, and pot tests of a range of crop species show strong yield responses. The rate of response will depend on conditions prior to the introduction of earthworms or practice changes that promote greater earthworm activity. In some of the trial work it is difficult to attribute yield responses specifically to earthworm activity. For example, practice change in cropping systems have typically involved application of compost or vermi-composts, reduced tillage and use of cover crop or pasture phases in rotation. These practices could have benefits separate to earthworm activity. However, the available data suggests increased earthworm activity has positive impacts on soil porosity, nutrient availability and root and plant growth, as well as potential disease control.

Other potential productivity gains from improved earthworm activity include:

- **Reduced soil strength and improved tilth.** This should reduce tillage costs and the need for tillage at depth. There is a 'chicken-and-egg' element to this on poorly structured and 'overworked' soils because tillage may be needed in the short term, but this will make it harder to establish earthworm populations that could reduce the need for tillage. Practices to increase soil organic matter/carbon and reduce tillage will need to be adopted to create the conditions under which earthworm activity can reduce the need for tillage.
- **Reduced fertiliser needs.** Although it is difficult to separate the role improvements in soil carbon and other soil biology might play in making nutrients more plant available, earthworms casts are nutrient rich and contain more stable soil carbon with cation exchange capacity, and are delivered within the root zone.
- **Reduced water needs and reduced surface pooling and erosion.** Again, it is difficult to separate the role earthworms play from that of increased soil carbon and other soil biological activity. However, earthworms clearly improve porosity and distribute SOM down the soil profile, which will improve infiltration and water-holding capacities of soils.
- **More even crops.** This is achieved by improving soil health across a paddock, through earthworm activity as well as practice changes promoting earthworm activity that have other soil health benefits.

A cost-benefit assessment of 'earthworm friendly' farming practices and net productivity outcomes if provided in section 5.

2.6 Practices to promote beneficial earthworm activity

On the basis of the literature review, the following table details vermiculture practices that are likely to promote earthworm activity or use vermi-products. This table describes the practices and details their benefits and disadvantages or risks, as well as providing commentary about the practices.

Table 1 Summary of vermicultural practices

Practice & description	Benefits	Disadvantages/risks	Comments
Reduced tillage:			
• Minimum/'no' till soil management with direct drilling of seeds or seedlings. • Reduced tillage intensity (narrow tines rather than rotary hoe)	• Reduced damage to earthworm numbers from tillage. • Reduces loss of SOC and nutrient. • Reduced tillage costs.	• Requires reasonably good soil structure. Can only be used if soil is not heavy or unstructured down the profile. Some tillage is required at most vegetable farms. • Typically requires greater use of broad spectrum knock down herbicides, some of which may impact on earthworm activity.	• May be suited to lighter soils and soils with good structure down the soil profile. Many soils on vegetable farms have been extensively worked and have poor structure down the profile. Management will be needed to improve soil structure and function before no till management can be used. Earthworms may have a role to play in 'tilling'/working soil down the profile.
• Shallow/surface tillage (upper 10cm). This would use shallow tines or power hoes to tease /'fluff up' upper layer into which seedlings can be planted.	• Reduced damage to earthworm numbers below 10cm. • Reduced fuel use and tillage time. • Less loss of soil moisture, organic matter and nutrients following tillage.	• Will require good soil structure down the profile, potentially with earthworms providing 'tillage'/earthworks at >10cm depth.	• Allowing surface soils to dry prior to tillage will result in earthworms migrating down the soil profile and avoiding damage from tillage.
• Strip tillage. This reduces the total area of tillage by confining tillage to the strip where seeds are to be sown and allows surface worms to escape direct impacts	• Reduced damage to earthworm numbers below 5-10cm. • Reduced fuel use and tillage time. • Less loss of soil moisture, organic matter and nutrients following tillage. • Over time, less fertiliser may be needed due to nutrient cycling in the soil and increased cation exchange capacity of soils.	• If soils have not yet achieved an acceptable level of soil structure, reduced strip tillage may not sufficiently loosen soil for plant root development	• There is great potential to use strip tillage for intensive vegetable production in view of the stated benefits as well as reduced impact on worms. Strip tillage can greatly reduce bed preparation costs, and soil health benefits reduce fertiliser costs and improve productivity.
Build and maintain soil organic matter (SOM)			
• Using cover crops and pasture phases	• Builds SOM and can allow earthworm numbers to build over an extended period of less disruption/ tillage. • Provides disease break.	• Can get significant drying of soil during cover crop and pasture phases if these are not irrigated.	• Although some herbicides can impact negatively on earthworm numbers, the creation of decaying SOM generally results in an increase in earthworm activity.

Practice & description	Benefits	Disadvantages/risks	Comments
	• Can allow herbicide control of broadleaf and other weeds. • Can help to improve soil structure down the soil profile, increasing the capacity for earthworms to work and further improve soil down the profile.	• Requires taking land out of intensive production for a period, although the practice should result in maintenance of higher yields. • Herbicides in weed control can impact on earthworm numbers.	
• Using manures to increase SOM and nutrient	• Adds labile SOM, nitrogen and other nutrients. • The SOM and nutrients can promote activity by more prolific 'compost'/epigeic as well as other deeper dwelling earthworms if soil moisture is high.	• SOM can be short lived compared to other sources. • Potential pathogens and weed seeds if manures are not composted /sterilised.	• Drenches used in livestock could potentially impact on earthworm activity. • Manures could be applied with epigeic earthworm casts and covered with mulch to get short-term boost in earthworm numbers and cast formation. This is unlikely to be practical.
• Using compost to increase SOM	• Adds labile and more stable SOM, some nutrients • Can add beneficial bacteria/fungi to soil. • Improves soil moisture retention and percolation down soil profile. • Improved soil structure and reduces bulk density. • Can provide 'buffering' on acid soil. • Potential disease suppression. • Composted mulches could be used to conserve soil moisture, improve water infiltration and make soil temperatures more constant, as well as contributing to SOC over time. • Composted mulches can be broadcast using a mechanical spreader reducing labour costs.	• Cost. Typically, a 2.5-5cm layer of composted mulch will cost $0.60-1.20 per square metre. • Potential for short term nutrient draw down and phytotoxicity with less mature composts can reduce germination and root growth. • Potential for physical and chemical contamination with some products. • Mulches can potentially provide habitat for insect pests. • Organic matter can reduce the effectiveness of some pre-emergent herbicides (herbicides can bind to organic matter and active ingredients bio-degrade more rapidly) and may have similar effects on other chemicals.	• Relative low cost immature compost products are available in many markets, but vegetable growers need higher nutrient and mature composts and these products typically command a premium price of >$25 per tonne, with application rates of >20 t/ha being needed to boost soil carbon (on a low carbon soil, approx. 80-120 t/ha would be required to boost soil carbon to the 4-5% desirable to sustain earthworm numbers. This could be done with multiple applications over several crops. • Composted mulches could conserve moisture and promote earthworm activity.
• Using vermicasts	• Concentrated nutrients and stable SOC • Potential root and plant growth promoting chemicals. • Potential disease suppression.	• Cost. Commercial vermicasts are very expensive and are often used to make liquid extracts. Vermicasts produced on farm might be used.	• Vermicasts are typically used as a fertility enhancer rather than a way to promote earthworm activity. However, there may be potential to spread earthworms and eggs

Practice & description	Benefits	Disadvantages/risks	Comments
		• Can contain weed seeds if they are not composted/pasteurised prior to earthworm activity.	with casts from a dedicated on-farm earthworm-beds.
• Using crop residues	• Lower cost way to increase soil carbon. • Retention of some nutrients.	• Volumes generated are unlikely to be sufficient for most crops. • Most of the organic carbon will be degraded. • Plant hygiene needs to be considered.	• Retention of residues will contribute, but is unlikely to build soil carbon significantly over time by itself.
• Using organic mulches	• Could be used to conserve soil moisture, improve water infiltration and make soil temperatures more constant, as well as contributing to SOC over time. • Cheaper than composted mulches.	• Cost of purchase and application. Units are available that 'roll out' and spread round bales but otherwise it is labour-intensive to spread mulches. • Potential nutrient drawdown. • Potential weed seeds. • Potential habitat for pest insects. • Might reduce effectiveness of some herbicides and pesticides.	• Mulches such as straw and hay are likely to promote earthworm activity by conserving moisture at the surface.
• Sod 'seeding'. Sods of earth with high numbers of eggs, juveniles and adults can be used to transplant earthworms into soils that have been managed to have high SOM and moisture.	• Earthworm numbers can be artificially increased across farms by transplanting earthworm rich sods into beds. • Can be used to repair earthworm numbers after tillage or chemical application. • Sod taking and seeding could be made more efficient and even mechanised through the taking and planting of 'cores'/'plugs' (although such systems do not yet exist)	• Labour intensive. • Does not always work. Some examples of trying to introduce new earthworm species to land have not been successful. • Some earthworm mortality can be expected in extraction and transport, and earthworms may migrate out of sods in transit. • Receiving soils will need high SOM, and moisture and already present earthworm numbers will build naturally. Seeding may reduce and repair the negative impacts of tillage. • Earthworms would need to be earthworkers rather than 'compost' earthworms to have long-term impact. • There is potential to spread weeds or soil-borne disease of sods are taken off-farm.	• Conditions in soils receiving sods need to be managed to suite work activity. • This technique has been used in pasture management but not vegetable production
• Creation of earthworm 'refuges'. This would involve creating strips	• Reduces the areas that need to be maintained for earthworm activity at all times. Other areas would still need to be	• Earthworms will stay where conditions are best, so refuges may need to be dried to promote migration to neighbouring soil.	• Such refuges could be maintained as isolated irrigated areas during cover crop or pasture phases.

Practice & description	Benefits	Disadvantages/risks	Comments
of zones near or on beds where conditions for earthworm activity are ideal, allowing activity, reproduction and migration to other areas. Refuges will have high SOM, no tillage, high moisture, high organics nutrient levels and no chemical application. A pile of manure or a manured area with an organic mulch	managed to have high SOM, reduced tillage and moisture during cropping stages. • Earthworms will migrate long distances if conditions in soil is good. • Sods from refuges that are high in eggs, juveniles or adults could be used to 'seed' areas with higher earthworm populations.		
Manage soil moisture. Moisture is essential to earthworm activity. Ideally soil will have 20-40% moisture in the top 30cm.			
• Irrigation	• Vegetable production generally uses constant irrigation and moisture levels required by crops should sustain earthworm populations.	• The cost of watering areas when they are not in crop is likely to be prohibitive.	• Watering to maintain earthworm numbers is unlikely to be viable, but limited watering with mulches and covers could create earthworm refuges.
• Use of plastic mulch	• Conserves moisture right to the surface of the soil, promoting earthworm activity. • Will also protect earthworms from birds and other predation. • Weed control.	• Often used with drip lines, resulting in 'wet' and 'dry' zones that could impede migration of earthworms. • Cost. • Post-use management and potential for plastic pollution or air pollution if it is burnt.	• Earthworms will stay where conditions are good, so dry zones will reduce migration which may mean earthworm numbers differ across an area.
• Use of organic mulch	• See above	• See above	• See above
• Drying topsoil before tillage or chemical application	• Drying will cause earthworms to migrate down the soil profile, so shallow tillage or pesticide application could kill fewer earthworms.	• Likely to make tillage more difficult and less effective in forming suitable seedling or seed bed. • Many not be possible in wet seasons or after rain events.	• This practice is worth considering if seasonal conditions allow it.

Practice & description	Benefits	Disadvantages/risks	Comments
Use of chemicals. Chemicals can negatively impact on earthworm activity through mortality or reduced health. However, management practices can reduce these impacts.			
• Herbicides	• Some herbicide use can increase earthworm numbers by building the stock of higher nutrient and degradable SOM.	• Herbicides can negatively impact on earthworm activity through death or reduced health.	• Chemical use needs to be planned and applied to minimise impact on earthworms. Some losses in earthworm numbers can be expected and the best way to manage this is create conditions for high levels of activity and reproduction so the stock of earthworm remains high so long as there is not a major kill event
• Insecticides	• No benefits to earthworms	• Many insecticides are toxic to earthworms.	
• Fungicides	• No benefits to earthworms	• Most are toxic to earthworms, including organic treatments containing copper.	
• Nematicides	• No benefits to earthworms	• Highly toxic to earthworms.	• Nematicide use is not compatible with earthworm activity. Some earthworms can reduce nematode numbers through predation.
• Fertilisers	• Likely to have a positive impact in most instances if nitrogen and other nutrients promote root growth and soil biology. Earthworms respond positively to higher nitrogen and particularly organic nitrogen sources	• Salts or short-term and lasting change in pH outside of 5.5-8.0 may reduce activity. • Fertilisers can 'burn off' SOC, reducing food for biota and earthworms.	• Managed well, fertilisers should improve conditions for earthworms
• Lime	• Earthworms prefer neutral to alkaline conditions.	• Short term exposure to pH greater than 8.0 may reduce activity.	• Likely to beneficial.
Soil fumigation or sterilisation. Fumigation methods will impact on both earthworm numbers and other soil biology on which earthworms feed.			
• Chemicals	• No benefit for earthworms	• Highly toxic to earthworms	• Chemical fumigation is incompatible with earthworms.
• Bio-fumigation crop	• Increased SOC following use of a bio-fumigation crop will have befit for surviving earthworms	• Likely to reduce earthworm activity and numbers	• Both fumigation techniques are likely to reduce earthworm numbers. • The best option will be to build SOM and other conditions so surviving earthworms can reproduce more rapidly. • Refuge strips of unfumigated areas outside beds could be maintained to allow earthworm survival and migration back into beds.
• Steam fumigation	• Less harsh than chemical fumigants	• Likely to be highly toxic to earthworms	

3 Field research and demonstration sites

This section summarises work undertaken at the two main field sites and 16 demonstration sites. These sites have all been surveyed for levels of earthworm activity, along with soil samples for laboratory analysis and field observations.

3.1 Earthworm and soil testing methods

Earthworm numbers are estimated using the following method that was developed following a review of methods used in previous earthworm research.

Sample points are selected at random at roughly equal (paced distances are used) points along a transect across the sites. At each sample point a spade is used to rapidly dig a hole comprising of 4 x 150 mm x 150 mm sods to a depth of at least 300 mm (i.e. a 300 mm x 300 mm x 300 mm sample). Figure 1 shows a typical sampling hole. The sides of the holes are cut vertically and all soil in the void removed and laid on a tarpaulin. Excavated materials are then hand-sorted, with earthworms being classified according to:

- Maturity (‘adults’, showing developed ‘saddles’ and typically with more visible genitalia; ‘large juveniles’, specimens without developed saddles but larger than 20 mm in length; ‘small juvenile’, specimens without saddles and larger than 20 mm).
- Type. This is first done on the basis of grouping similar-looking earthworms and then field and laboratory identification of representative samples using identification guides and taxonomic dichotomous keys. Most earthworms found have fallen into a small number of introduced ‘agronomic’ earthworm types and most can be identified in the field. Although the relative low diversity of earthworm species seems remarkable given that there are over 700 native species of earthworms in Australia, it is consistent with previous research that has found that only a small number of earthworm species are adapted to co-exist with conventional cropping and improved pasture production systems. This suggests that native species are highly sensitive to tillage and disruption of pre-European ecosystems, and also possibly farm chemical use.
- Location in the soil profile. Most the earthworms found have been readily identifiable endogeic (upper soil dwelling species that are most active in the upper 5-300 mm of soil, migrating deeper to ‘hibernate’/aestivate if sub-soil conditions allow it). A few ‘hot spots’ of epigeic species (surface dwelling species that live in the upper 300 mm of the soil profile) were found on areas under pasture, but most have been endogeic species. The endogeic species are those most likely to provide agronomic benefits such as increased porosity, nutrient cycling and production of root growth stimulants in the root zone. Deep dwelling (anecic) species have not been found by the survey and little evidence has been found of their deep vertical burrows and surface feeding in cultivated areas, although some growers reported finding deep dwelling earthworms when excavating and evidence has been observed on uncultivated areas (see Figure 2).

Figure 1 Typical sampling hole (300 mm x 300 mm x 300 mm) and hand sorting for earthworms

Hand sorting has been shown by previous studies to capture over 90% of earthworms in the sample, and our sorting method is very thorough, with each sample of soil being sorted through at least three times or until no further earthworms are being detected in the sample (for example, if an earthworm is found in the sample on the third sorting of the sample, then the sample will be sorted for a fourth time, and so on until a re-sorting does not find any further earthworms). This method captures most adults and juveniles longer than 5mm. In many instances, smaller juveniles and eggs were also detected, but these smaller organisms are more likely to not be detected using this method. The sorting teams were overseen by the authors of this report and a consistent sampling method was used across all sites. In 2018/19 some observational sites were sampled using a simpler smaller sod (150 mm x 150 mm x 300 mm) method and compared with the 300 mm X 300 mm X 300 mm sod method. This found that on sites with higher earthworm numbers, the small sod method provided a good indication of earthworm numbers, but on sites where earthworms were less common, the large sold method was more likely to detect the presence of earthworms than the small sod method. However, the small sod /single spade-full sampling method is a useful tool for land owners to determine whether they have healthy earthworm populations, and allows more points to be sampled in a shorter period of time.

For the main field research sites there are three replications of five treatments, and three sample points are made in each of the 15 plots. For the observational and demonstration sites, five test holes are dug across the test area. The number of earthworms recorded is converted to an estimate of earthworms per square metre by dividing the counted number by 0.09 m^2 (0.3 m x 0.3 m). The average earthworm counts from each of the test holes is used as an estimate of earthworm numbers over the sample area.

Effects of moisture and tillage

One of the key findings of this project has been that soil moisture and recent tillage have very significant impact on earthworm activity and counts in the upper 300-400 mm of soil. Sites that have had high earthworm counts previously or have practices that should foster healthy populations of earthworms have been found to have much lower counts when the soil is drying or the area have been worked within the previous 2-3 months. Under low moisture or drying conditions earthworms migrate either down the soil profile or to areas where soil moisture is more favourable. The means that it is not always valid to compare counts from year to year as an indication of trends in population – a lower or higher count in one year does not necessarily indicate a change in levels of earthworm numbers if soil moisture conditions are different. This means that year-to-year comparisons of earthworm number are less meaningful than comparing the relative number of earthworms found under different treatments at the same sampling time.

Other variables

In addition to soil moisture and recent tillage, a range of factors can affect earthworm activity at the time of sampling including:

- The time of day and weather conditions. Earthworms are more likely to be higher in the soil profile in the early morning and on cooler and less sunny days.
- Conditions in neighbouring areas/plots. Earthworms will migrate to areas with more favourable conditions.
- Plant species in the sample area. Some plant species create conditions that are attractive or repulsive for earthworms. Mustards, some brassicas and ilium species are thought to repel earthworms.
- Chemical use in the sample area. Some chemical applications are toxic to earthworms and although they might not be killed, they will migrate down the soil profile and to areas that have not been treated with chemicals.
- Season/time of the year and conditions in previous 6-12 months. Earthworms are not prolific breeders and hatched juveniles take months to achieve maturity. A late or poor autumn break will delay hatchings and the numbers of more mature earthworms found months later. One vermiculturalist has observed that earthworms migrate further down the profile when the moon is full, but this has not been verified in the literature.

The net effect of these variables is that it has been difficult to obtain statistically strong data and it is difficult to compare earthworm counts from year to year. However, main research sites have provided some statistical data, and the data collected and observations made on site across all sites have contributed to knowledge about the relative significance of practices that benefit or harm earthworm numbers.

The outcomes of the research are detailed in the following sections.

3.2 Main field research sites

Blue Environment and SESL Australia established two main field research sites. These were designed to assess different management practices on earthworm activity and soil health attributes.

The treatments used at the research sites were:

1. Control – the treatment used by the grower across the non-trial area
2. Compost application – this treatment should increase levels of soil organic carbon and promote soil micro-biology
3. Vermicast application – this treatment increases levels of soil organic carbon, promotes soil microbiology, and also tests the potential for vermicast products to boost soil health. It can also be seen as simulating the effect of increased earthworm activity in producing vermicasts in the soil.
4. Biofumigant cover crop – this treatment allows examination of the impacts of biofumigant crops on levels of earthworm activity. Logically, although biofumigant crops have other positive disease and pest control benefits, effective biofumigation is likely to impact negatively on earthworm numbers.

5. Cover crop/green manure. This treatment looks at the effect of cover crops on soil health and earthworm activity. Logically, cover crops should increase levels of soil organic carbon and labile organic matter, boost microbiological activity and increase earthworm numbers.

Earthworm counts and soil samples were undertaken in 2016, 2017 and 2018.

The trial sites and outcomes are detailed below.

Dicky Bills/Australian Fresh Salads/Dicky Bill, Maffra, Victoria

Dicky Bills/Australian Fresh Salads, also trading as Dicky Bill, is an intensive producer of packaged leafy and Asian salads. The Maffra farm was established in 2012 on former dairy and beef pasture and has adopted practices to build and maintain healthy soils from that time. Practices include:

- Reduced depth and intensity of tillage. Power hoes are used to work the upper 100 mm of the soil. The soil structure below this is good, allowing aeration, drainage and root penetration. This soil structure appears to be at least in part due to earthworm activity and other soil biology.
- Permanent beds with controlled traffic. This avoids soil compaction.
- Precision farming. Farm inputs are managed using GPS tracking and agricultural software that applied fertilisers according to specific need.
- Cover crops. The property is intensively and close to continuously cropped, growing baby leafy and Asian greens on short rotations. Production is in the order of 10 tonnes of leafy cut salad per hectare per year. Some cover crops have been introduced into the rotation to help to maintain soil carbon levels and avoid 'fallow' periods.
- Compost application. Composts and compost-fertiliser blends meeting the Australian Standard for compost (AS 4454-2012) are used to contribute to soil carbon and health.
- Biofumigant crops. These are used to control soil-borne diseases and pests.
- Sensitive chemical use. Fungicides are being phased out, and herbicides and insecticides are being used responsively rather than as part of a scheduled spraying program.
- 'Pro-biotic' biological sprays 'brewed' using compost and other inputs. These are being used to boost beneficial soil microbiology.

The soil is a clay loam, with reasonably heavy clay down the soil profile at depths of greater than 250 mm. Earthworm activity in the form of burrows and casts were observed down the soil profile to depths of 300-400 mm. During drier periods irrigation is managed to only keep the upper 250 mm root zone moist with limited infiltration further down the profile. This may reduce earthworm activity down the soil profile and increase the impact of even shallow tillage in the upper 100 mm on the total active earthworm population. In some areas the subsurface clay is forming a hard-pan, but in others earthworm activity appears to be contributing to greater porosity of the heavier clay layer to greater depths. Deep ripping is periodically used to break up the forming hard pan, but this is only needed every three to five years rather than as a regular soil management practice.

The randomised block design used at the site is shown in Figure 3. Immediately prior to the establishment of the trial in 2016 the site had been under a biofumigant cover crop (Caliente mustard), and in 2017 and 2018 trial beds at the time of testing were under a range of leafy and Asian green salad varieties, tatsoi, green and red mustard and other leafy greens. The site is fairly level.

The biofumigation crop prior to the establishment of the site could be expected to reduce earthworm numbers and create a 'level playing field' across the site for earthworm numbers and soil-borne diseases and other micro-biology.

Figure 2 Maffra field trial design

Block 1	Compost	Biofumigant crop	Green manure	Worm casts	Control
Block 2	Worm casts	Control	Compost	Biofumigant crop	Green manure
Block 3	Biofumigant crop	Green manure	Worm casts	Control	Compost

Figure 4 shows monthly rainfall at the Maffra weather station in 2016, 2017 and 2018. This shows:

- In 2016, rainfall was above average in June and July, below average in August and higher in September prior to sampling. At the time of sampling, moisture content was observed to be good down the soil profile and was recorded at around 23-26% across the site.
- In 2017, rainfall was significantly below average in June and July, slightly above average in August and then dry prior to sampling in September. However, soil moisture conditions were observed to be generally good at the time of sampling, with some drying down the profile. Irrigation was keeping the upper 250mm wet, but in some areas the soil profile was drying below this and some earthworms were observed to be aestivating. The number of earthworms counted is likely representative of levels of earthworms active in the soil when conditions are good.
- In 2018, autumn and winter rainfall was below average, and the site was drying at the time of auditing. Uneven irrigation meant that moisture levels varied across the sampled area and there was some variability, with block 3 being notably drier than the other two blocks and this was reflected in the relative numbers of earthworms observed in this block compared to the other two. In Blocks 1 and 2, soil moisture was generally good down to 250-300mm. This is reflected in the higher counts on these blocks compared to Block 3 samples.

Figure 3 The Maffra trial site

Figure 4 Annual rainfall data for Maffra 2016-2018

Source: www.bom.gov.au

Results - Maffra

Earthworm counts for treatments for each year are summarised in Table 2.

Table 2 Changes in average earthworm numbers 2016 to 2017, Dicky Bills/Australian Fresh Salads, Maffra, Victoria

Year	Earthworm maturity	Average number of earthworms per square metre by treatment					Average all
		Compost	Biofumigant	Green manure	Vermicast	Control	
2016	**Total**	**70**	**37**	**93**	**89**	**56**	**69**
	Adults	22	19	41	19	7	21
	Juvenile	48	19	52	70	48	47
2017	**Total**	**311**	**330**	**963**	**324**	**393**	464
	Adults	107	96	444	102	89	168
	Juvenile	204	233	519	222	304	296
2018	**Total**	748	241	1,011	533	607	628
	Adults	67	22	385	274	81	166
	Juvenile	681	219	626	259	526	462
Percentage change from 2016-2017	**Total**	**344%**	**792%**	**935%**	**264%**	**602%**	**572%**
	Adults	53%	159%	377%	15%	59%	143%
	Juvenile	191%	530%	458%	149%	443%	329%
Percentage change from 2016-2018	**Total**	**969%**	**551%**	**987%**	**499%**	**985%**	**810%**
	Adults	-5%	-40%	314%	208%	46%	140%
	Juvenile	874%	491%	573%	191%	839%	570%

A healthy number of earthworms is considered to be at least 100-200 per square metre, so in both 2017 and 2018, all treatments including the Control showed very healthy numbers of earthworms.

In all years, nearly all of the juveniles were larger specimens (>20mm in length) rather than hatchlings, and were not classified as adults because they did not have a fully formed saddle. The higher number of adults under some treatments may be the result of earthworm migration to more favourable conditions from other treatments.

Data collected at the site has been assessed by a biometrician (see Appendix 1). For the Maffra sites, this found that:

- Numbers of earthworms were statistically higher under the Green Manure treatment than the Control and other treatments.
- Although the average numbers of earthworms under Compost and Worm Cast treatments were higher than the Control, variability within the data meant that this was not statistically higher under a 95% confidence interval.
- There was an apparent relationship between potassium permanganate oxidisable carbon (PPOC) and earthworm numbers. When this factor was corrected for, the number of earthworms under the Worm Cast treatments was also statistically significantly higher than the Control treatment.
- Due to variability in data across all treatments, few strong correlations were found between other tested soil parameters and earthworm numbers.

It is worth noting the levels of soil organic carbon, total nitrogen and soil microbiology indicators were 'healthy' across all treatments in 2017 and 2018, including the Control, and this possibly reflects that the standard management practices at the Maffra site are close to best practice. The farm was established on long-term dairy pasture and has been well managed, so the Control treatment represents a well-managed soil in terms of organic matter, reduced intensity of tillage, controlled traffic and sensitive chemical use. This is reflected by the relatively high average earthworm numbers under the control treatment, and discounts the positive effects of green manure, compost and vermi-cast treatments.

Although the results are not statistically strong, some observations can be made about the relative performance of treatments.

Figure 5 compares earthworm counts in each year and shows the variability in Block 3 treatments in 2018. Overall, the trend was toward increased earthworm numbers compared to 2016. This was not surprising as the site had been bio-fumigated in 2016 which would have reduced earthworm numbers. The greatest increases were observed under the Green Manure and Compost treatments. Again, an issue to consider on this site is that the Control treatment represents good soil management practices associated with less intensive tillage, sensitive chemical use and a history prior to the trial of managing soil organic carbon levels.

Figure 5 Earthworm counts across treatments and repetitions by year

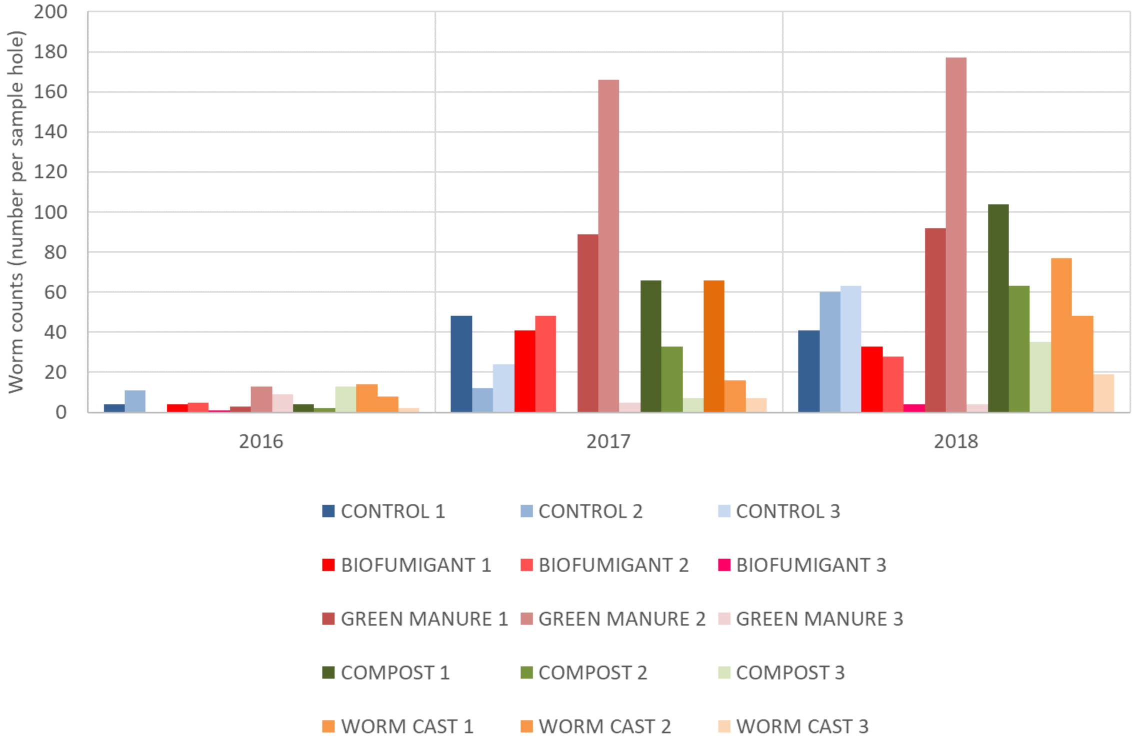


Figure 6 compares earthworm counts between treatments in each year. Standard error bars are shown. Figure 7 shows trends in earthworm numbers under different treatments.

Figure 6 Comparison of treatments per year, Maffra

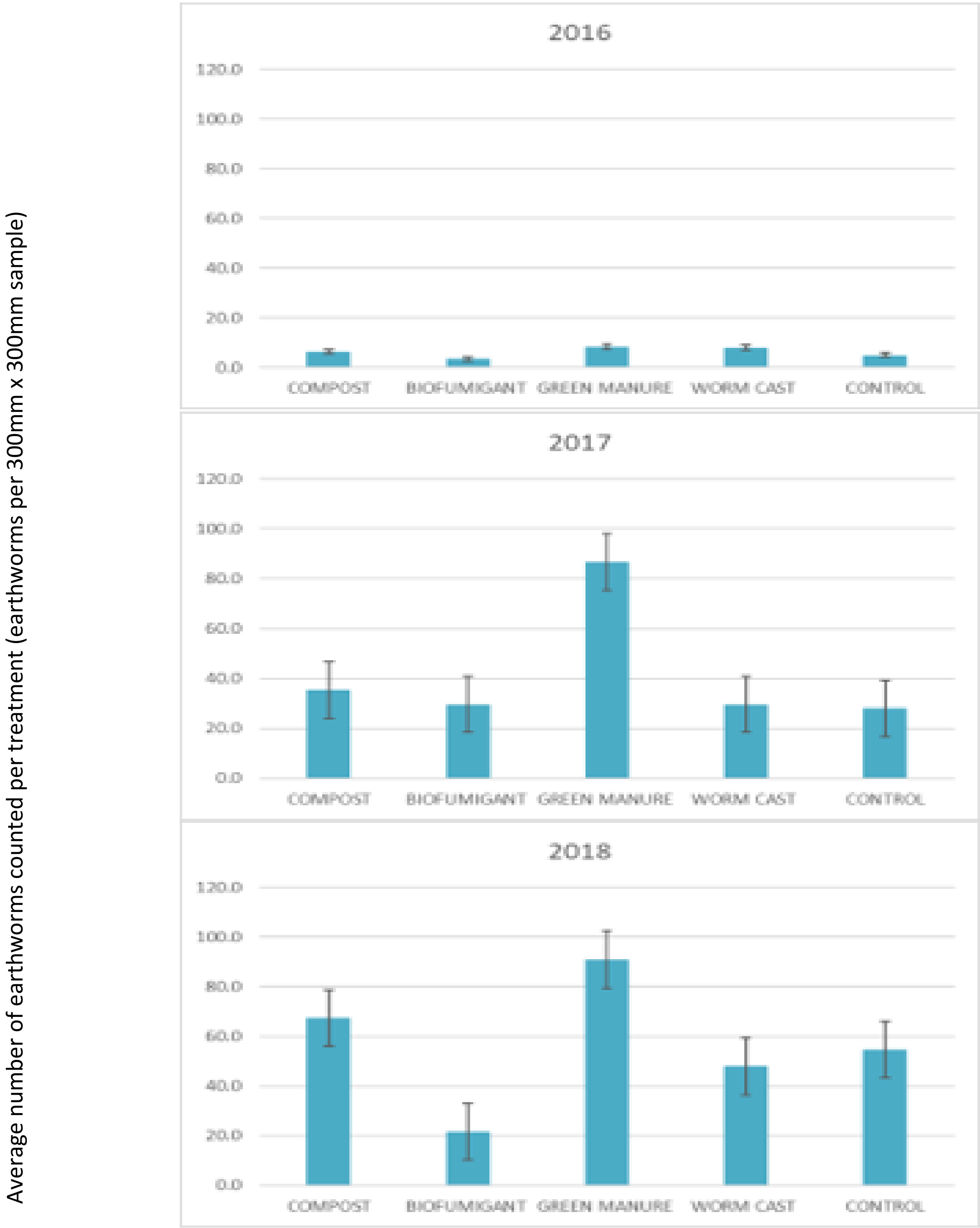
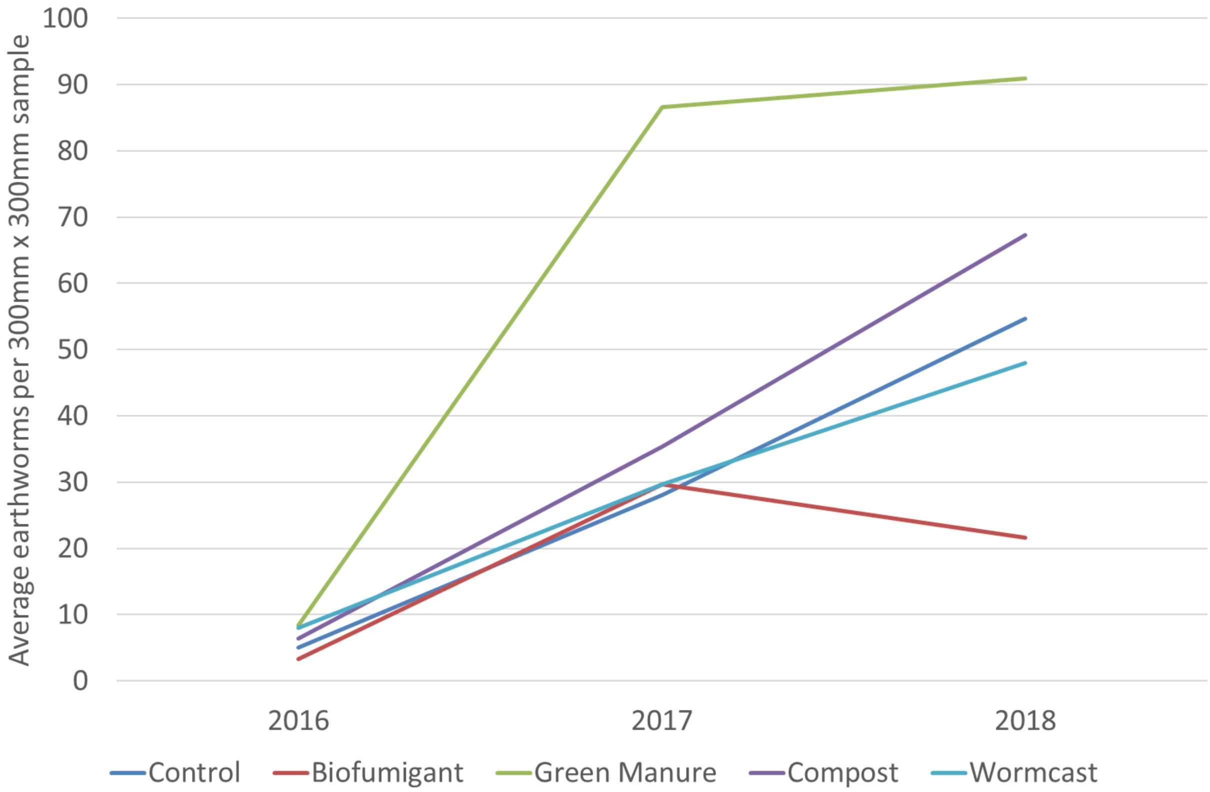


Figure 7 Trends in observed earthworm counts, Maffra



These, as well as the data presented previously in Table 2, suggest the following:

- Very high levels of earthworm activity are found across all treatments. Earthworm numbers were healthy at greater than 20 per 300 mm X 300 mm sampling hole in all treatments in 2017 and 2018. A healthy population of at least 100-200 earthworms per square metre is equivalent to 9-18 earthworms per 300 mm x 300 mm sampling hole. All treatments have healthy levels of soil carbon.
- There was a significant increase in earthworm numbers from 2016 to 2017. This can in part be attributed to the use of a biofumigant crop across the site immediately prior to establishment of the different treatments, and suggests the use of biofumigant crops does not have longer term impact on earthworm numbers if soil health favours earthworm activity. Other factors that could have contributed to lower earthworm numbers in 2016 include soil moisture, seasonal conditions, temperature and time since tillage, but these factors were similar in both years, so the biofumigant crop is considered the most likely cause of the lower numbers.
- Soil moisture at the time of sampling is highly significant on the number of earthworms present in a sampling area. In 2018 the site was drying in some areas and wet in others. Earthworm numbers were low across much of Block 3, resulting in low earthworm numbers.
- The Green Manure treatment resulted in the highest numbers of earthworms in 2017 and 2018. Interestingly, the levels of soil organic matter and soil microbiology under the Green Manure treatment were not statistically higher than other treatments at the time of soil sampling. This reflects the close to best practice soil management practices already used by Dicky Bills/Australian Fresh Salads. The higher earthworm numbers may reflect a more conducive year-round environment for earthworms under Cover and Green Manure crops. It is also possible that organic material and microbial populations were higher during cover cropping and immediately following green manuring and this supported higher earthworm populations, but at the time of sampling the

levels of soil organic matter and biology under the Green Manure treatment had fallen to a similar level to other treatments.

- The Compost treatment had higher average earthworm numbers than the Control treatment, but this was not statistically significant at a 95% confidence interval.
- Earthworm numbers were lowest under the biofumigation treatment. This is unsurprising as bio-fumigation will kill many earthworms as well as disrupt the soil bacterial and fungal populations on which earthworms feed.

Figure 8 Examples of the effects of earthworm on soil activity being visual apparent, Maffra

This figure clearly shows the extent of soil aeration through earthworm burrowing. Also visible are globular ('ball shaped') casts that contribute to formation of stable soil peds and soil aeration and drainage. The casts also contain plant-available nutrients, compounds that stimulate plant root growth and soil biology, and more stable organic carbon that increases cation exchange capacity. Exudates ('slime') released by earthworms to lubricate their movement through the soil also contain organic-calcium carbonate compounds that can have a soil conditioning effect.

Charlton Farm/Addison's, Moriarty, Tasmania

Charlton Farm site was converted from dairy pasture to vegetable growing in 2002. Crops sown on the site since 2003 are listed:

- 2003/4 Green beans
- 2004/5 Onions
- 2005/6 Ryegrass sheep grazing
- 2006/7 Potato
- 2007/8 Green beans
- 2008/9 Poppies
- 2009/10 50% onions 50% grass ungrazed
- 2010/11 Ryegrass sheep grazing
- 2011/12 50% peas 50% onions
- 2012/13 potatoes
- 2013/14 Green beans
- 2014/15 Poppies

- 2015/16 Broccoli
- 2016/17 Peas, followed by fodder maize in non-trial areas
- 2017/18 Broad beans followed by rye cover crop in non-trial areas
- 2018 a potato crop had been sown weeks prior to sampling and was emerging. Raised beds had been formed and the area was under boom irrigation.

Since 2011/12 an ungrazed ryegrass cover crop and green manure has been sown post-harvest over autumn-winter, and sprayed out in July prior to direct drill seeding of crops. Narrow tined ripping is used in most years to a depth of 300-350 mm to manage a clay layer, and light ploughing with a power hoe to 200-250 mm is used to prepare the seed bed in some seasons. The result of this management is that all treatments, including the Control, have healthy levels of organic carbon.

The site layout is shown in Figure 5. The treatments were applied after earthworm counts and soil testing in 2016.

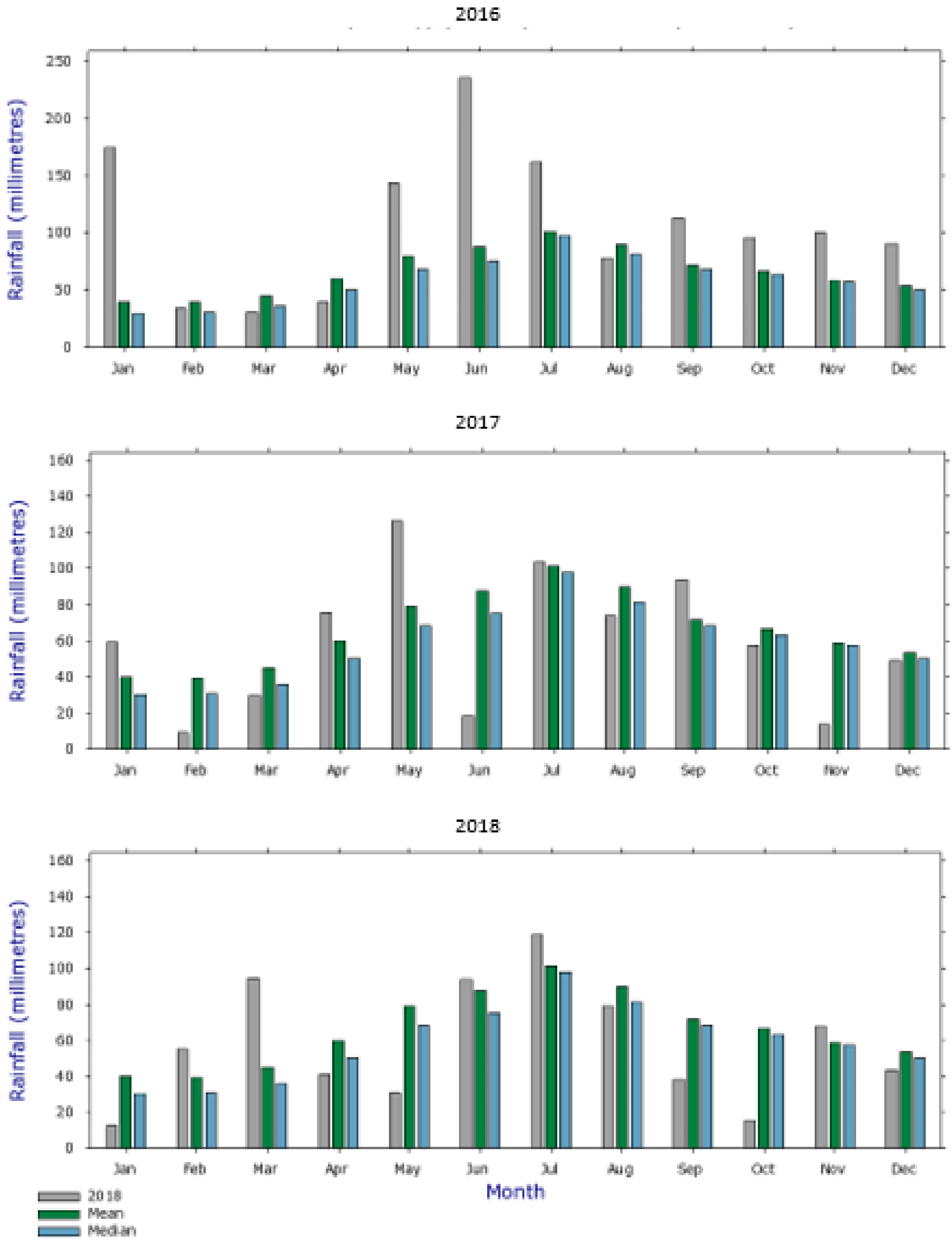
Figure 9 Design of Charlton Farm field research site

Green manure	Worm casts	Control	Compost	Biofumigant crop
Control	Compost	Biofumigant crop	Green manure	Worm casts
Biofumigant crop	Green manure	Worm casts	Control	Compost

The soil is a clay loam overlying a heavier clay and gravel at 300-400 mm. The site is gently sloping, with shallower soils further up the slope. At the time of sampling in 2017 there had been a recent heavy rainfall event in addition to irrigation, and some beds – particularly further down the slope – were wetter than others. Earthworm numbers were typically higher under wetter conditions. At the time of earthworm counting the entire site was sown to broad beans which were at first flowering stage.

Rainfall in 2017 near Moriarty compared to average and median data is shown in Figure 6. This shows fairly average rainfall in 2017, other than a significantly drier-than-average June following a wetter May.

Figure 10 Rainfall 2016-2018 compared to long term average, Hamley (approximately 4 km from Moriarty site)



Source: www.bom.gov.au

A summary of earthworm counts at the Moriarty site in 2016, 2017 and 2018 is shown in Table 3.

Table 3 Changes in average earthworm numbers 2016 to 2017, Charlton Farm, Moriarty, Tasmania

		Treatment					Average all
		Compost	Biofumigant	Green manure	Vermicast	Control	
2016	Total	244	422	263	419	274	324
	Adults	170	248	93	226	159	179
	Juvenile	74	174	170	193	115	145
2017	Total	296	319	437	304	504	372
	Adults	70	37	111	96	130	89
	Juvenile	226	281	326	207	374	283
2018	Total	63	30	133	107	44	76
	Adults	81	11	85	37	22	47
	Juvenile	144	41	219	144	67	123
Percentage change from 2016-2017	Total	21%	-25%	66%	-27%	84%	15%
	Adults	-59%	-85%	20%	-57%	-19%	-50%
	Juvenile	205%	62%	91%	8%	226%	95%
Percentage change from 2016-2018	Total	-74%	-93%	-49%	-74%	-84%	-77%
	Adults	-52%	-96%	-8%	-84%	-86%	-74%
	Juvenile	95%	-77%	29%	-25%	-42%	-15%

The biometrician's report (See Appendix A) did not find statistically significant differences in treatments at the site. This was due to variability within treatments and the farmer's use of land management practices that promote soil health across all treatments including the Control treatment. The results are described below.

Figure 11 compares earthworm counts in each year. This shows fairly uniform earthworm numbers across the site under all treatments. This may reflect good soil health management by the farmer prior to the establishment of the trial. It is only in 2018, when conditions were drier, that some differences can be seen.

Figure 12 compares earthworm counts between treatments in each year. Standard error bars are shown. Figure 13 shows trends in earthworm numbers under different treatments.

Due to variability across the site there were no statistically significant differences between the treatments in 2017. However, the results show:

- Healthy earthworm numbers in both 2016 and 2017 with over 200 earthworms per square metre under all treatments in both years, and an average of over 320 across the site in both years.
- An overall slight increase in earthworm numbers under all treatments other than the biofumigant and vermicast treatments. The decline under biofumigant treatment is expected as it can be expected to reduce earthworm populations. The reason for the decline under the vermicast treatment is unknown and may be due to variation across the site.

- An increase in earthworm activity under the green manure and 'control' (which was a ryegrass cover crop). This shows the benefits of green manures and cover crops. The higher number of adults under the green manure treatment may be due to migration of earthworms to the site.
- A decline in the number of adult earthworms from 2016 to 2017. This is most probably due to sampling being undertaken slightly earlier in the year in 2017. The number of juveniles increased and many of these were approaching maturity at the time of sampling (i.e. they were large juveniles that had yet to develop obvious 'saddles' or visible genitalia).

The impacts of treatments and higher levels of tillage associated with establishing a potato crop at Moriarty in 2018 will be assessed by the 2018 earthworm counts.

The results from the Maffra and Moriarty sites do not show strong differences in earthworm numbers on any treatments other than the green manure crop.

Figure 11 Earthworm counts across treatments and repetitions by year, Moriarty, Tasmania

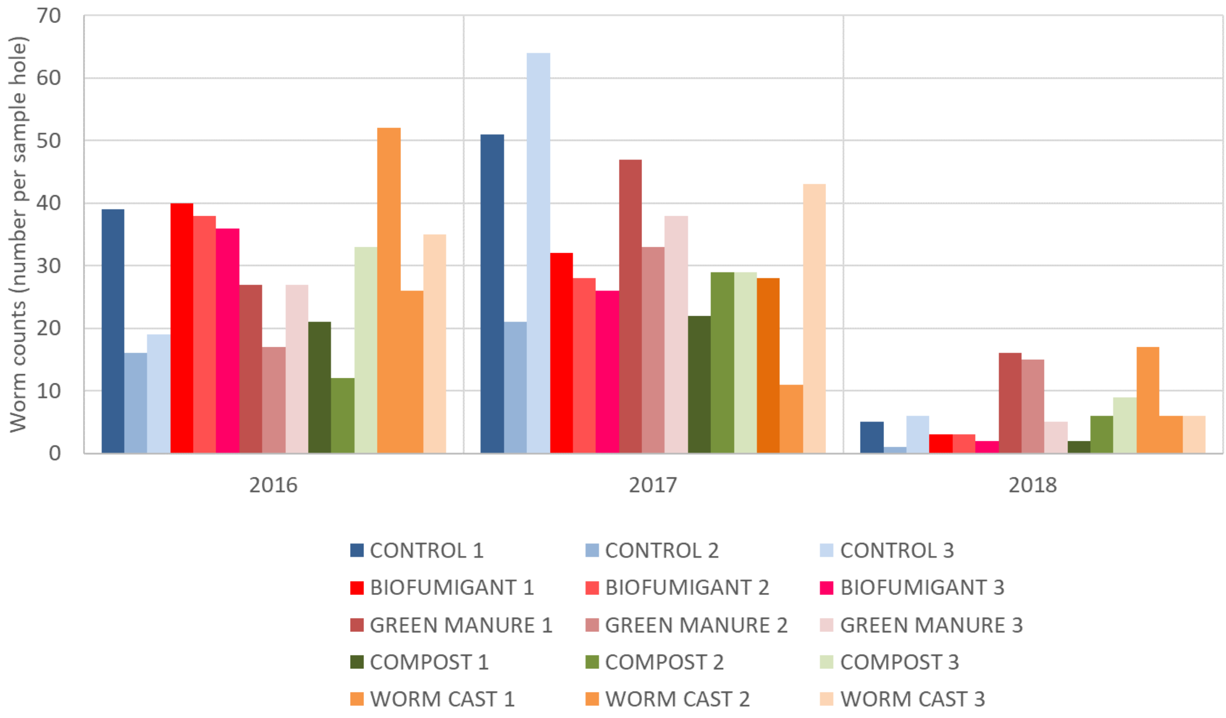


Figure 12 Comparison of treatments per year, Moriarty

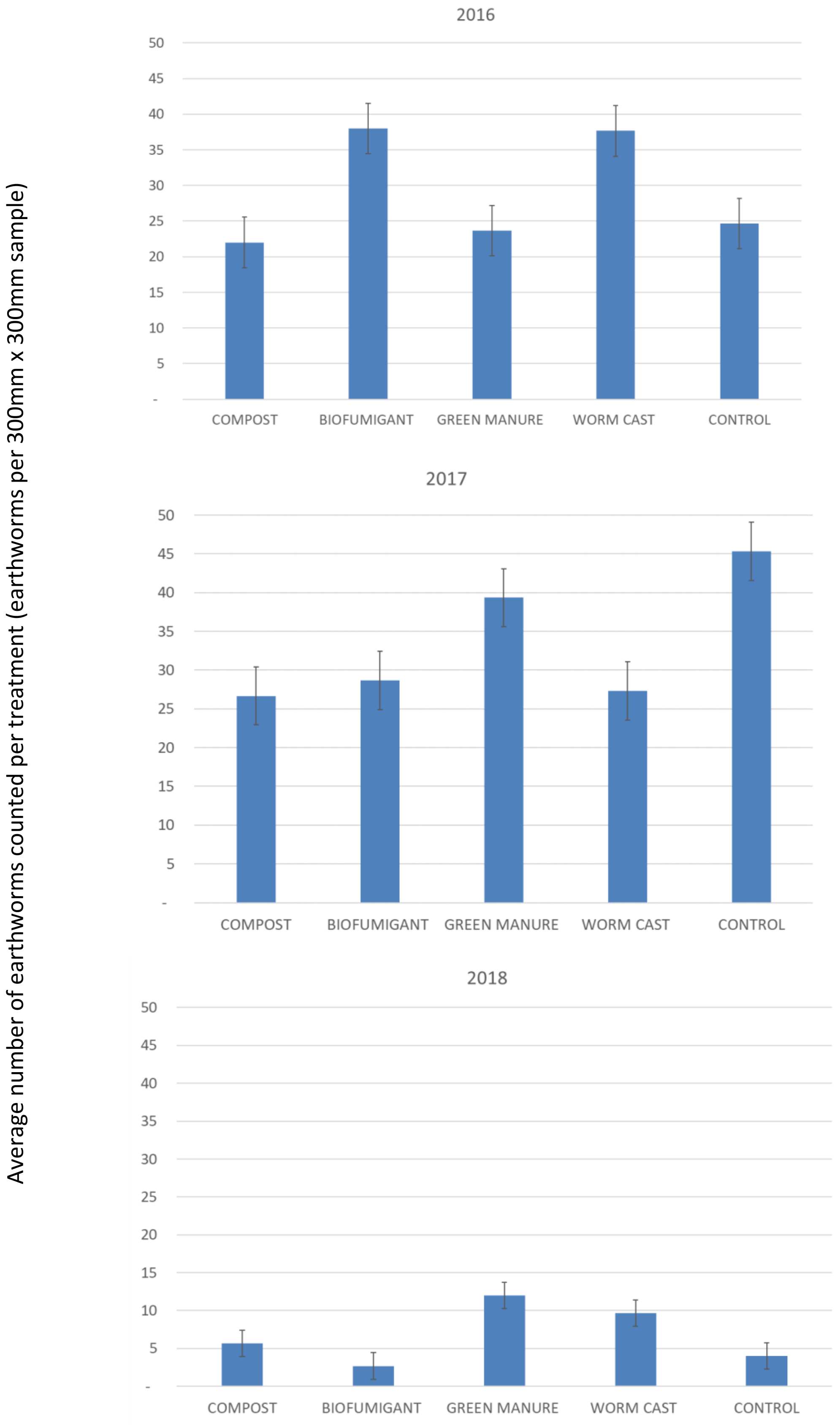
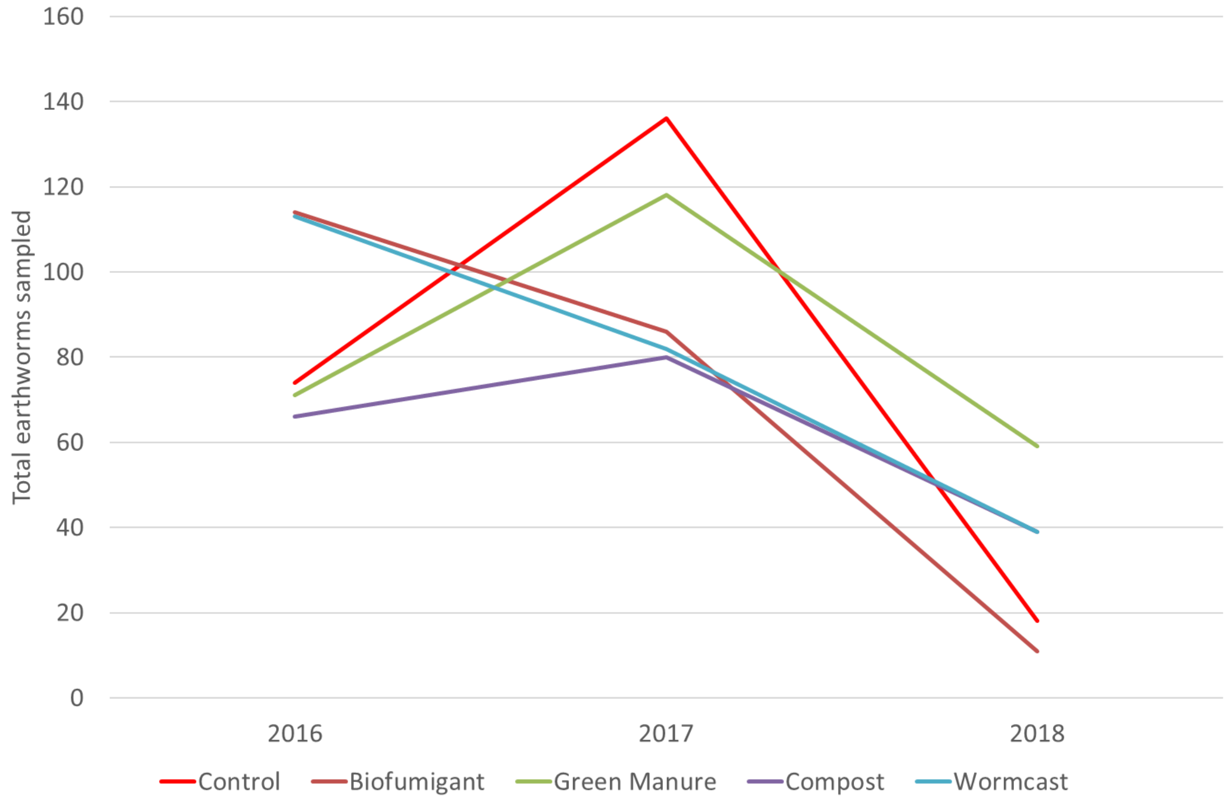


Figure 13 Changes in average earthworm numbers, Moriarty



3.3 Observation and demonstration sites, 2016-2018

Our team also secured access to observational and demonstration sites in NSW, Queensland, South Australia, Tasmania, Victoria and Western Australia.

All sites were surveyed in 2016 and 2017, and results are summarised in Table 3. This shows average earthworm numbers recorded at the sites, as well as key soil health indicators and details of land management. Discussion about each of the sites follows. Variability within and between the sites, as well as many variables means that data from the sites is not showing strong correlations between earthworm numbers and numeric soil health measurements. The variability within and between sites can be attributed to factors such as soil textures, soil moisture at the time of sampling, tillage and seasonal conditions, as well as historic management of the sites.

Some of the sites were surveyed again in 2018.

3.3.1 NSW

All of the NSW sites are located on or near the middle Nepean River from Theresa Park to Hobartville. In 2016, there was lower than average rainfall during autumn, major storm events and high rainfall in June, followed by slightly above average rainfall through until September. Soil moisture condition were good at the time of sampling. In 2017, conditions were very dry, with below average rainfall from April and no rainfall events in July and September. Moisture conditions were reasonable under irrigated areas, but the soil profile was dry and not favourable to earthworms. In 2018, conditions were extremely dry.

Hobartville

Despite soil-improving management practices such as cover crops, composts and reduced intensity of tillage, the farm has no viable earthworm population. The farm manager and staff report 'never' seeing earthworms on the property when working the soil or taking soil samples. The manager reported one recently found near a tap on the site, but this was the first time he had seen one at the site. At the time of the audit, the authors found no earthworms in the sample area or anywhere on undisturbed areas including neighbouring pasture (the soil was very dry) nor on the unworked and wet edges of worked areas. It seems earthworms are virtually 'extinct' on the site. This may be due to historic practice, but also due to the very sandy soils, very low organic matter and recent periods of extremely dry conditions over winter and spring. Also, the farm was not established as a vegetable growing site until after the millennium drought and the land was unirrigated pasture and cropping land during this period. Extreme dry conditions may have reduced earthworm populations to the point of virtual 'extinction'.

Agnes Banks

The farm is Agnes Banks is an intensive vegetable growing property producing brassicas, lettuce, and corn. The property has been farmed intensively since the mid-1980s. Soils are alluvial from historic flooding of the Nepean river and are naturally sandy. They are now being managed to improve soil structure and function. Since 2011/12 compost and reduced tillage have been used. Biofumigant and green manure crops are also being used, and traffic is being managed to reduce compaction. These practices are paying off, with the soil displaying good soil heath characteristics. However, very low earthworm numbers were observed in both 2016 and 2017, with only two to fourearthworms per square metre. Although sandy soils can reduce earthworm activity, a test hole on similar but undisturbed soil on the farm under a small irrigated citrus and olive grove found earthworm numbers in excess of 200-400 earthworms per square metre. This suggests intensive vegetable farming and tillage has reduced earthworms on the vegetable growing areas. Blue Environment used some of the earthworms harvested from the grove to 'seed' beds in an attempt to artificially increase earthworm numbers. It is uncertain whether this will be effective because of dry and hot conditions at the time of, and immediately following, the site survey. The farmer reported finding large anecic (deep dwelling) earthworms when digging irrigation pipe trenches to more than 1 metre, but no evidence of these earthworms in the form of surface casts or deep vertical burrows was observed on the site at the time of the audit. Blue Environment tried to establish a population of earthworms to the trial area by introducing earthworms found in uncultivated areas, but this does not appear to have been successful. The dry conditions in 2018/19 have not favoured earthworm activity.

Theresa Park

This site is a potato, corn and bean farm located on a heavy clay loam. The grower is using cover crops and compost applications to boost soil carbon and microbiology. Due to some density and compaction issues tillage is intensive using a combination of ripping, rotary hoeing and ploughing. Soil carbon levels were recorded as 1.5% in 2016 and 1.35% in 2017. In 2017 there had been unseasonably hot and dry conditions and the sub-surface soil was dry at the time of sampling.

The trial site had the following rotation:

2015/16

- corn (spring/summer)
- mixed cover crop (autumn/winter)
- potatoes (sown four weeks prior to earthworm survey in 2016) (spring/summer)

2017

- beans (autumn/winter)
- potatoes (sown two weeks prior to earthworm survey) (spring/summer).

The observed earthworm counts for 2016 and 2017 in Table 3 show a very significant fall in earthworm numbers between 2016 and 2017. This is most likely due to the dry conditions and heavy tillage prior to the sowing of the 2017 potato crop. In addition to dry conditions impacting on earthworm numbers, a dry sub-surface may have resulted in most earthworms migrating to the upper 150-200 mm of the soil profile where they would have been vulnerable to rotary hoeing and other tillage.

Soil health characteristics show reasonable levels of nitrogen, soil carbon and labile carbon. The lower levels of soil microbiology and earthworm numbers most likely reflect the recent tillage for the establishment of the potato crop only two weeks prior to the 2017 audit and the atypically dry and warm conditions experienced in the area prior to and at the time of the earthworm audit.

Table 4 Summary of average earthworm numbers and soil health parameters 2016 and 2017

State	Site	Earthworm numbers in year: 2016	2017	N (% dry wt)	OC (% dry wt)	Labile C (mg/kg)	Microbial biomass (mgC/kg)	Soil texture	Level of production	Intensity of cultivation	Chemical use practices	Mean district rainfall (mm/yr)	Other practices	Historic land use
NSW	Hobartville	0	0	0.06	0.74	296	98	Sandy loam	High - Continuous cropping with cover crops	Moderate - power hoeing of upper 100-150 mm	Conventional	800	Cover crops, compost	Intensive with heavy tillage
	Agnes Banks	2	4	0.16	1.81	520	177	Sandy loam	High - Continuous cropping with cover crops	Moderate - power hoeing of upper 100-150 mm	Conventional	800	Cover crops, compost	Intensive with heavy tillage
	Theresa Park	64	0	0.39	1.35	470	161	Clay loam	High - Continuous cropping with corn, potatoes, beans and other crops.	Moderate	Conventional	800	Cover crops	Intensive with heavy tillage
Queens-land	Lowood	2	16	0.20	2.50	756	224	Medium clay overlying heavy and compacted clay	High - continuous cropping, corn, beans, brassicas, pumpkins	Very high	Conventional	770	Compost	Intensive with heavy tillage
	Thornton	104	4	0.18	1.51	668	227	Medium clay overlying heavy and compacted clay	High - continuous cropping - corn, beans, brassicas	Very high	Conventional	770	Compost, poultry manure	Intensive with heavy tillage
	Lockyer Valley	7	2	0.15	2.32	687	214	Medium clay overlying heavy and	High - continuous cropping - corn, beans,	Very high	Conventional	770	Compost	Intensive with heavy tillage

State	Site	Earthworm numbers in year: 2016	2017	N (% dry wt)	OC (% dry wt)	Labile C (mg/kg)	Microbial biomass (mgC/kg)	Soil texture	Level of production	Intensity of cultivation	Chemical use practices	Mean district rainfall (mm/yr)	Other practices	Historic land use
								compacted clay	brassicas, onions					
South Australia	Hay Valley	-	260	0.11	1.03	386	233	Very fine sandy clay loam overlying heavy clay	Moderate - pasture and broadacre cropping, with periodic brassica crops	High- very high for vegetable production	Conventional	765	Periods of pasture	Moderate , with heavy tillage for cereal and brassica crops,
	Mount Barker	49	333	0.27	3.53	887	472	Loam to clay loam	Moderate - pasture and broadacre cropping, with periodic brassica crops	Moderate - power hoeing of upper 100-150 mm, with deep ripping	Conventional	765	Periods of pasture	Moderate , with heavy tillage for cereal and brassica crops,
	Hillier	67	0	0.18	1.30	503	205	Sandy clay loam	Very high. Continuous cropping under greenhouse. Capsicums, chillies,	High – rotary hoeing to dry soil after flooding	Conventional	435	Compost and vermi-extract liquid treatment	Intensive with heavy tillage
Tasmania	Charlton Farms/Addison's	324	372					Clay loam	Moderate to high - continual cropping with green manure and broadacre and pasture phases	Moderate - power hoeing to 200-250 mm, deep ripping	Conventional, some effort to reduce and use sensitively/responsively	795	Rye green manure, legumes (broad beans and beans) in rotation	Intensive with heavier tillage and chemical use
	Hagley	504	869	0.23	3.00	778	230	Clay loam to loam	Moderate - pasture and broadacre	Moderate - power hoes	Sensitive/conventional	700	Periodic pasture and cereal	Moderate

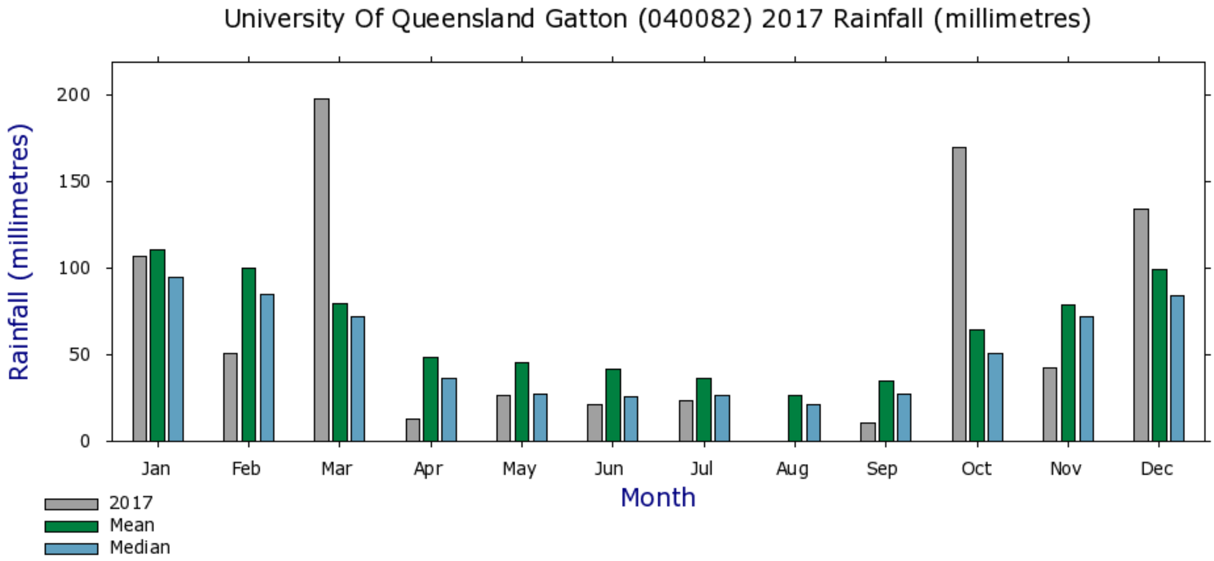
State	Site	Earthworm numbers in year: 2016	2017	N (% dry wt)	OC (% dry wt)	Labile C (mg/kg)	Microbial biomass (mgC/kg)	Soil texture	Level of production	Intensity of cultivation	Chemical use practices	Mean district rainfall (mm/yr)	Other practices	Historic land use
									cropping included in the rotation, potatoes, onions carrots				and legume crops, green manures and controlled traffic	
	Forthside	0	51	0.33	4.36	811	271	Clay loam	High - close to continuous with some cover cropping	Moderate-high	Conventional	960	Cover crops	Intensive
Victoria	Dicky Bills/Australian Fresh Salads	69	464	0.15	3.40	581	280	Loam to clay loam	High - continuous cropping of leafy and Asian greens	Moderate - power hoes in upper 100-150 mm, deep ripping as required	Mostly conventional, sensitive chemical use and used of 'biological' sprays	542	Cover crops, compost, biofumigants, controlled traffic	Moderate
	Middle Tarwin	100	0	0.47	8.10	1,229	372	Loam to clay loam	High - continuous cropping with cover crops	Moderate-high	Conventional	915	Cover crops, compost	Moderate
	Werribee	2	0	0.26	2.10	641	133	Heavy clay	High - continuous cropping	High- very high - multiple workings with rotary hoes to depth of 300-250 mm	Conventional	538	Compost, poultry manure	Intensive

State	Site	Earthworm numbers in year: 2016	2017	N (% dry wt)	OC (% dry wt)	Labile C (mg/kg)	Microbial biomass (mgC/kg)	Soil texture	Level of production	Intensity of cultivation	Chemical use practices	Mean district rainfall (mm/yr)	Other practices	Historic land use
Western Australia	Brook-hampton	51	31	0.16	4.45	465	196	v. fine sandy clay loam	Moderate - periods of cereal and legume cropping and pasture	High	Biological applications used	975	Use pf organic inputs	Intensive
	Manjimup	0	2	0.14	4.20	701	240	Loam to clay loam	High	Moderate-high	Conventional	993	Green manures, biofumigants, broadacre cropping and pasture phases.	Intensive
	Donny-brook	91	78	0.15	3.95	578	152	Sandy clay loam	Low - mod. Periodic brassica crops in pasture	Moderate-high	Biodynamic	975	Pasture phases, composts and manures, biodynamic additives	Moderate

3.3.2 Queensland

The Queensland sites are located around the Lockyer Valley and surrounding areas. At the time of the 2017 audit there had been a significantly drier than average autumn/winter and early spring period (see Figure 8 for regional weather station data). The farms sampled had dry soil, and even irrigated crops were dry down the soil profile. In 2016, sampling occurred in November following a wetter than average September but significantly drier October. None of the sampled sites had healthy earthworm levels of activity, although recently hatched juveniles were present and earthworm numbers may be higher at other times. At two of the sites, sampling in unworked areas that had adequate soil moisture found healthy earthworm populations suggesting that tillage and other practices are responsible for the low earthworm activity observed. All sites have heavy clay soils and issues with soil structure that the host growers are working to address. However, at this stage all sites use heavy tillage to prepare beds to overcome these soil conditions. This reduces the potential for earthworms to establish healthy and beneficial populations and perpetuates the need for on-going heavy tillage.

Figure 14 Rainfall in area in 2017 compared to averages



The three observational sites are described under the following headings.

Lowood

The farm in Lowood recorded low earthworm numbers with a slight increase from 2016 levels, but this was due to the discovery of a few isolated ‘hotspots’ of recently hatched juveniles. No mature adults or large juveniles were found. The site is continuously cropped and has some issues with soil structure. The soil is a medium clay overlying a heavy clay at a depth of 100 mm. Severe compaction from tillage and harvest means that the site must be heavily cultivated to obtain a uniform surface and seed bed. Compost blended with poultry manure is currently applied at rates of 10-15 tonnes per hectare per crop, with typically two crops per year. Although soil carbon levels are moderate (2.5% by weight), and levels of labile carbon and soil microbiology indicate reasonable soil health, levels of soil nitrogen were low. At the time of auditing, the site was under a crop of broccoli, which has followed a beans, corn and beans rotation. From recent trimming waste on the surface, rates of decomposition of organic matter appeared to be fast, but healthy levels of biological activity were not matched by earthworm numbers. The area had been dry and warm prior to sampling but was irrigated. The grower reports that he used to observe high earthworm activity under windrowed corn stubble/trash, but has not seen this in recent years. Contract harvesting causes severe soil compaction and wheel rutting at the site, and the grower feels the need to cultivate heavily to reduce compaction and produce a level sowing area. As a smaller grower he feels he cannot afford to upgrade equipment to match wheel and bed spacings on sowing and maintenance equipment to match contract harvesting equipment. Contract growers are typically on schedule and will harvest even when the ground is too wet, and large and heavy equipment that can severely damage soil, sometimes leaving deep wheel ruts and heavily compacted soils.

Thornton

The area previously sampled in 2016 was fallowed and dry when the audit team arrived for the 2017 audit. Earlier planned sowing of the area had been delayed because of atypically dry conditions, and the areas had recently been tilled. The audit team found no earthworms in this area, and moved to an adjacent paddock that had been irrigated over previous weeks in preparation for the sowing of corn. Earthworm numbers were also very low in this area, which may be due to the season and tillage. The results from 2016 and 2017 are therefore not comparable. The soil in the new area had low to moderate levels of nitrogen, organic carbon, labile carbon and microbial biomass. The soil has significant structural issues with a highly compacted A2 horizon at around 150 mm. Compost and chicken shed litter/manure are applied at rates of around 12 tonnes and 2 tonnes respectively for sowing. Urea is also added with the compost at a rate of 400 kg/ha. As much as he can, the grower undertakes controlled traffic to reduce compaction when the beds are being prepared and crop is in, but beds are only semi-permanent, and harvesting contractor vehicles can significantly damage soils. The land is typically deep and heavily ripped at least 3-6 times, harrowed and power-hoed to prepare the beds for sowing. This tillage, as well as low rainfall, would contribute to the low earthworm numbers observed. The grower believes there is little potential to reduce tillage because of the compaction issues and compaction caused by harvesting. Harvesting vehicles have wheel spacings incompatible with the equipment to establish and maintain growing areas, so there is limited potential to introduced controlled traffic management.

Lockyer Valley

Earthworm numbers were found to be low in both 2016 and 2017. This is likely due to tillage and possibly dry conditions. The cropped area was under onions, and there is some suggestion that earthworms do not 'like' onions and may migrate away from such crops. The grower applies compost with each crop in a continual cropping rotation of barley>corn>beans>brassicas (cabbage)>onions. At the time of sampling the sampled area was under onions that were 6 to 8 weeks off harvest. The area had been prepared with deep ripping after the preceding cabbage crop, fallowed from November 2016 to April 2017 (the wetter months), then worked with a power-harrow four weeks after ripping and immediately following compost application. The soil had a light 'fluffy' structure in the upper 70-100 mm that had been power harrowed, but a very heavy sub-soil below this. Earthworms were found in uncultivated areas where there was adequate soil moisture.

The site was again visited in May 2018. It has been under a barley/green manure crop and the soil was drying down the profile. Earthworm numbers were again low.

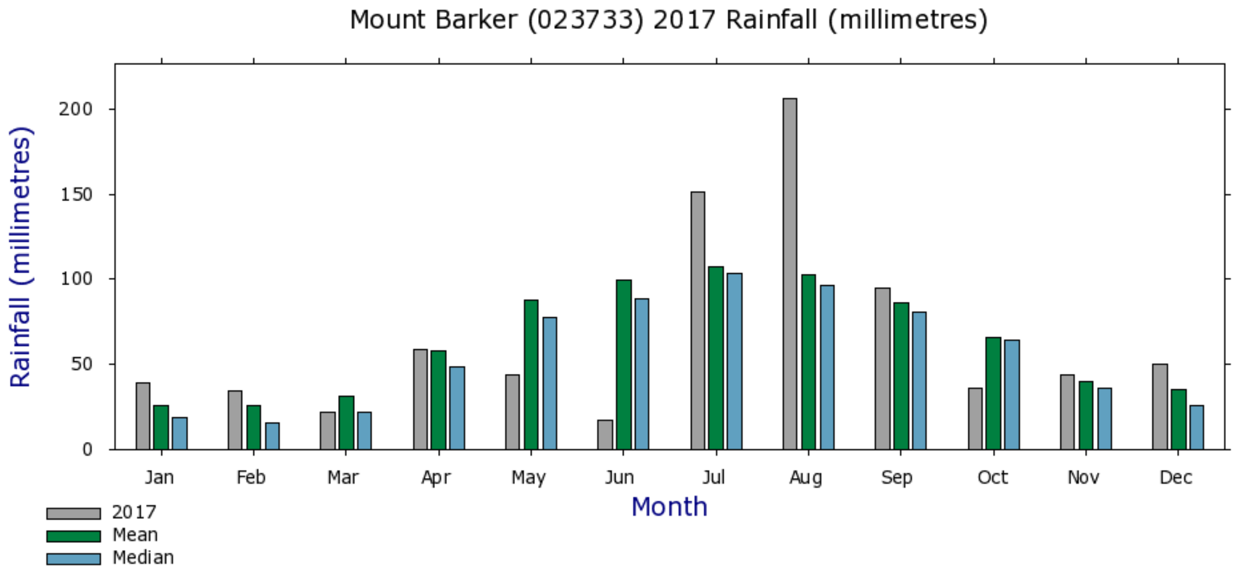
Mulgowie

During the 2017 Queensland audits, our team was made aware of a nearby agribusiness that had used controlled traffic and reduced tillage for over ten years. Although there was only time for a quick visit to the site, we observed vastly improved soil structure and interviewed the farm manager. He reports greatly reduced fuel costs and improved yields per unit of input as the main drivers for using controlled traffic management. Although a cursory dig of a recently prepared and fairly dry area found few earthworms, the farm manager reported that high numbers of earthworms are observed on the site during soil sampling in the wetter months. He suggested March to May as times when earthworm activity was greatest when soil moisture levels are usually high and temperatures have dropped. In May 2018, Blue Environment visited the site and undertook surveys in areas with both conventional chemical and Certified Organic practices. Both areas have had controlled traffic, reduced tillage and use of cover crops and retention of organic matter for 10-15 years. Both areas had recently been irrigated and had good levels of soil moisture down the profile, although it was dry in unirrigated areas. Inexplicably, no earthworms were found at depths to 500mm at multiple sampling points across both areas. On the Certified Organic area there was some evidence of earthworm burrows and casts in soil, with mainly horizontal burrows suggesting the activity of endogeic (middle-depth dwelling or 'worker' earthworms). Some deeper vertical burrows were also observed, suggesting the presence of anecic or deeper-dwelling earthworms. However, no earthworms were found at the time of sampling, even in moist soil that was under irrigation. The reason for this is unknown. It may have been that upper layers of soil were too warm and that earthworms had migrated down the profile. There was strong sunlight and ambient temperatures of around 28-30°C at the time of sampling, and soil temperatures were recorded at around 22-24°C in the upper 400 mm. It is also possible that earthworms had responded to seasonal conditions and migrated down the profile to aestivate (hibernate).

3.3.3 South Australia

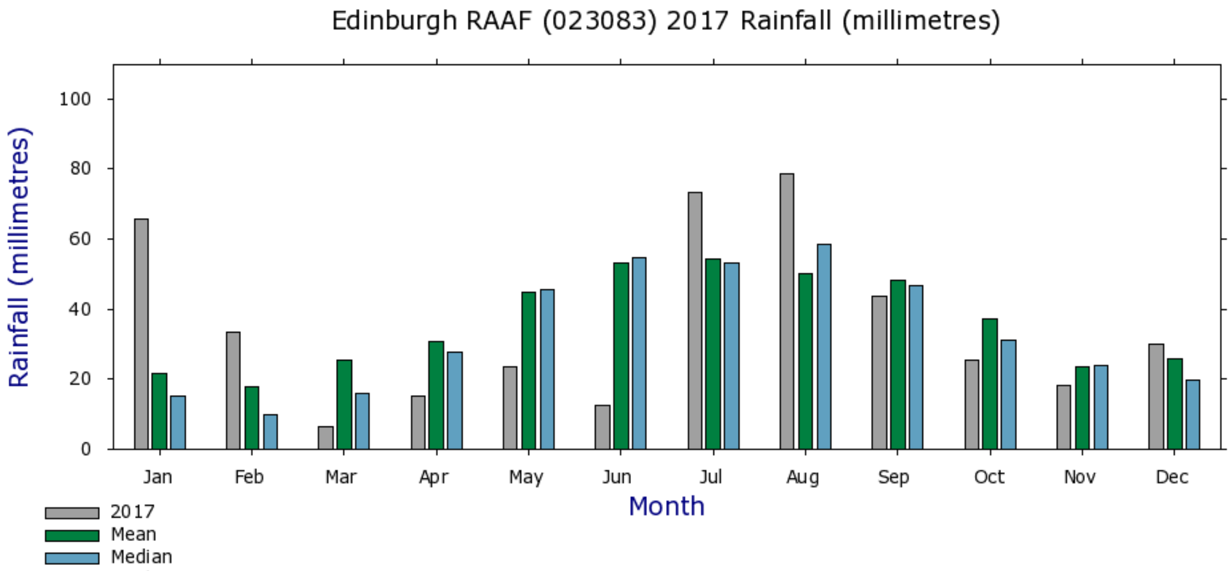
The observational sites in South Australia are near Mount Barker and Edinburgh. Results from average rainfall charts are shown in Figures 9 and 10. These show below average autumn and early winter rainfall, followed by above average rainfall, which was mostly in major storm events, in the months prior to auditing. This rainfall pattern may have delayed earthworm hatching and activity in autumn, and in one instance (farm in Hillier) resulted in first water logging and then heavy tillage to dry soil for sowing.

Figure 15 Comparison of seasonal and average rainfall, Mount Barker (proximate to the farms in Hay Valley and Mount Barker)



Source: *www.bom.gov.au*

Figure 16 Comparison of seasonal and average rainfall, Edinburgh (proximate to the farm in Hillier)



Hay Valley

The site was sampled in 2016 when it was very dry pasture. No earthworms were found in the cropping area and soil structure was observed to be poor and compacted. In 2016, testing in a drainage line that had not been cropped or worked for many years found reasonably high levels of earthworms even when conditions had been dry. Although the original intent was to return the land to vegetable cropping in 2017, the grower decided to keep it in pasture and crop other paddocks. The 2017 audit was therefore also done on a dry pasture. As Figure 9 shows, rainfall in the months prior to sampling had been significantly above average, but the soil profile was still dry and compacted suggesting poor infiltration. Table 3 shows average earthworm numbers increasing from none in 2016 to 260 per square metre. Most of the earthworms were large juveniles and a large proportion of the earthworms were from a 'hot spot' of epigeic (surface/pasture-living) worms and would be unlikely to survive cropping of the area. These earthworms were identified as *Eisenia* and *Micoscolex* species.

Mount Barker

As shown in Table 3, the Mount Barker farm was found to have healthy earthworm numbers in 2017, with an increase from 48/square metre in 2016 to 333/square metre in 2017. The farm is managed to have good soil health, with long rotations involving periods of pasture and cereal and legume cropping before sowing of brassica crops before being returned to pasture. A form of controlled traffic management is used during the vegetable production stage to avoid soil compaction, and this is evident in the friable and porous upper 300 mm of soil. Organic matter levels are visibly high, and healthy soil biology is indicated by rapid biodegradation of crop residues. This is borne out by the soil test results. Our team has discussed the potential for the grower to reduce the intensity of tillage by reducing routine deep ripping to see whether this further increases earthworm activity. The structure of the soil profile is such that ripping may not be needed, particularly if earthworm and other soil microbial activity helps to 'work' and aerate the soil at depth.

It is proposed to hold field days and produce case studies about this site, as well as continue monitoring. The site is good example of what can be achieved with sensitive soil management.

This site was initially selected because the grower was using compost and had previously had some earthworm research conducted at the site. The land our team was directed to sample has remained in pasture, and other than showing some recovery in earthworm numbers during this phase is of limited value to the project.

Hillier

The Hillier site is continuously cropped under a polyhouse. The main crops in rotation are cucumbers, capsicums and leafy greens on a sand clay loam overlying a heavy clay at depth of 300 mm. The grower has used compost at a rate of at least 20 tonnes/hectare per crop (40-60 tonnes per year) and is also using dissolved molasses and neem oil in fertigation lines to feed the soil and control nematode problems. The compost and molasses will be beneficial for earthworms, but the neem may have some negative effect[1].

In 2016 the average number of earthworms was 67 per square metre, but in 2017 no earthworms were found. This can be attributed to very heavy tillage used to dry out soil after a major storm event caused leaking in the poly house and saturation of the soil. The soil had to be dried to get the next crop in and was worked even more heavily than usual. Conventional tillage practice used a combination of deep ripping and rotary hoeing, and this would be detrimental to earthworm numbers. The grower feels such tillage is unavoidable because the soil structure slumps and forms a hard-pan without it. In 2018, the average earthworm numbers in this area was 35 per square metre, with the area under a young capsicum crop.

In all years, large numbers of earthworms were observed on uncultivated land outside of the polyhouses where soil moisture levels were favourable, including in areas between polyhouses where runoff from the houses maintains high levels of soil moisture. The light sandy loam soil may make it easy for earthworms to migrate through the soil into the polyhouses to colonise areas.

In 2018/19 the grower started to use vermiculture liquid extracts in fertigation and has observed high earthworm numbers under areas where land has not been cultivated for several months. In 2018, Blue Environment visited the farm and sampled several areas. This found:

- Low to moderate earthworm numbers in the area sampled previously in 2016 and 2017. This was under a young capsicum crop that had followed cucumbers after the heavy tillage incident mentioned above, and had had heavy tillage before the establishment of the crops.
- High earthworm numbers under mature cucumber crops in other poly houses. In both instances, the soil has not been disturbed for 9-12 months and permanent buried irrigation lines were present. These may provide 'refuges' for earthworms to survive and recolonise beds following cultivation. In one of the polyhouses, vermiculture liquid extract was being used via fertigation and high numbers of earthworms were observed under this area. This may be a result of increased soil microbiology or some attribute of the vermiculture liquid extract that attracts earthworms to migrate to treated areas.

Compost is seen as a way of improving soil structure and building soil organic matter. Soil testing suggests organic carbon fell from a healthy 3.5% by weight in 2016 to 1.3% in 2017. This suggests significant loss of soil carbon that is likely to be due to tillage. In the same period labile carbon fell from 695 mg/kg to 503 mg/kg but levels of microbial biomass rose from 158 mg C/kg to 205 mg C/kg, which may indicate a higher level of biological activity and biodegradation of organic matter in 2017 as a result of tillage and high moisture conditions.

1.1 [1] Studies of the impact of neem on earthworms suggests a mild cytotoxic effect, but conclude that they should not be detrimental at recommended application rates (see: *Toxicity of Commercial Neem Extract to Earthworms* https://www.hindawi.com/journals/aess/2011/925950/).

Earthworm numbers in unworked (but slightly compacted) areas inside the polyhouse were moderate, and outside of the polyhouses there were very high levels of earthworms. This suggests tillage rather than any seasonal factors is responsible for low earthworm numbers.

A field day was held at the site in 2018, and was attended by 15 growers, as well as agronomists, and representatives from Ausveg and the composting business, Pete's Soils.

3.3.4 Tasmania

The Tasmanian sites are concentrated in the north central areas south of Devonport. The area has a milder climate and higher and more evenly distributed rainfall than the mainland demonstration and research sites. In 2016 rainfall was above average in most months and in 2017 there was a dry June, followed by average July rainfall and then below average rainfall in August and September. In 2018 conditions were atypically dry.

Charlton Farms/Addison's, Moriarty

This property is one of the detailed research sites and is described in section 3.2. It has healthy earthworm numbers across the site.

Hagley

This property is a 530-hectare intensive farming operation with a cropping program consisting of alkaloid poppies, onions, processing peas, broccoli and potatoes. Also grown are an array of seed crops including carrot, beet, clover and ryegrass seed. The grazing program consists of an Angus cow herd of 170 head and a 5,000 head fat lamb trading operation. The family have farmed the land since the 1850s and the current farmer has adopted best practice soil management methods including periods of pasture in the rotation, minimum tillage, strip tillage, controlled traffic management, integrated pest management to reduce routine chemical use, and cover crops and green manuring.

In 2016, the sampled area was under point-of-harvest canola and in 2017 it was under a carrot seed crop. Organic carbon in 2016 was 5% by weight, dropping to 3% in 2017. Soil nitrogen, labile carbon and soil biomass also fell in 2017, but earthworm numbers were found to be higher. Sampling conditions were close to ideal in both years, with good soil moisture and soil temperature at 15-20^{o}C.

The site was sampled again in 2018. Conditions were drying and earthworm numbers were lower than in the previous years, but the evidence of earthworms 'working' and aerating sub-soils was apparent.

Forthside

The Forthside farm has operated since 1963 as a vegetable growing research and demonstration facility, with intensive cropping and chemical use on the site for over 50 years. In recent years, more work has and is being conducted demonstrating practices to improve soil health, and rotations now routinely incorporate green mature and cover crops. Controlled traffic farming is standard practice across the site, which hosted a Soil Wealth demonstration site[2]. Soil additives including compost, biochar, chaffs and pyrethrum marc have been trialled. Areas not in use for field research are used to produce commercial crops, and commercial principles are applied in the choice of crops and

[2] see: *http://www.soilwealth.com.au/demo-sites/forthside-tas/* and *https://www.facebook.com/SoilWealthForthside/*

management of the farm. A wide range of crops including green beans, brassicas, potatoes, carrots, onions, corn and leaf green vegetables are grown at the site. The biofumigant crop, caliente, is also used as part of an integrated pest and disease management program.

The soil is a clay loam, with high levels of organic carbon (3.9% by weight in 2016 and 4.4% in 2017), labile carbon and soil microbial biomass. The trial site was located in an area where a green manure trial has been running for about 12 years. Inexplicably, no earthworms were found on the demonstration site or neighbouring areas in 2016 despite excellent levels of soil moisture and the land having been under a rye grass manure crop sown five months before sampling. No reason for this absence of earthworms has been identified other than the possibility of historical tillage and chemical practices depleting numbers to such low numbers that they had not recovered due to on-going soil disturbance in the trial area (for example the preparation and harvest of potatoes and carrots) and the use of biofumigant crops.

In 2017, earthworm numbers were higher, at an average of 51 per square metre, but still not as high as might be expected given soil conditions and climate. The land was under a ryegrass green manure that had been sprayed. Earthworms from other areas were introduced into part of the trial site to investigate the potential to artificially increase earthworm numbers through such introductions, but the area has since been sown to potatoes. Although reduced tillage practices have been used to establish the potato crop, the harvesting can be expected to impact on soil and earthworm numbers.

In 2018, conditions were dry and earthworm numbers were low compared to 2017. The land had been heavily worked and disturbed during bed preparation and harvesting of a potato crop. The numbers of earthworms in the areas where earthworms were introduced were higher, but not statistically higher than the rest of the sample area.

3.3.5 Victoria

Sites were established in Maffra, Middle Tarwin and Werribee. Rainfall in each of these districts is shown in Figures 12, 13 and 14 respectively.

Dicky Bills/Australian Fresh Salads, Maffra

This is one of the main research sites discussed in section 3.2.

Middle Tarwin

This site has best practice soil health management practices and has been managed with these since it was converted to vegetable growing from pasture in 2015. The farm produces celery, leeks and baby greens and uses cover crops, minimum tillage and compost to building and maintain soil health. The soil appears to be in excellent condition. Soil organic carbon levels are the highest of any of the surveyed sites at 5.3% by weight in 2016 and 8.1% in 2017. Levels of labile carbon, nitrogen and microbial biomass are also high. Inexplicably, the site has very low earthworm numbers, with an average of 100 earthworms per square metre in 2016, but no earthworms found in the surveyed area in 2017. The land had had a celery crop harvested 6 weeks prior to the 2017 survey, and a rye corn cover crop had been directly drilled immediately following harvest. Neighbouring areas under pasture had high earthworm numbers.

The site was sampled again in 2018. The soil was drying and once again very few earthworms were present.

The reason for extremely low earthworm numbers is unknown. It is possible earthworm numbers were damaged when land was first converted from pasture due to tillage and bed-forming practices. It is also possible farm chemicals used in the celery crop or seed treatment of the rye corn has impacted on earthworm numbers.

Werribee

This site produces mainly brassicas, lettuce and celery, and uses compost and poultry manures as well as BioActive™ microbial soil additives to build soil organic content and health. In both 2016 and 2017 the sampled area had been worked relatively recently and was dry, and no earthworms were found. The site has low to moderate levels of soil organic carbon and labile carbon but relatively low microbial biomass. The soil is heavy and unstructured clay that has been intensively and continuously cropped for decades. Heavy cultivation using deep ripping and multiple workings with rotary hoe to depths of 250-300 mm is seen as necessary to maintain a viable seedbed. Composted manure is being used to improve soil structure and carbon.

In 2018 the original study area had been developed as seedling raising houses, so other areas on the farm were sampled. High numbers of earthworms were found in areas that had not been worked for three or more months and had established irrigated brassica and celery crops. The grower was interviewed about management practices on these areas. These include:

- Periodic cover crops and green manuring.
- Addition of composted poultry manures for nitrogen and organic matter.
- Retention and integration of crop residues.
- Semi-permanent beds and irrigation lines. Sampling found healthy populations of earthworms along the irrigation lines and it is possible these acts as ‘refuges’ for earthworms that the recolonise other areas after tillage.
- Integrated crop/pest management involving:
  - Disease-breaking crop rotations
  - Monitoring of insect and foliar disease, with responsive chemical application
  - Use of biological agents (Trichoderma) for disease control
- Sensitive chemical use, without soil fumigation and selection of less harsh/toxic chemical where possible.

Soils are ripped and rotatory hoed to depths of 250-300 mm before seed beds are formed. The soil is a deep clay (a red sodosol, typical of Werribee vegetable production) and it seems likely that some earthworms survive cultivation at depths greater than this and then recolonise beds.

The 2018 results suggest that the low counts in 2016 and 2017 were due to recent cultivation and the drying soil.

3.3.6 Western Australia

Brookhampton

The Brookhampton farm is a mixed broadacre cropping and vegetable farm that mainly grows brassicas, pumpkins and zucchinis. The farmer is using green manure crops, pasture, organic manures and stubble retention of grain and legume crops to build soil organic matter. The farm also uses biological farming methods, applying beneficial microbes and using Australian Mineral Fertiliser™ products which combine mineral fertilisers, manure and seaweed extracts, enzymes and beneficial microbes to improve soil fertility. The farmer’s brother is a local distributor of products, and the farm has seen improvements in soil health and productivity, with increased yields, more even crops and reduced input costs. The soil is a very fine sandy clay loam overlying a heavier gravelly clay at 300-500 mm. Beds are prepared using a combination of deep ripping and rotary hoeing. In 2016 the land was under irrigated pumpkins, but the soil was dry at the time of surveying. In 2017 the area was under an unirrigated ryegrass and oats green manure that had patchy establishment due to the unseasonably dry and warm conditions. In both 2016 and 2017 soil organic content was at a healthy level (4.6% and 4.5% respectively). Levels of labile carbon and soil microbiology were good in 2016 but declined in 2017 – most likely due to the dry and conditions.

In both years the soil was dry and 2017 was unseasonably dry and warm. Average earthworm numbers were low in both years. The farmer reports moderate numbers of earthworms when plastic mulches are lifted, suggesting soil moisture is a constraining factor to earthworm activity at the site. Tillage practices are also likely to reduce earthworm numbers.

Manjimup

The farm property in Manjimup is a Soil Wealth demonstration site and uses a range of practices to build soil health including reduced intensity tillage, cover and green manure crops, biofumigant crops, and periods of pasture in the rotation. The farm grows potatoes, lettuce, chard and leafy greens. The sample area is under a rotation of biofumigant (caliente following leafy green crops)-lettuce-oats (green manure)-chard-return to pasture for at least two years. Soil health indicators in both 2016 and 2017 were good, with soil organic carbon levels of 3.8% and 4.4% by weight respectively, as well as moderate levels of labile carbon and microbial biomass. The soil is clay-loam overlying a heavier gravelly clay at 300 mm. Deep ripping is used and power hoes and harrows are used to prepare seedling beds for vegetables. Green manures and pastures are direct drilled. In 2016 the site had recently been bio-fumigated and the residue had been power hoed after rolling and bio-fumigation. This has reduced the residue to a chaff and rapid biodegradation was apparent. In both years the soil was drying and the active earthworm population was non-existent (2016) or low. Sample holes were dug to 500 mm to investigate the presence of aestivating earthworms, but none were found. It is possible that bio-fumigation reduced earthworm numbers on the site and cultivation and dry conditions have prevented populations from re-establishing. Testing of undisturbed and more moist areas adjacent to the test area found healthy earthworm populations.

This site is an excellent example of practices to improve soil health, but earthworm numbers were observed to be low on the nominated survey area. This is likely to be due to a combination of use of a biofumigant crop and drying conditions at and prior to sampling.

Donnybrook

This farm is a certified Biodynamic property growing brassicas in a relatively low-intensity rotation of three to five years of pasture followed by two years of brassicas. The soil is a sandy clay loam overlying a heavier gravelly clay at 200-300 mm. In addition to pasture phases, the farm uses composted manures and biodynamic additives/soil enhancers. The sampled area has healthy levels of soil organic carbon (6.6% in 2016 and 4% in 2017). Levels of soil carbon, labile carbon and microbial biomass fell between 2016 and 2017, most likely due to drier conditions. The drier conditions may also contribute to an observed slight fall in average earthworm numbers from 91 per square metre in 2016 to 78 per square metre in 2017. The earthworm population at this site is possibly lower than would be expected given the relative low intensity of cropping and good soil health indicators. Damage from chemical applications can be ruled out because the site is farmed according to Biodynamic principles and no fungicides, herbicides or insecticides have been used in the sampled area. This suggests tillage and drier than average conditions may have impacted on earthworm numbers. The lighter topsoil overlies a much heavier gravelly clay hardpan at only 200-

300 mm. Soil moisture was observed to 'sit' on this hardpan and it is possible earthworms do not readily migrate through the hardpan, meaning they would be susceptible to rotary hoeing.

Trials of 'seeding' areas with earthworms

Some of the observational sites have management practices that should favour earthworm activity, but were found to have low earthworm numbers despite soil having favourable soil moisture levels at the times of sampling. On two of these sites (Forthside, Tasmania and Agnes Bank, NSW) earthworms were harvested from uncultivated areas on the farms and introduced to the surveyed areas. The method used was to extract sods of soil containing earthworms and then plant these into the soil profile by making a hole of similar size to the sod. This method has been used by previous researchers to successfully introduce earthworms in pastures. The seeding occurred in 2017 and the trial sites were surveyed in 2018. The results were inconclusive, with low numbers of earthworms recorded in seeded and control areas on both sites. At the Tasmanian site the numbers of earthworms in the seeded area were slightly higher, but not significantly. In both instances, sites had been cultivated quite heavily between the initial seeding and surveying, and the Tasmanian site has had a potato crop sown, with significant soil disturbance at harvest. This may explain the low numbers of earthworms observed.

The authors suggest the potential for seeding areas with earthworms should be explored further. Many intensive vegetable farms will periodically need to use practices that can devastate earthworm numbers. Practices such as: biofumigation or other fumigation/sterilisation; heavy tillage to wet or dry soils or form beds; harvesting of root crops; and application of some chemicals can all impact on earthworms, and it may take 12 or more months for earthworm numbers to recover. The introduction of earthworms could help numbers to recover more quickly when conditions are favourable.

Options for seeding areas with earthworms have been investigated, and include purchase of earthworms or establishment of on-farm worm beds that could be harvested for worm-rich sods.

Blue Environment has undertaken research to identify commercial suppliers of 'agronomic' endogeic earthworms. At the time of writing, only one Australian provider has been located. The worm-farmer, Kookaburra Worms, sells 'worm bombs' of live earthworms and eggs for use as 'garden' worms. The species present are *Amynthus sp* and *Perionyx excavatus*. Although neither of these species were found through the survey work to date, they are recognised as species that could provide benefit under 'garden' conditions, but it is unproven whether they can survive and thrive under commercial vegetable growing conditions.

A New Zealand worm farm sells grey worms *(Aporrectodea caliginosa*), which is one of the most prolific endogeic earthworm species found by the earthworm survey. Unfortunately, earthworms are not currently permitted for import from NZ to Australia. The Department of Agriculture and Water Resources has advised that application could be made to have *A. caliginosa* included on the list, but this process would likely take years even though this species is already very common in Australia. Concerns over the import of pathogens with earthworms, casts and soil make it unlikely that this could be achieved within the project timelines. However, the NZ vermiculturalist harvesting and selling endogeic earthworms suggests this could be replicated in Australia. One Victorian vermiculturalist consulted believes they could develop a cost-effective method for harvesting earthworms if there was market demand for them.

Vermiculturalists based in Victoria and SA produce mainly compost worms but report high and harvestable populations of endogeic earthworms in the soil under the compost worm beds. These earthworms are more difficult to harvest than the compost worms, but vermiculture beds are a potential rich source of endogeic species. It may also be possible for vegetable growers to foster earthworm numbers by establishing 'worm beds' in dedicated uncultivated areas. A worm bed can be established by adding crop residues to an area, covering with straw or mulch and keeping the area wet. Only a small area of a couple of square metres would provide a source of earthworm-rich 'sods' that could be used to seed areas. Sod-seeding involves cutting sods out of earthworm-rich areas and planting these into areas with low earthworm numbers but where soil conditions are favourable for earthworm activity such as:

- healthy levels of soil organic matter (>2 % by dry weight), and particularly high levels of 'fresh' or labile carbon from green manures.
- soil moisture levels of 20-40% in the upper 300mm; and
- no planned deep or heavy tillage, soil disturbance from root crop harvesting, or soil fumigation within the next 12 months so that earthworm numbers can become established.

Use of earthworm refuges

On a number of sites, low earthworm numbers were observed on cropped areas where soil organic matter and other conditions were favourable, but heavy and deep tillage practices were used and had reduced earthworm numbers. On two of these sites, healthy earthworm numbers were observed in areas that had not been cultivated for two or more months, including adults. This is likely due to the presence of permanent buried irrigation lines that are not cultivated and harbour healthy populations of earthworms that can then recolonise cultivated areas. It may be possible to enhance the role of permanent irrigation lines as earthworm refuges by growing cover crops on these areas or mulching them with straw or other organic matter.

3.4 Discussion and key findings

In most instances it has not been possible to obtain statistically significant results. This is due to variability in earthworm numbers within and between sites, as well as many variables associated with tillage and crop rotation practice, soil type, climate and conditions at the time of surveying. Similarly, statistical correlations between soil health parameters and earthworm numbers have been weak, because some properties with favourable soil health conditions have had low earthworm numbers due a combination of historic practices, intensive tillage and dry conditions. Chemical use may also impact on levels of earthworm numbers, with some growers reporting observed earthworm mortalities following the application of some chemicals. A combination of factors may be stopping the re-establishment of healthy earthworm populations. There have also been some inexplicably low earthworm numbers at two sites that otherwise have excellent soil health indicators and less intensive tillage. We intend to 'seed' these with earthworms to see whether populations can be artificially increased.

The detailed research sites both show positive response in earthworm numbers from the use of green manure crops and reduced intensity of tillage. No other significant effect of treatments was found, possibly due to variability across the sites and the fact that soil health was well managed prior to establishment of the sites, so the 'control' treatment already has good practice and good earthworm numbers.

Key observations are:

- Highest populations of earthworms were generally found where higher levels of soil carbon were present, with corresponding healthy levels of labile carbon and microbial biomass. Compost treatments have probably elevated soil carbon on some sites, but earthworm activity more closely corresponds with levels of labile carbon. This suggests carbon on composts alone may not have a direct effect on earthworm activity. However, compost can be expected to improve nutrient retention, nutrient cycling, soil structure and biological activity, and where this is achieved, conditions for earthworm activity will be improved.

- The intensity of tillage impacts on earthworm activity. Figure 17 shows earthworm numbers under different levels of soil tillage. This shows higher earthworm numbers were generally found on properties with less intensive tillage.
- The intensity of farming has some effect on levels of earthworm activity, although one farm with close to continuous cropping systems and multiple crops per year was found to have healthy soil and an active earthworm population, and the farm with the least intensive cropping rotation (but intensive tillage and a dry and shallow soil profile) had a relatively low earthworm population. Farms that include pasture, cover crop and green manure phases generally had more active earthworm populations.

Figure 17 Average earthworm numbers under different levels of tillage intensity

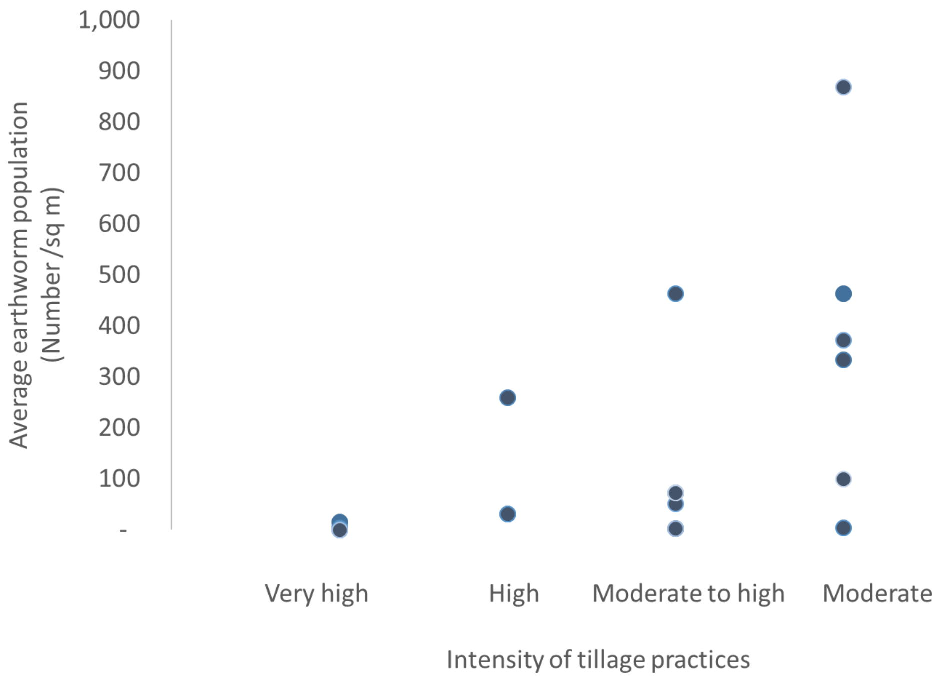
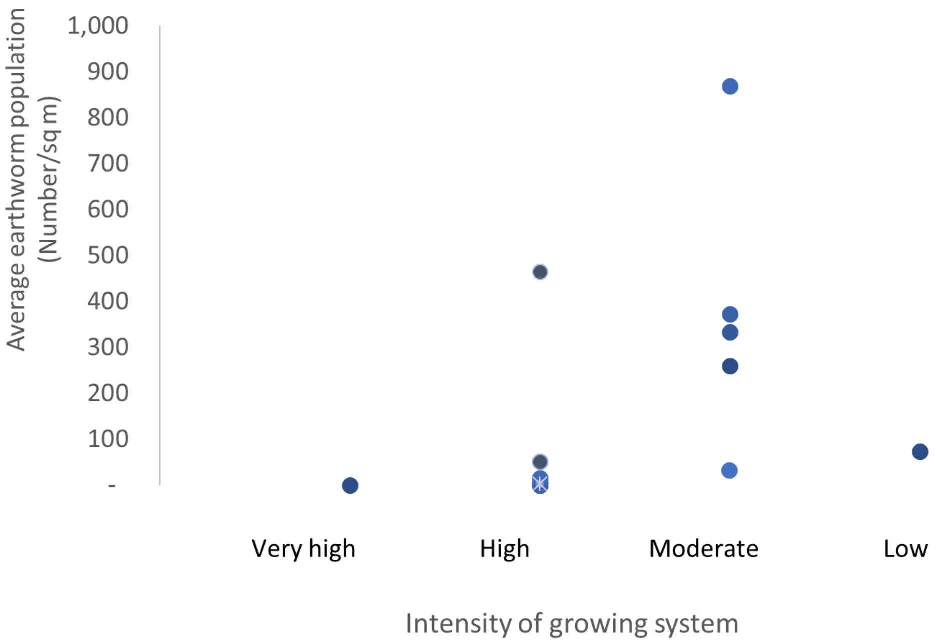


Figure 18 Average earthworm numbers under different levels of intensity of farming system


Average earthworm population (Number/sq m)
1,000
900
800
700
600
500
400
300
200
100
-
Very high
High
Moderate
Low
Intensity of growing system

4 Factors affecting earthworm activity and preferred practices

The outcomes of the field trial work and review of literature have been used to make observations about key factors affecting levels of earthworm activity, and the relative significance of other factors known to have some impact.

Key practice changes that promote earthworm activity are:

- Increasing organic carbon and beneficial soil micro-biology. Earthworms feed on bacteria, fungi and other micro-organisms as well as decaying organic matter. Compost, vermi-casts, manures, green manures and cover crops could be used to achieve this. Our works suggests that the availability of labile (readily degradable) carbon is more important than more stable levels of carbon. Mature composts, which have a higher proportion of stable/less-labile carbon have less benefit than cover crops/green manures, integration of crop residues or application of manures and immature composts. Biochar, containing very stable/non-labile carbon, has limited effect on earthworm numbers.
- Using cover crops and green manures in preference to fallow periods. In addition to adding organic material to soils, cover crops and green manures 'feed' soil microbes through their roots as they grow, improve soil structure and depth, and provide shade to soil. If irrigation is used to raise the cover or green manure crop it will help to maintain soil moisture at levels conducive to microbiological and earthworm activity.
- Reduced intensity of tillage. Preferred practice is to minimise disturbance of the soil. Heavy ploughing and rotary hoeing can reduce earthworm numbers by 80-90% at each working, and prevent re-establishment of earthworm populations even when other soil characteristics are favourable. Favoured practices include:
  - use of knock down herbicides and direct drilling/sowing of seeds or plugs
  - only working plant row lines for row crops with only two or three rows per bed (e.g. brassicas, head lettuce)
  - using shallower tillage, such as chisel ploughing or power hoes to 100-150 mm to prepare seed beds
  - use of narrow tines for deep ripping where sub-surface clay pans are forming
  - increasing organic matter down the soil profile
  - using gypsum to improve the structure of clay soils
  - using deep rooted cover or other crops in rotations.

  In many instances, some tillage is unavoidable, and many intensive cropping systems that sow multiple crops per year (for example: leafy green, Asian greens, lettuce, brassica, onion and carrot growers) have soil structure constraints from historic tillage practices that virtually oblige them to maintain high levels of tillage. These systems will typically require several years of changed practice such as application of compost and use of cover crops to rebuild soil structure to the point where reduced tillage intensity is a viable option.
- Reducing soil compaction using controlled traffic and permanent or semi-permanent beds. Compaction from vehicles reduces earthworm activity and creates a need for more intensive tillage.
- Managing shallower soils and the formation of hardpans. Earthworms need to migrate down the soil profile to aestivate during dry periods. This is not possible on shallower soils and where hardpans form due to traffic and cultivation practices. Earthworms will migrate over 400mm down the profile if conditions allow it, and this means more will survive cultivation of the upper soil. If rotary hoeing and other heavy cultivation occurs to the depth of a hardpan or other

dense sub-surface layer, few earthworms will survive. Earthworm activity can help to break up hardpans, but deep ripping, building soil carbon, and the addition of gypsum may be needed to break up hardpans to improve root growth and create conditions where earthworms can survive down the profile.

- Nitrogen availability. Application of nitrogen has a positive effect on earthworm numbers, most likely due to 'feeding' of soil bacteria and healthier plant growth. However, over-application of nitrogen, including synthetic fertilisers and poultry and other manures, or other fertilisers may be detrimental if it results in toxic concentrations of salt or temporary or lasting shifts in soil pH outside the 5.0-8.0 range.
- Sensitive chemical use. Most fungicides and insecticides and some herbicides will impact on earthworm activity to different extents. Even 'ecological' and Certified Organic chemicals containing copper or 'natural' pesticides such as pyrethrum can reduce earthworm activity. However, when soil conditions and management are favourable to earthworms and chemicals are used in accordance with label directions, earthworm numbers will typically be resilient and 'bounce back' after chemical application. Where populations are stressed by other factors and conditions are not suitable chemical use can damage the already small populations and numbers will not recover rapidly. Building soil organic matter down the soil profile and using less intensive tillage will allow healthy earthworm populations down the soil profile to survive the use of most chemicals and active soil biology helps to biodegrade the chemicals. Application of chemicals with irrigation, when soil is wet, or before heavy rainfall will result in migration of chemicals deeper into the soil which may impact more on earthworm populations. Herbicides used on cover crops to reduce the need for tillage have been found to have a net beneficial impact on earthworm activity compared to use of tillage to integrate organic material into the soil. However, it is important to note that the range of herbicides used for vegetable growing will likely have a range of impacts – from benign to toxic – on worm populations. Some manures may contain traces of nematicides from veterinary 'worm drench' chemicals Strategies for avoiding lasting damage to earthworm populations include: maintaining healthy soil with high organic content and active microbial populations; choosing products with lower invertebrate toxicity; reducing the frequency of spraying through integrated pest management and disease breaks in cropping rotations; and, if possible, spraying during stronger daylight and when conditions are drier so earthworms will be further down the soil profile.

Some of the demonstration sites have been improving soil health through adoption of such practices but were found to have low earthworm numbers, even when soil moisture conditions were favourable at the time of surveying. This is likely due to historic management that has reduced earthworm populations to a point of 'local extinction' and where the impacts of even reduced tillage, chemical use and seasonal factors is preventing earthworm numbers from recovering. In some instances, historic management of soils has degraded soil structure to the point that heavy tillage is periodically necessary to prepare beds for crops. One option for addressing this is to artificially boost earthworm numbers through the introduction of live earthworms of viable eggs harvested at other sites on or off farm.

The authors have discussed the intensity of tillage practices with participating growers. Most participating growers using intensive tillage believe that they need to maintain this level of tillage to overcome soil structural issues and this is almost certainly true unless other practices to progressively improve soil structure are adopted.

5 Economic comparison of management methods and earthworm activity

This report confirms that practice changes are required to promote earthworm activity to the point where they can provide 'agronomic services' by improving top- and sub-soil structure and fertility, and reducing the need for tillage and fertiliser application.

Table 5 summarises the main farm practices that will foster increased earthworm activity and the benefits and costs of the practices compared to 'conventional' intensive vegetable production. In reality, many growers use one or more of such practices.

The main costs associated with practices that promote soil health and earthworm activity are:

- The cost of establishing and maintaining cover crops and green manures. This includes the costs of sowing and maintaining cover crops, and the costs of integrating cover crops as a green manure. The costs of cover crops will depend on the types of plants sown, whether fertilisers are needed and the amount of tillage required to establish the crop. Cost for common cover crop plantings range from $300-$1,000 per hectare depending on bed preparation methods, fertiliser use and the seed mix used. The higher costs are associated with heavier tillage.
- The time that land is taken out of production during the cover crop and green manure phase. If cover crops are sown over less productive periods or when land would be fallowed, this is not a major consideration.
- Increased labour/personnel time associated with monitoring crop health under an integrated crop management program. These costs are typically off-set by lower chemical application costs and less labour costs associated with chemical application.
- Where they are used, compost and other organic carbon additives have costs in the order of $400-$1,300 per hectare per application if applied at rate of 10-20 tonnes per hectare assuming product costs of $30-$50 per tonne delivered to farm and spreading costs of $10-$15 per tonne.

The value of the cover crop and green manure will vary according to the type and management of the crop. Potential values include:

- Reduced soil compaction through deep rooted cover crop plants and the action of earthworms, with avoided deep ripping costs of $450-$650/ha per crop.
- Soil fumigation/disease break effects, and disease suppression by healthy soil microbiology and earthworm activity. This will avoid costs of at least $600-$1,000/ha that would be required for soil fumigants or fungicides.
- Nitrogen fixation if legumes are included in the cover crop. Legumes can fix >100kgN/ha contributing a value of >$100/ha in nitrogen costs.
- Increased nutrient availability from the action of earthworms and other soil biology, as well as increased soil organic matter.
- Increased nutrient use efficiency from improved soil structure and enhanced organic matter levels.
- Greater conversion of irrigation water to plant growth/yield due to better water infiltration and retention by soil, as well as deeper root growth.
- Increased marketable yields. Previous studies have conservatively estimated 5-10% yield increases over conventional practice, with the benefits being enjoyed in several subsequent crops. For high value crops, this will be worth thousands of dollars per hectare per crop.
- Improved pack out from greater uniformity in crop production.

Table 5 Economic comparison of 'conventional' and 'earthworm and soil health promoting' practices

Lands management practice	'Conventional' practices	Earthworm and soil health promoting practices	Impact on earthworm activity	Benefits/Advantages of earthworm and soil health promoting practices	Costs/Disadvantages
Tillage – surface (upper 300-400mm)	▪ Repeated workings to 300-400 mm ▪ Use of deep ripping and rotary and power hoes	▪ Fewer and shallower (100-200 mm) workings to prepare seed bed. ▪ Strip tillage ▪ Periodic deep ripping as required ▪ No use of deeper rotary hoeing	▪ Very high	▪ Reduced fuel, equipment and labour costs ▪ Earthworm activity provides sub-surface 'tillage' ▪ Better water infiltration ▪ Improved soil carbon down the soil profile	▪ Reduced root depth if earthworms do not prevent formation of dense clay layers on heavier and poorly structured soils
Tillage- sub-surface (management of clay pans/heavier soils)	▪ Multiple deep rippings per year	▪ Periodic deep ripping if required ▪ Use of deep-rooted cover crop plants to penetrate hard pans	▪ Moderate	▪ Reduced fuel, equipment and labour costs ▪ Increased organic matter down the soil profile	▪ Potential formation of hard pans and shallow root growth
Rotations and land resting/ fallow periods	▪ Minimal period of bare fallow between crops ▪ Sowing according to market demand with chemicals being used to manage disease and pest risks	▪ Integrated Crop Management, with rotations designed to break disease and pest cycles ▪ Cover crops and green manuring used to maintain cover and soil health, as well as break disease, improve soil structure, improve soil fertility and allow weed control.	▪ High	▪ Increased soil organic matter resulting in slow release nutrients, healthy soil biology and increased soil water and nutrient holding capacities.	▪ Loss of land to production for longer when under cover crops ▪ Potential nutrient drawn down from decaying green manure
Soil organic management	▪ Not deliberately managed. Organic carbon is present from crop residues and potentially application of composted poultry manure	▪ Use of cover crops and green manures	▪ High	▪ As above	▪ Loss of land to production under cover crop
		▪ Use of composts to add organic carbon	▪ Low to moderate	▪ Composts contribute to slow release nutrients, water and nutrient holding capacities of soil, and improved soil structure.	▪ Costs of purchase and spreading of compost

Lands management practice	'Conventional' practices	Earthworm and soil health promoting practices	Impact on earthworm activity	Benefits/Advantages of earthworm and soil health promoting practices	Costs/Disadvantages
Soil compaction	▪ Cultivation and deep ripping	▪ Controlled traffic management ▪ Less intensive and shallower cultivation ▪ Earthworms, cover crop roots and increased soil organic matter reduce soil compaction	▪ Moderate	▪ Reduced fuel, equipment and labour costs ▪ A functioning soil with soil organic matter, healthy soil microbe and earthworm activity is less prone to compaction	▪ Controlled traffic can be difficult if bed preparation and harvesting equipment have different wheelbase widths compared to the widths of beds.
Moisture management	▪ Irrigation of productive crops as needed	▪ Irrigation of productive crops as needed ▪ Irrigation of cover crops if required ▪ Soil organic matter contributes to water holding capacity of soil	▪ High	▪ Increased earthworm activity and other soil biology can improve the permeability of soils, helping water move down the profile. This deeper moisture will help to sustain earthworms during dry periods.	▪ Costs of irrigating cover crop if required (growing cover crops over winter can avoid the need for much/any irrigation)
Root disease control	▪ Routine use of fungicides, nematicides and soil fumigants	▪ Integrated crop management to anticipate and treat disease as required ▪ Use of 'biologicals' to combat and suppress root disease ▪ Use of biofumigant crops (these will initially damage earthworms but contribute to soil organic matter that should support earthworm activity.	▪ Moderate to high	▪ Reduced chemical and application costs ▪ Biofumigant crops add to soil organic matter and deep-rooted mustard species can be used to penetrate soil hard pans.	▪ More personnel time required to monitor disease ▪ Chemical treatments can be more reliably effective because of their broad-spectrum toxicity ▪ Biofumigant crops require land to be taken out of production
Fungal and bacterial plant disease control **Insect pest control**	▪ Routine/scheduled use of chemicals without regard for toxic effects on soil biology and earthworms.	▪ Integrated crop management ▪ Disease-breaking crop rotation ▪ Monitoring disease with responsive use of chemical as required ▪ Use of 'biological' agents and less broad-spectrum chemicals ▪ Use of insect baits/traps	▪ Moderate (higher for some chemicals)	▪ Reduced chemical and application costs ▪ Reduced impact on soil health	▪ Risk of disease outbreak or cosmetic damage to produce ▪ Some 'organic' treatments such as copper sprays and pyrethrin are quite toxic to earthworms

Lands management practice	'Conventional' practices	Earthworm and soil health promoting practices	Impact on earthworm activity	Benefits/Advantages of earthworm and soil health promoting practices	Costs/Disadvantages
		▪ Not applying chemicals with water or when soil is saturated/irrigated			
Weed control	▪ Use of herbicides without regard for toxic effects on soil biology and earthworms. ▪ Heavy cultivation	▪ Selecting 'softer' herbicides ▪ Spot or wick application of herbicides Use of cover crops to reduce weeds setting seed ▪ Hand-weeding ▪ Not applying chemicals with water or when soil is saturate/irrigated ▪ Shallow surface cultivation	▪ Mostly low (herbicides may have short term toxic effect but in the longer term provide labile organic matter that feeds soil biology and earthworms)	▪ Reduced chemical costs ▪ Potentially high labour costs (hand weeding or spot application of chemicals) ▪ Reduced risk of herbicide resistance	▪ Potential for higher levels of weeds if integrated crop management measures are not effective
Maintain earthworm 'refuge' areas	▪ Not considered	▪ Permanent irrigation lines or intercrop rows could be used to maintain a population of earthworms to recolonise other areas. Cover crops or organic mulch could be used to make these more conducive to earthworm activity.	▪ Uncertain – likely to be of benefit where there is opportunity to maintain such refuges	▪ Opportunistic use of permanent irrigation lines.	▪ Cost of establishing cover crop or mulch. ▪ Potential for any covering plant to become a weed in crops

5.1 Cost-benefit assessment

'Earthworm-friendly' practices have productivity benefits independent of earthworm activity, but greater earthworm activity will typically provide additional benefits. The main benefit is their 'tillage' and 'manuring' of sub-surface soil. Our research suggests that the main financial advantage of promoting earthworm activity is likely to be reduced cultivation costs. Increased earthworm activity may also increase yields and allow reduced fertiliser use, as well as improve infiltration of water down soil profiles, but these benefits are harder to quantify for different soils, climates, crops and rotations.

The field data available from our research was not able to provide yield response data that could be related to earthworm activity. It is difficult to isolate the benefits of greater earthworm activity from other soil health and function benefits that arise from the same 'earthworm friendly' practices.

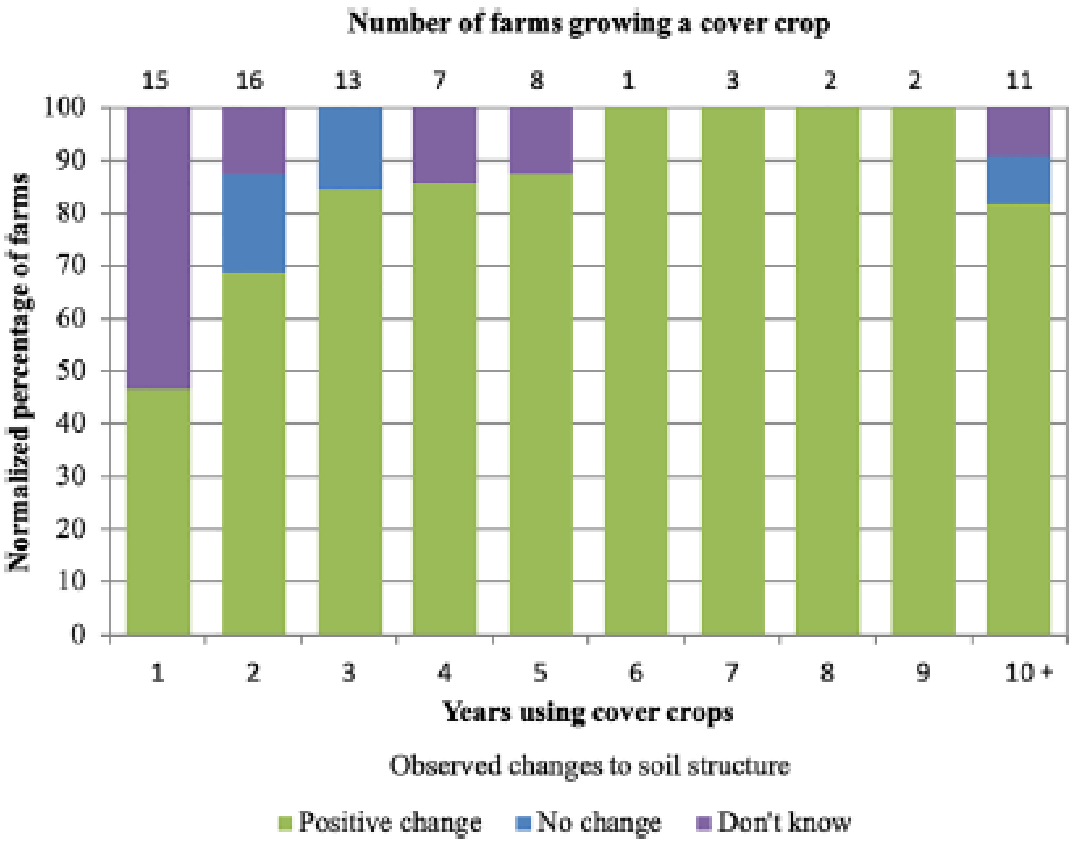
Previous studies of the benefits of practices such as reduced intensity tillage, cover crops, green manures, application of composts, integrated pest and crop management, and sensitive chemical use have not isolated how much different factors contribute to noted yield or soil health benefits. Previous work by CSIRO and the Victorian Department of Agriculture attributed increases in pasture and broadacre yields to higher earthworm activity, but without apparent consideration of other factors associated with soil health and function such as soil organic carbon levels and soil microbial activity that may also have contributed to increases in yield. Many of the benefits of practice changes to enhance soil health and function are observed progressively over a number of years, and may not be apparent during shorter term trials. For example, a recent survey of UK vegetable farmers using cover crops found that growers who had been using cover crops for more than 3-5 years were more likely to observe positive changes in soil structure than those who'd only more recently adopted the practice (Figure 19, Storr et al 2018). More recently, the same researchers have found earthworm numbers under commercial vegetable growing systems using cover crops are on average three times greater than under systems not using cover crops (Storr et al, 2019).

The following discussion considers benefits and costs associated with earthworm friendly activities and how these impact on farm productivity. This is considered under sub-headings for different practices.

Reduced tillage intensity and depth

Earthworm populations are highly sensitive to tillage and can take over 12 months to rebuild populations after major soil disturbance (e.g. deep rotary hoeing or repeated ploughing/tyning that can reduce earthworm numbers by 80-90%). Our research suggests shallower tillage (down to 100-150 mm) and less intensive/disruptive tillage (e.g. strip tillage, tyning with fewer passes rather than rotary hoeing) can allow higher levels of earthworm survival and potential to recolonise disturbed soil. The impact of tillage will depend on the depth of friable soil below the depth of tillage. In most instances, hard pans or dense clay or gravel layers at 300-400 mm restrict the area where earthworms are active, but on some deeper loams and self-mulching clays earthworms were active at lower depths and populations are more resilient to tillage.

Figure 19 Vegetable growers' observed changes to soil structure under systems using cover crops



Many of the farmers involved in the trial feel the need to cultivate to 300-400 mm and relatively heavily use rotary hoes to prepare seed and seedling beds, and justifiably believe that due to historic tillage practices the soils will slump and reduce yield if they are not heavily worked prior to sowing. A transition to soil conditions that requires less intense tillage may take a number of years, and may involve introduction of green manures and/or application of organic amendments to improve soil structure and porosity and increase soil biology, including earthworm activity. Most of the farms studied with sub-soil structure being obviously affected by earthworm activity had cover crops or non-vegetable cropping and pasture phases in their rotation, as well as other practices designed to build and maintain soil organic carbon including reduced tillage.

The financial benefits of less intensive tillage include reduced fuel, labour and equipment maintenance costs. The cost savings will vary according to soil type and tillage practices, and net revenue will depend on yield responses to less intensive tillage, as well as the value of the crops. Reduced tillage intensity is often coupled with other practices aimed at improving soil structure and function such as cover crops and green manures, controlled traffic/permanent bed management and application of organic amendments. The net effects of these practices combined with reduced tillage on improving and maintaining the yield potential of land need to be considered in assessing the financial costs and benefits of changing tillage practices. In some instances, such practices are adopted in order to halt declines in the yield potential of soil. Previous assessments of the financial and productivity advantages of reduced and 'no till' vegetable farming systems have found significant cost savings. This varies according to soil type and conventional cultivation practices, as well as fuel and labour costs.

Some growers cultivate deeply to break-up hard pans. Deep rotary hoeing can contribute to hard pan formation, but some soils tend to form hardpans naturally. Unless soil conditions down the soil profile are hostile to earthworms (for example, an impermeable and highly acid or alkaline clay), higher earthworm activity should reduce the formation of hard pans. Periodic deep ripping, and potentially applying organic amendments in rip-lines (so called 'deep manuring') can be used as a less disruptive alternative.

A comparison of bed preparation costs using different cultivation methods is shown below. This shows that, where growers can manage soils so that earthworms and other factors[3] maintain friable soil conditions in the upper 400-500 mm, the costs of reduced or no till systems are only 3-40 % of the costs of more conventional bed preparation.

It is important to recognise that there are some situations within rotations where heavier tillage will be required (for example, if farm equipment or livestock have compacted soil, or soil is waterlogged and needs working to dry it out to meet a scheduled sowing) and that harvesting of some root crops may result in deeper soil disturbance and higher earthworm mortality. Where heavier tillage or soil disturbance is periodically required, management that will reduce earthworm mortality or reintroduce earthworms to allow them to recolonise soils should be considered. Options for this include: leaving uncultivated and uncompacted 'strips' at least every 30 m in a paddock (permanent irrigation lines can serve this function); reducing the depth of intensive cultivation to the minimum required (e.g. using ripping tynes for deeper cultivation, and power hoes or shallower rotary hoeing for upper bed preparation); where possible, timing deeper cultivation to periods where upper soil is drier and earthworms have migrated down the soil profile to more moist conditions (note that cultivation when deeper soil is dry and upper soil has been irrigated may result in high earthworm mortality rates because earthworms will migrate to the moister conditions).

[3] Such as: particulate and humic soil carbon contributing to soil structure; and soil microbiology and plant-soil relationships that promote deeper friable conditions.

Table 6 Indicative cost comparison of conventional versus reduced

Conventional	Passes	Indicative costs ($/ha)			
		Fuel costs	**Labour costs**	**Equipment costs**	**Total cost**
Deep ripping	1.0	$ 10.00	$ 6.33	$ 2.50	**$ 19**
Tyne preparation	3.0	$ 18.75	$ 11.40	$ 4.50	**$ 35**
Rotary hoeing	2.0	$ 18.75	$ 12.67	$ 5.00	**$ 36**
Bed formation	1.0	$ 3.75	$ 4.75	$ 0.63	**$ 9**
TOTAL		**$ 51.25**	**$ 35.15**	**$ 12.63**	**$ 99**
Reduced tillage on semi permanent beds	**Number of passes**	**Indicative costs ($/ha)**			
		Fuel costs	**Labour costs**	**Equipment costs**	**Total cost**
Deep ripping	1	$ 10.00	$ 6.33	$ 2.50	**$ 19**
Power hoeing	1	$ 6.25	$ 3.80	$ 1.50	**$ 12**
Bed formation	1	$ 3.75	$ 4.75	$ 0.63	**$ 9**
TOTAL		**$ 20.00**	**$ 14.88**	**$ 4.63**	**$ 40**
'No'/minimal tillage on permanent beds	**Number of passes**	**Indicative costs ($/ha)**			
		Fuel costs	**Labour costs**	**Equipment costs**	**Total cost**
Deep ripping	1	$ 10.00	$ 6.33	$ 2.50	**$ 20**
Strip sowing	1	$ 3.75	$ 3.80	$ 0.50	**$ 8**
TOTAL		**$ 13.75**	**$ 10.13**	**$ 3.00**	**$ 28**

Cover crops and green manures

Our field and literature research suggest that cover crops and green manures are a key strategy for building and maintaining agronomically useful earthworm populations. These practices are promoted to build soil organic carbon and improve soil structure. Plant species grown as cover crops and green manures can be used as disease-breaks and soil nitrifiers (legumes used in green manures), and deep-rooted species can be used the 'break up' sub-soil. They can also be used as weed control tool by crowding out weeds species or allowing selective herbicide use during the cover crop stage.

Biofumigant crops can be grown as cover-crops and will provide organic matter to the soil. However, they will reduce earthworm numbers directly through toxicity and indirectly by killing soil microbes that earthworms feed on.

There are costs associated with sowing and maintaining cover crops and taking cropping land out of production in order to grow these. Previous assessments of these have shown that cover crops and green manures have value in building and maintaining soil function and yield and in reducing the need for other inputs. Green manures grown to nitrify soil can significantly reduce fertiliser costs. There is potential to grow irrigated summer fodder crops that can contribute to soil organic matter and soil nitrification whilst also generating farm income.

Other methods for increasing soil organic matter and active soil biology

Earthworms feed on bacteria, fungi, decaying organic matter and other soil microorganisms. Although our research indicates that levels of labile organic matter from green manures has greatest positive effect on earthworm numbers, other methods for increasing and maintaining soil carbon include:

- **Retention and reuse of crop biomass.** This involves incorporating residues from crops and packing sheds into the soil. This is essentially a zero or very low-cost management option, with the main constraints being disease. pests and weed management associated with residues and some fruiting bodies in residues. Where there are concerns about disease, pests or weed spread from residues, the residues could be treated on-farm via composting or vermiculture-beds before the treated organics are used. Vermiculture beds could also be used to produce earthworm-rich sods that can be used to re-populate low-earthworm areas on the farm. The main costs of these practices would be labour. There are potential cost savings if growers previously paid to transport residues off site.
- **Addition of manures with organic carbon content.** Poultry manures are widely used as an affordable source of readily plant available nitrogen, and these also contain high levels of organic carbon in faeces and litter materials (e.g. rice hulls, chaff, wood shavings). The nitrogen and organic matter in these inputs will feed soil microbe and boost earthworm populations. This is not considered to add to production costs where manures are used as a source of nitrogen.
- **Addition of composts.** Composts can be used to build soil carbon. They provide a combination of particulate and humic organic matter that improves soil structure, feeds soil biology, improves soil fertility and provides some 'slow release' plant nutrients. Some compost products are also promoted as having 'probiotic' populations of beneficial microbes. The levels of labile carbon that feeds the soil microbes that earthworms feed on will depend on how 'mature' /biologically stable composts are. Less mature composts will contain more labile carbon and feed soil microbes more than will mature/stable composts. The costs of using compost can be high, with commercial composts selling into agriculture for $25-$60 per tonne, with application costs $3-$5/tonne, and application rates of greater than 10-20 tonnes per hectare per year in most vegetable growing applications. This equates to costs of $280 to over $1,200 per hectare per year. Composts are useful for rapidly building soil carbon levels on degraded soils or maintaining soil carbon during intensive periods of cropping, but green manures and residue management are likely to be more cost-effective ways of maintaining soil carbon over time, possibly with periodic applications of compost at lower rates.
- **Addition of vermicasts**. Vermicasts are promoted as have fertiliser, soil health and plant growth promoting benefits. They are generally applied at low rates (<5-10 tonnes per hectare) and have relatively high costs (e.g. $200-$300/tonne plus application costs). They will have some contribution to soil organic carbon and microbial activity, but this is not the primary reason for using products.
- **Reduced tillage.** Tillage exposes soil carbon from down the soil profile to more rapid biodegradation. It also kills fungal matter and earthworms that would otherwise play a role in converting organic matter into more stable forms of soil carbon.

Integrated pest and crop management and sensitive chemical use

There is evidence that some farm chemicals can reduce earthworm numbers and activity through either direct toxicity or by reducing the soil microbes on which earthworms feed. Integrated pest and crop management works to break disease, pest and weed reproduction cycles through crop rotations, promotion of beneficial microorganisms, insect traps, and more strategic chemical use. It typically reduces farm chemical and application costs, but has higher costs associated with monitoring the presence of disease, weeds and pests. The net cost-benefit of ICM practices will depend on the practices and crops.

Soil fumigation practices, including alternatives to conventional chemical treatment, such as steam and bio-fumigant methods, will greatly impact on earthworms and the soil microbiology on which they feed. Biofumigant crops will provide SOM that will feed soil microbiology and earthworms in subsequent years, but our field work suggests it can be devastating to earthworm populations and have lasting effects for 1-2 years following bio fumigation.

5.2 Net cost-benefit and productivity outcomes

The productivity value of earthworms and earthworm-friendly practices compared to conventional practices will vary depending on cropping systems, soil types and the value of inputs and products. The extent to which productivity gains from the adoption of such practices can be solely attributed earthworm activity is unclear. However, earthworm activity will provide additional and significant benefits associated with improving soil porosity down the soil profile, as well as contributions to soil fertility and aggregate formation. Previous research on pasture and broadacre crops suggest earthworm activity can greatly increase yield potential compared to conventional practices, but there are limited data showing similar responses in vegetable production. However, earthworm-friendly practices in commercial vegetable cropping systems have been shown to be able to increase or maintain yields and reduce costs in many instances.

Greater earthworm activity is likely to amplify other benefit from soil management practices that build SOM and beneficial soil microbiology. Earthworms 'work' and fertilise the soil, and improve formation of aggregates or peds that improve soil porosity, structure and stability. These activities reduce the need to cultivate the soil. Earthworm activity, as well as the SOM and soil microbiology in which they feed, help to cycle plant-available nutrients and stimulate root growth.

The main productivity benefits from earthworm-friendly soil and crop management practices are likely to result from reduced tillage costs, reduced fertiliser costs, and sustainable yields resulting from improvement and maintenance of soil health and function. Integrated crop management practices can significantly reduce chemical use costs. The productivity gains from reduced tillage are likely to be greatest on soils that have a tendency become compacted further down the profile.

Making the transition from a conventionally cultivated soil with poor resting structure and low porosity to a soil where earthworms are aerating the soil may take several years in which high-biomass and deep-rooted cover crops, green manures, pasture phases, and potentially application of compost or other organic matter are used to increase SOM and improve soil structure. The intensity and depth of tillage will also need to be reduced over time to allow earthworm numbers to build to levels where they are agronomically useful.

6 Key findings

Key findings include:

- There are multiple variables impacting on earthworm numbers and activities. Key factors are:
  - intensity of tillage practice
  - soil organic carbon levels, and particularly levels of labile carbon
  - soil moisture
  - levels of soil biological activity
  - cover crops/green manures
  - site history/historical land management.
- The variability between and within sites has made it impossible to obtain strong statistical data and correlation between earthworm numbers and different soil attributes. Two sites with 'good' soil conditions were found to have inexplicably low earthworm numbers, and one site with less favourable soil conditions had 'hot spots' of surface dwelling, pasture worm varieties; the site has been under pasture for two years. These results as well as other variability across sites has prevented statistical validation of observed trends.
- Variability across the two detailed research sites, as well as favourable soil conditions under the control treatments, has also reduced the statistical significance of observed trends, with only a weak to moderate statistical correlation between green manure crops, labile soil carbon and higher earthworm activity being observed.
- The most significant factors influencing the earthworm activity appear to be:
  - The use of green manures and crop rotations that build levels of labile carbon. On the studied soils, the farms that had green manures or pasture phases in their rotations have high levels of earthworms and the effect of burrows and casts on sub-soil structure was apparent.
  - Reduced intensity and depth of tillage. On most, but not all, of the studied soils, rotary hoe tillage to greater than 300 mm greatly reduced earthworm numbers. This was more marked at sites where tillage was to the depth of clay pans or gravel layers. Two sites with intensive tillage were found to have healthy earthworm numbers but these both had sub-soils deeper than the tillage depth, allowing some earthworms to survive and recolonise areas.
  - Soil moisture. Soils that experienced significant and prolonged drying down the soil profile had low earthworm numbers despite good soil management practices.
  - Sensitive chemical use. Sites using integrated soil management and biological agents for disease control and soil health enhancement had higher earthworm numbers. However, some sites with scheduled regular use of insecticides and fungicides, but with high levels of labile soil carbon and reduced intensity tillage, had healthy earthworm numbers.
- The economic benefits of soil management practices that promote earthworm activity include reduced input costs and increased yields. The main economic values of earthworm activity are likely to be:
  - reduced soil compaction and reduced need for tillage.
  - reduced need for fertilisers due to 'manuring' with earthworm casts.
  - deeper and healthier plant root growth.
  - increased yields per unit of input. Little work has been done on the impacts of earthworm activity on vegetable crops, but on pasture and cropping systems, yield increases in excess of 10% have been reported. Trials of soil management practices that improve soil organic matter levels and soil structure in vegetable farms have reported yield increases of 5-10%. This cannot all be attributed to earthworm activity, although they can make a significant contribution to soil structure and fertility.

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Appendix A: Biometrician report on research sites

Analysis of trials on the effect of treatments on earthworm numbers

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17 April 2019

Executive Summary

Two replicated field trials, one in Maffra, Victoria, and the other in Addison, Tasmania, were conducted from 2016 to 2018 to examine the effect of five treatments on earthworm numbers – Biofumigant, Compost, Control, Green manure, and Worm casts. There were 3 replicates of each treatment at each site, randomised to plots in a statistically balanced experimental design. The data from the trials were explored graphically and statistically analysed. Initial earthworm numbers and measurements on various soil variables (taken in 2016) were tested, and if appropriate, corrected for in comparing the effect of treatments on 2017 and 2018 earthworm numbers.

There was considerable variability in the earthworm numbers, and so even though there were some large apparent differences between treatments, there were not many conclusive results. There were clear differences between years, but in opposite directions – Maffra had more earthworms in 2018, and Addison more in 2017.

At Maffra, Green manure resulted in the most earthworms, with a mean of around 90 per plot in both years. The initial level of potassium permanganate oxidisable carbon was positively correlated with earthworm numbers, and when this was accounted for, Worm casts was found to have the least number of earthworms. The other three treatments were in between.

At Addison, Green manure also resulted in the most earthworms, with a mean of around 40 per plot in 2017 and 20 in 2018. However, it did not result in a lot more earthworm numbers than the other treatment means. The initial level of soil microbial biomass was negatively correlated with earthworm numbers, and when this was accounted for, Biofumigant was found to have significantly lower numbers than Green manure. The other three treatments were in between.

1. Introduction

In 2016 the Statistical Consulting Centre (SCC) was engaged by SESL Australia to design two field trials to examine the effect of various treatments on earthworm numbers. The two experimental sites were located in

(1) Maffra, Victoria

(2) Addison, Tasmania

Measurements were taken on the trials in 2016 (prior to the treatments being applied) and again in 2017 and 2018.

In 2019, SESL provided a set of Excel data files to the SCC with all the measurements from both trials. These were arranged into a suitable form for analysis. Measurements were taken in all three years on the following soil variables:

- Earthworm numbers
- Total nitrogen
- Potassium permanganate oxidisable carbon
- Total organic carbon
- Microbial activity indicator
- Soil basal respiration
- Soil microbial biomass

Other quantities were measured in 2016 and 2018 (and not 2017), or in 2016 only, and were not included in the data analysis.

2. Experimental designs

There were five experimental treatments – the same five at both sites. They were, in alphabetical order:

1. Biofumigant
2. Compost
3. Control (normal farm practice)
4. Green manure
5. Worm casts

At each site there were three replicates of each treatment, resulting in 15 plots. Treatments were randomised to plots in "row-column" designs, as shown in the following diagrams:

Maffra, Victoria randomised block design

Compost	**Biofumigant crop**	**Green manure**	**Worm casts**	**Control**
Worm casts	**Control**	**Compost**	**Biofumigant crop**	**Green manure**
Biofumigant crop	**Green manure**	**Worm casts**	**Control**	**Compost**

Moriarty, Tasmania randomised block design

Green manure	Worm casts	Control	Compost	Biofumigant crop
Control	Compost	Biofumigant crop	Green manure	Worm casts
Biofumigant crop	Green manure	Worm casts	Control	Compost

Within each site, each row (shown horizontally here) had exactly one of each of the five treatments, and each column (shown vertically here) had no more than one of each treatment. Within each column, each treatment occurred with each other treatment either once or twice. This row-column arrangement ensured that the experimental designs were as balanced as they could be in both directions.

3. Exploration of data

The data were explored with graphs of each variable vs year of measurement. The graphs of earthworm numbers (mean of each treatment) are shown on the next page; graphs of the other six variables are shown in Appendices 1 and 2.

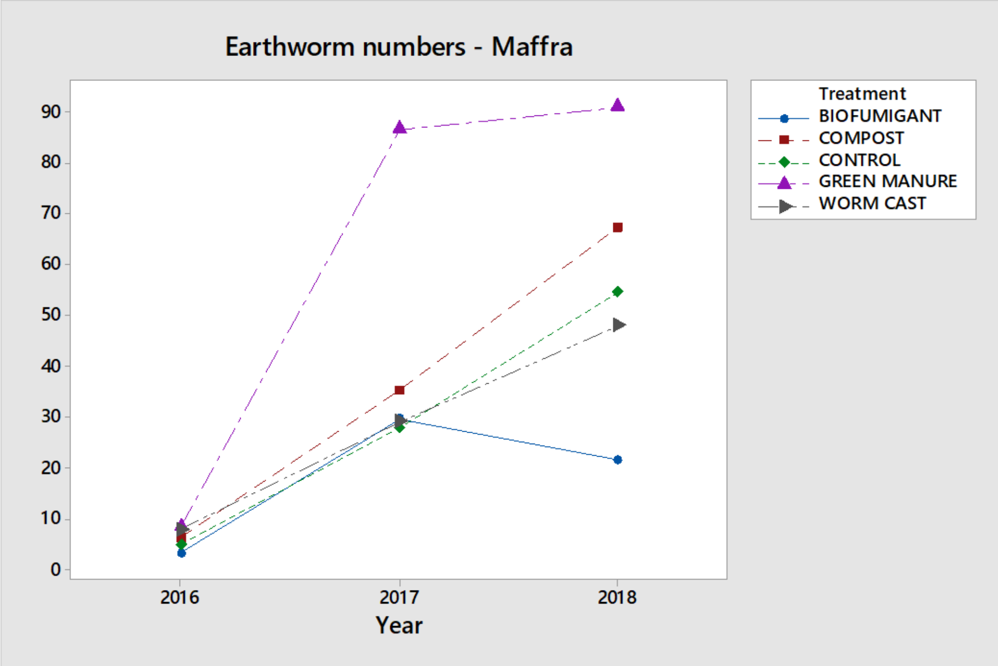
It is evident from the graphs that the results at the two sites were very different. At Maffra, all treatments (including the control) resulted in substantially increased earthworm numbers in both 2017 and 2018, with Green manure producing a very large increase. At Addison, some treatments (including the control) resulted in an increase in 2017, but by 2018 they had dropped below 2016 levels.

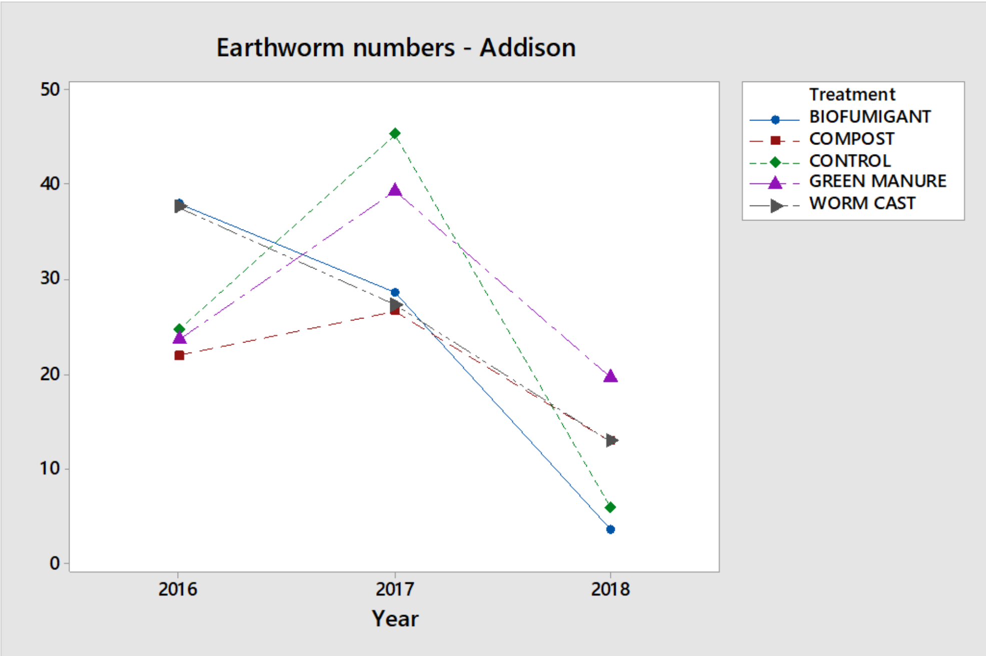
4. Statistical analysis

The data from each site were analysed separately. An analysis combining the data from both sites was also conducted, but it did not reveal anything new or assist in interpretation, and so it is not reported here.

At each site, the data analysis followed these steps:

- A "linear mixed model" was conducted to determine if rows and columns should both be included as factors in the analysis of earthworm numbers. It turned out that variation between columns had little effect on the outcome, and so it was then dropped from the statistical model; this enabled the more straightforward analysis of variance (ANOVA) to be used.
- An ANOVA was conducted to analyse earthworm numbers. The statistical model included the main effects of treatment and year, and the treatment by year interaction. In addition to the P-value, the least significant difference (LSD) was calculated to compare pairs of treatment means using a 95% confidence interval for the mean difference.





2016 measurements of each of the six other variables were included in the statistical model as a potential covariate to be corrected for, and tested for significance. A covariate should normally be measured before the treatment is applied, otherwise its effect can be confounded with that of the treatment. If any of the covariates was significant at the 0.05 level, it was retained in the model; if not, it was removed. If it was retained, comparisons between treatments were again performed, adjusted for the covariate, and 95% confidence intervals recalculated.

- Plots of residuals vs fitted values were constructed to assess the assumptions of the statistical model, and whether a transformation of the earthworm numbers was needed. Such plots were reasonably consistent with the assumptions, and the data were not transformed.

5. Results

(i) Maffra

The following table shows the mean earthworm numbers at Maffra, for each treatment and each year, together with LSDs (at the 0.05 significance level) for comparing pairs of means using 95% confidence intervals, and the P-values for overall comparisons.

Year	Biofum-igant	Compost	Control	Green manure	Worm casts	All	LSD (P=0.05)	P-value
2017	29.7	35.3	28.0	86.7	29.3	41.8		
2018	21.7	67.3	54.7	91.0	48.0	56.5	9.0	0.005
All	25.7	51.3	41.3	88.8	38.7	49.2		
LSD			69.3				69.8	
P-val			0.36					0.058

The LSD of 69.3 and the P-value of 0.36 relate to the treatment means averaged over both years. For example, the estimated mean difference between Biofumigant and Compost is 51.3 – 25.7 = 25.6, with a 95% confidence interval of 25.6 ± 69.3 = (–43.7, 94.9). We are therefore 95% sure that the true mean difference is between about –44 and 95 worms. Because this interval easily includes 0, the difference is not close to being significant at the 0.05 level.

The LSD of 9.0 and the P-value of 0.005 relate to the year means averaged over all treatments. The estimated mean difference between 2017 and 2018 is 56.5 – 41.8 = 14.7, with a 95% confidence interval of 14.7 ± 9.0 = (5.7, 23.7). We are therefore 95% sure that the true mean difference is between about 6 and 24 worms. Because this interval does not include 0, the difference is significant at the 0.05 level, which is confirmed by the P-value.

The LSD of 69.8 relates to the treatment means for a particular year. For example, the estimated mean difference between Control and Green manure in 2017 is 86.7 – 28.0 = 58.7, with a 95% confidence interval of 58.7 ± 69.8 = (–11.1, 128.5). We are therefore 95% sure that the true mean difference is between about –10 and 130 worms. Because this interval almost includes 0, the difference is close to being significant at the 0.05 level.

The P-value of 0.058 relates to the treatment by year interaction. Because it is fairly small, there is some evidence that the difference between treatments was not consistent across the two years. This is confirmed by the graph above.

Correction for potassium permanganate oxidisable carbon

In testing each variable as a potential covariate, it was found that potassium permanganate oxidisable carbon (PPOC) in 2016 was a significant predictor of earthworm numbers in 2017 and 2018. The above analysis was therefore repeated with PPOC included in the statistical model. The following table shows the mean earthworm numbers at Maffra, corrected for PPOC in 2016. These means are estimates at the average value of PPOC, and so should be understood relative to each other rather than in absolute terms.

Year	Biofum-igant	Compost	Control	Green manure	Worm casts	All	LSD (P=0.05)	P-value
2017	66.5	32.1	32.0	87.3	–8.9	41.8	9.0	0.005
2018	58.5	64.1	58.7	91.6	9.7	56.5		
All	62.5	48.1	45.4	89.4	0.4	49.2		
LSD	48.5						46.2	
P-val	0.035							0.058

The LSDs for comparing treatment means have been considerably reduced by including the covariate; this is because PPOC has explained a substantial amount of the variability between plots, resulting in a more precise comparison between treatments (also evidenced by the smaller P-value). The P-value for PPOC was 0.006, and its estimated coefficient (slope) was 1.09; this can be interpreted to mean that for each additional mgC/kg of PPOC, the number of worms is estimated to increase by about 1.1.

No other variables were significant as covariates, so it is not worth reporting earthworm numbers corrected for those. This includes 2016 earthworm numbers.

When PPOC was corrected for, the estimated mean number of earthworms for Biofumigant increased markedly (because it started with a low average PPOC – see the graph), and the estimated mean number of worms for Worm cast decreased markedly (because it started with a high average PPOC). The difference between these treatments is now significant at the 0.05 level; the estimated mean difference is 62.5 – 0.4 = 62.1, with a 95% confidence interval of 62.1 ± 48.5 = (13.6, 110.6), which does not include 0.

Green manure stands out as resulting in the highest earthworm numbers, particularly in 2017, where it had a significantly larger mean than all other treatments except Biofumigant (using the LSD of 46.2).

(ii) Addison

The following table shows the mean earthworm numbers at Addison, for each treatment and each year, together with LSDs and P-values.

Year	Biofum-igant	Compost	Control	Green manure	Worm casts	All	LSD (P=0.05)	P-value
2017	28.7	26.7	45.3	39.3	27.3	33.5	8.7	<0.001
2018	3.7	13.0	6.0	19.7	13.0	11.1		
All	16.2	19.8	25.7	29.5	20.2	22.3		
LSD	14.2						18.3	
P-val	0.30							0.29

The LSD of 14.2 and the P-value of 0.30 relate to the treatment means averaged over both years. For example, the estimated mean difference between Biofumigant and the Control is 25.7 – 16.2 = 9.5, with a 95% confidence interval of 9.5 ± 14.2 = (–4.7, 23.7). We are therefore 95% sure that the true mean difference is between about –5 and 24 worms. Because this interval includes 0, the difference is not significant at the 0.05 level.

Because the treatment by year interaction was clearly not significant, comparisons are best made between the overall treatment means; there is no need to consider a particular year.

The earthworm numbers for Addison were much smaller than at Maffra. So too was the variability, as evidenced by much smaller LSDs. Another obvious difference is that the numbers were much lower in 2018 at Addison.

Correction for soil microbial biomass

In testing each variable as a potential covariate, it was found that soil microbial biomass in 2016 was a moderately significant predictor (P = 0.061) of earthworm numbers in 2017 and 2018. The above analysis was therefore repeated with this variable included in the statistical model. The following table shows the mean earthworm numbers at Maffra, corrected for soil microbial biomass in 2016. These means are estimates at the average value of Biomass, and so should be understood relative to each other rather than in absolute terms.

Year	Biofum-igant	Compost	Control	Green manure	Worm casts	All	LSD (P=0.05)	P-value
2017	23.7	24.8	46.5	42.0	30.4	33.5	8.7	<0.001
2018	–1.3	11.2	7.2	22.3	16.0	11.1		
All	11.2	18.0	26.9	32.1	23.2	22.3		
LSD	12.9						17.5	
P-val	0.074							0.29

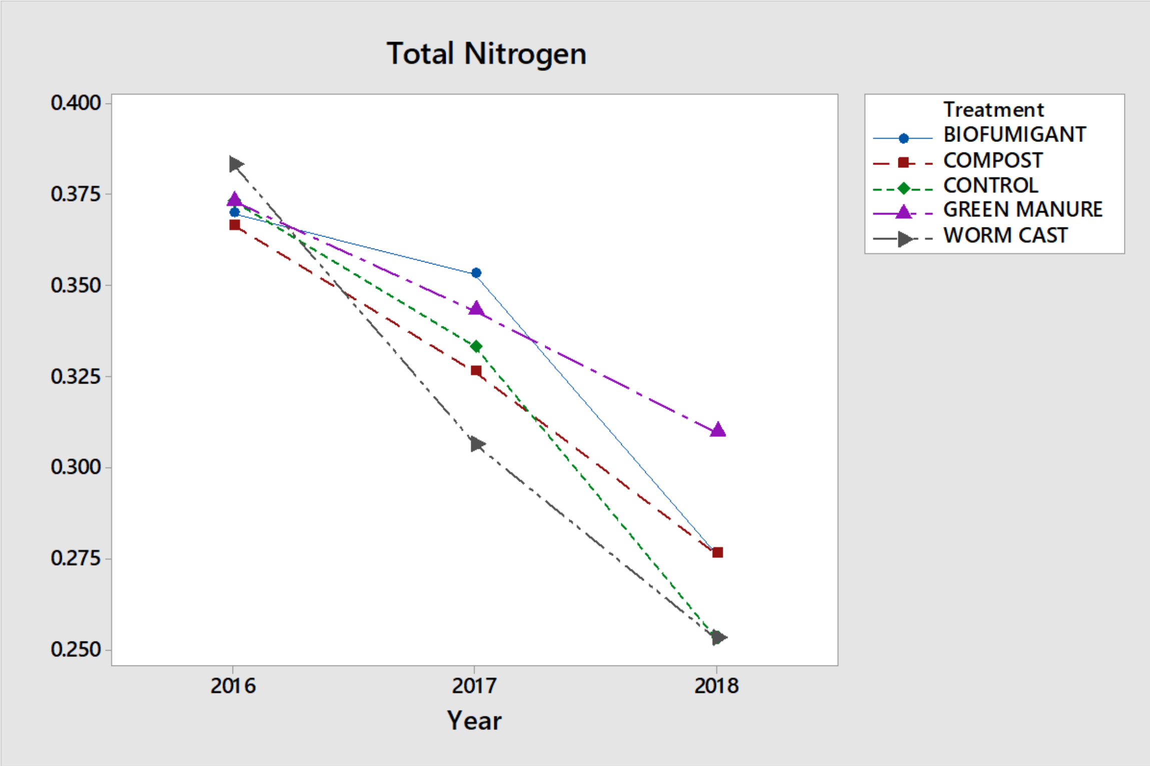
The LSDs for comparing treatment means have been modestly reduced by including the covariate; that is because soil microbial biomass in 2016 has explained a reasonable amount of the variability between plots, resulting in a more precise comparison between treatments (also evidenced by the smaller P-value). The Control and Green manure now have significantly larger means than Biofumigant.

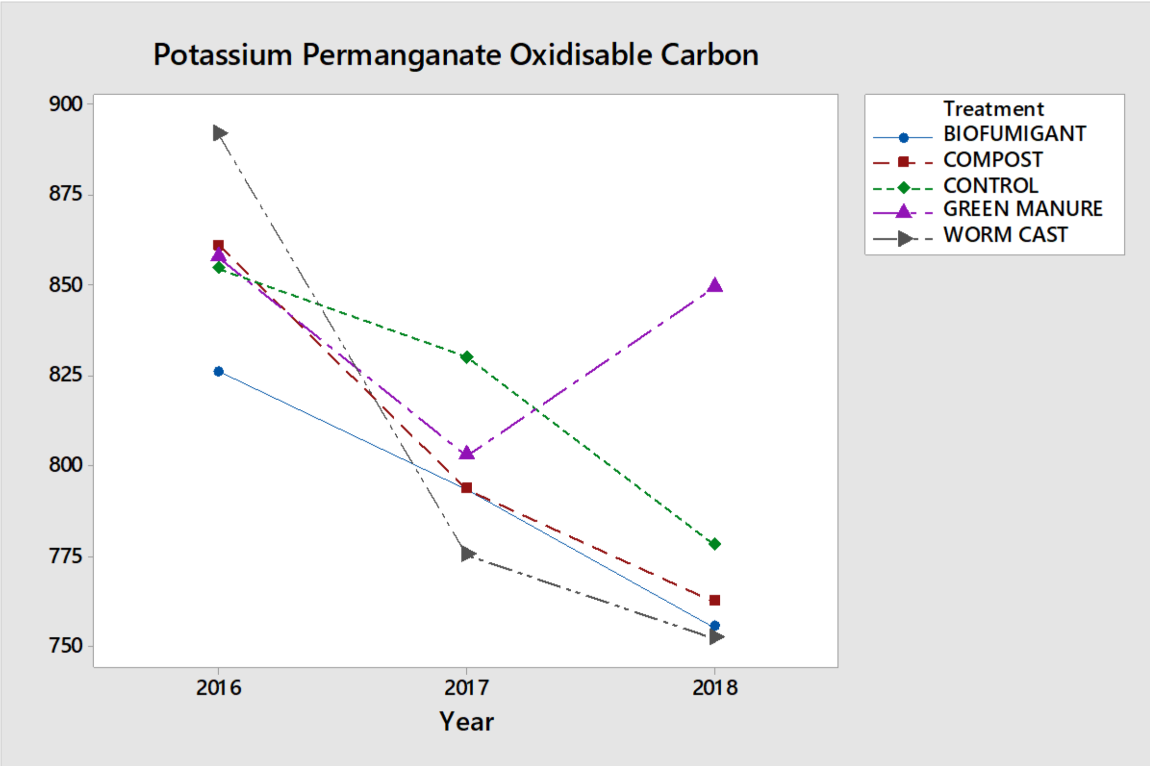
The estimated coefficient (slope) of soil microbial biomass was –0.105; this can be interpreted to mean that for each mgC/kg soil increase in Biomass, the earthworm numbers are estimated to decrease by about 0.1.

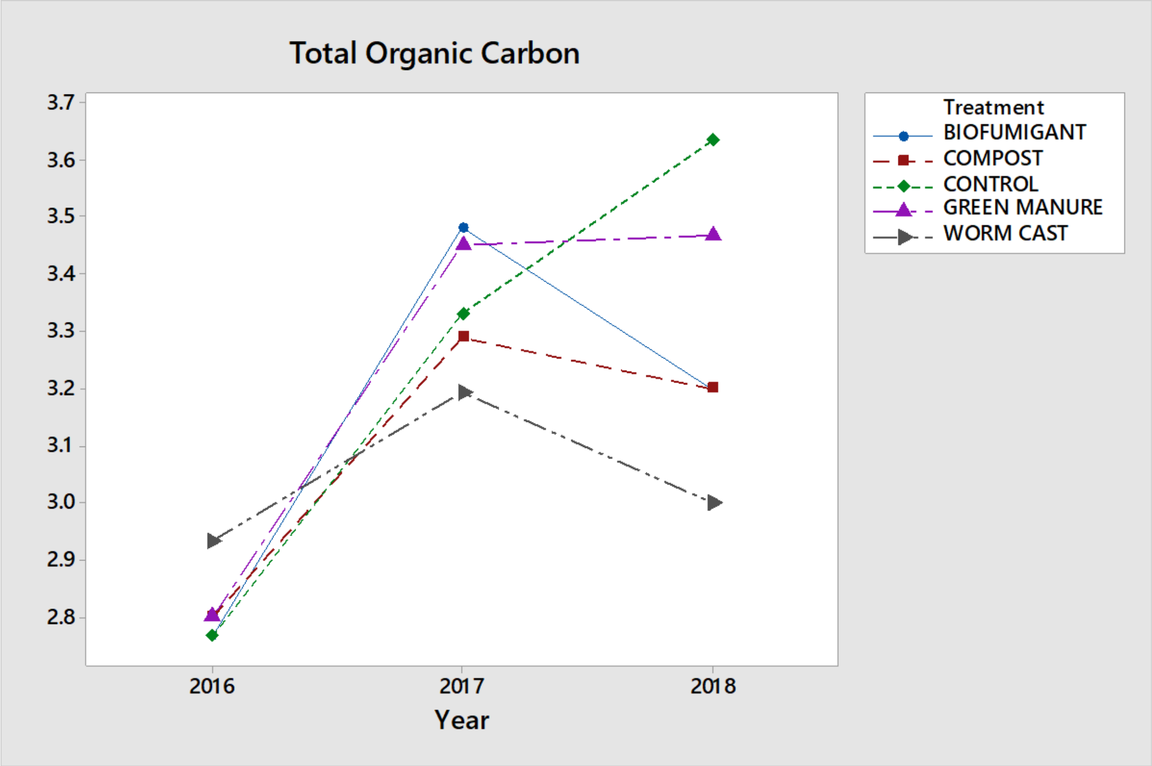
No other variables were significant as covariates, so it is not worth reporting earthworm numbers corrected for those. This includes 2016 earthworm numbers.

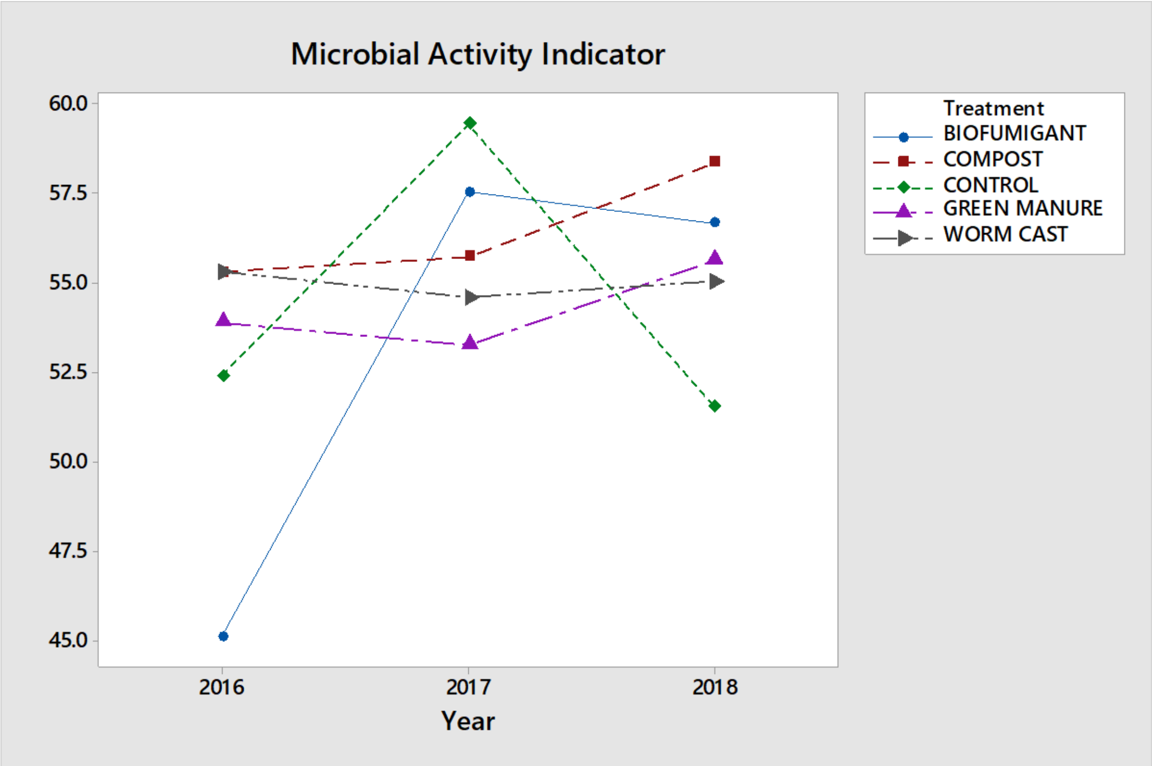
Overall, no treatment stands out as resulting in the highest earthworm numbers.

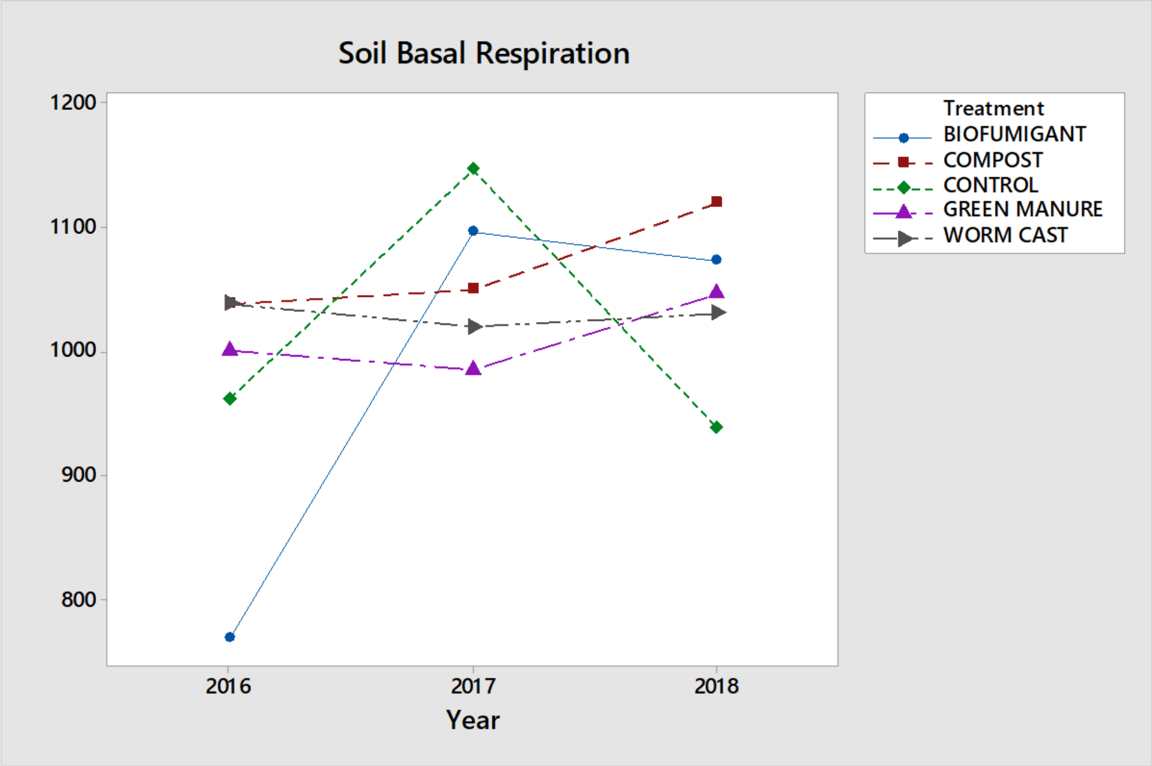
Appendix 1: Graphs of each variable vs year of measurement, Maffra, Victoria

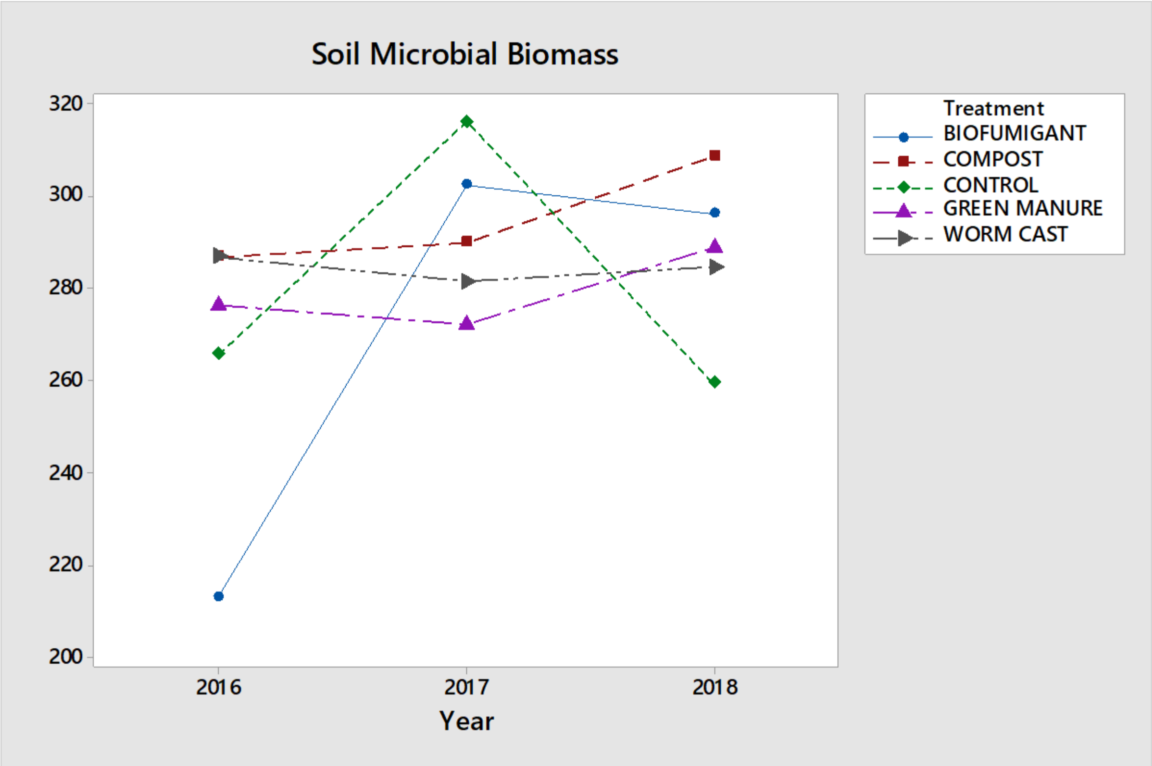




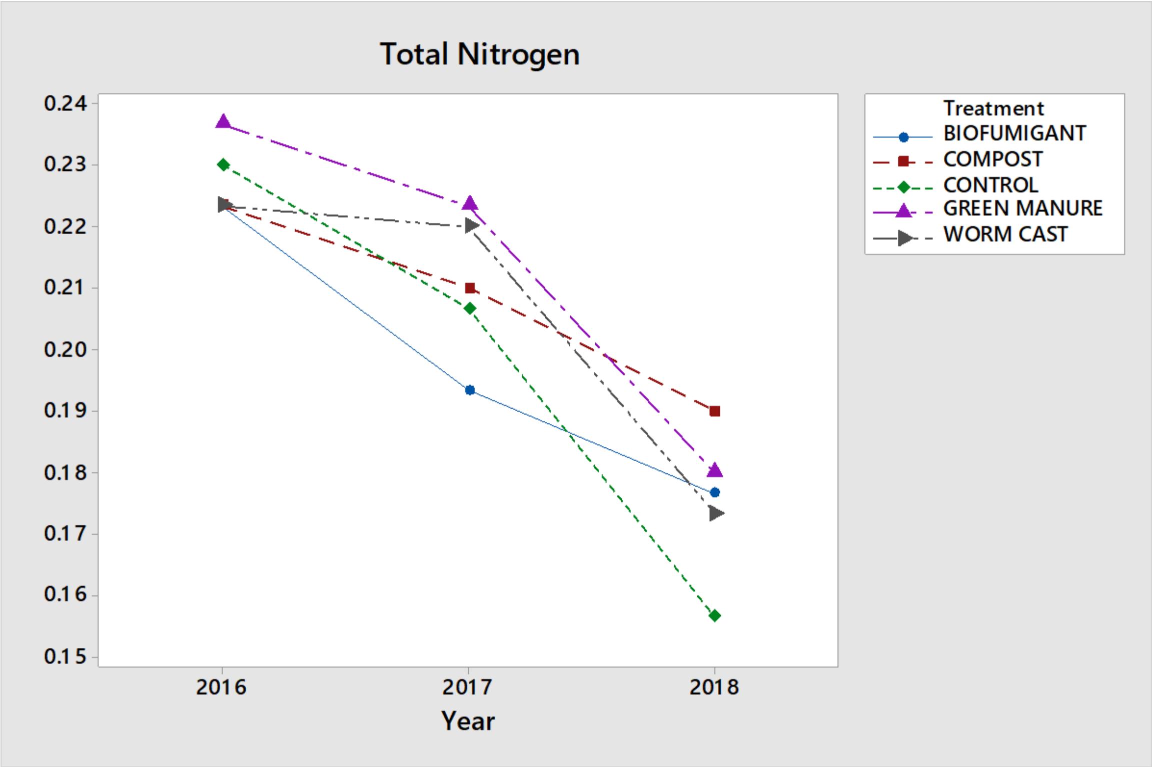

Total Organic Carbon
3.7
3.6
3.5
3.4
3.3
3.2
3.1
3.0
2.9
2.8
2016
2017
2018
Year
Treatment
BIOFUMIGANT
COMPOST
CONTROL
GREEN MANURE
WORM CAST

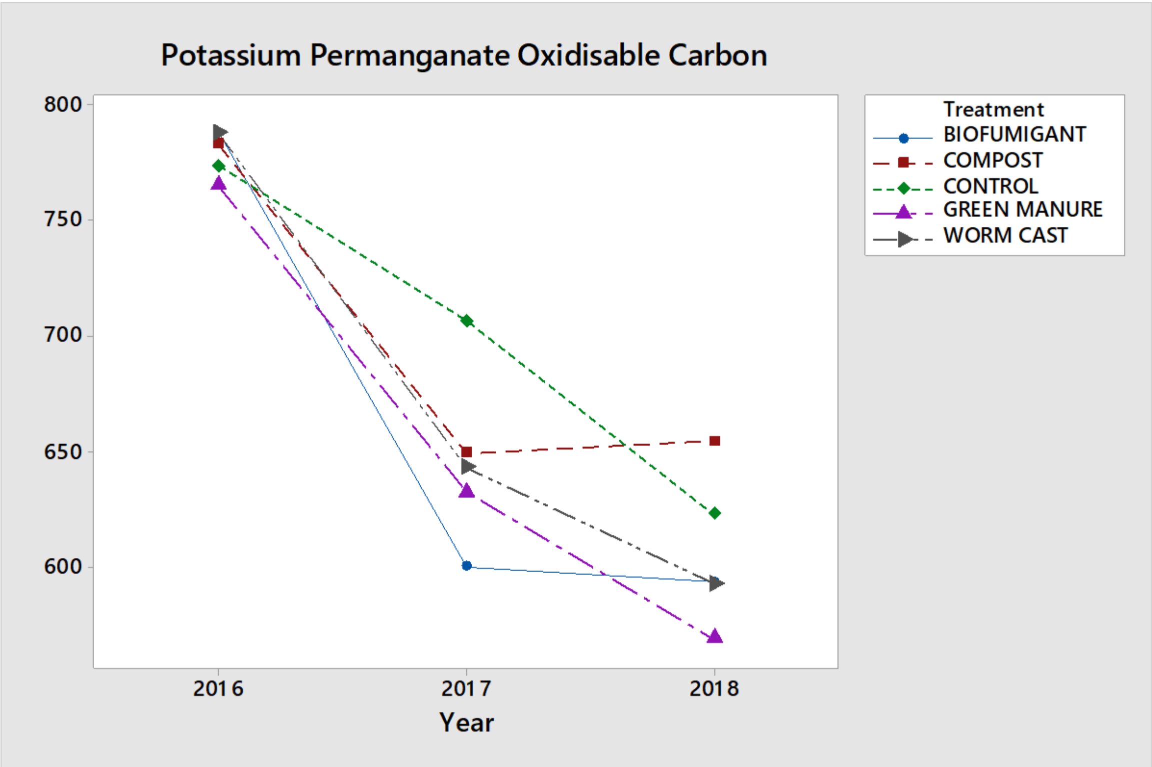

Microbial Activity Indicator
60.0
57.5
55.0
52.5
50.0
47.5
45.0
2016
2017
2018
Year
Treatment
BIOFUMIGANT
COMPOST
CONTROL
GREEN MANURE
WORM CAST

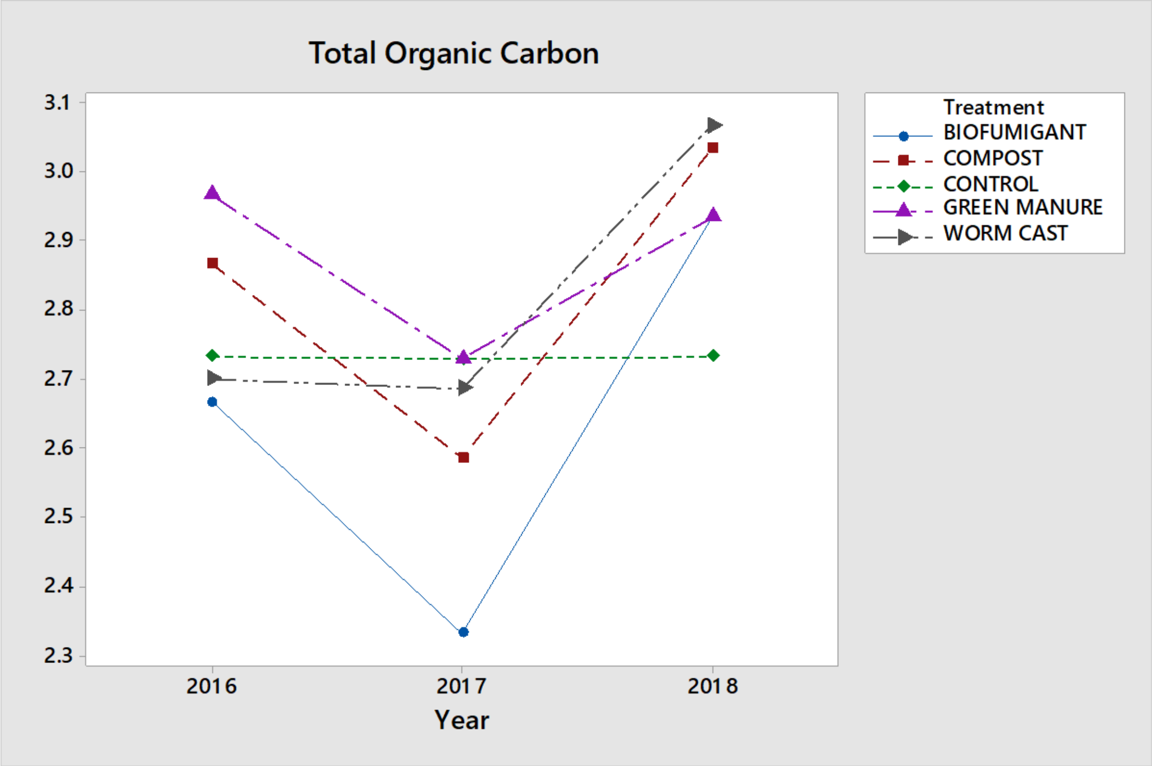

Soil Basal Respiration
1200
1100
1000
900
800
2016
2017
2018
Year
Treatment
BIOFUMIGANT
COMPOST
CONTROL
GREEN MANURE
WORM CAST

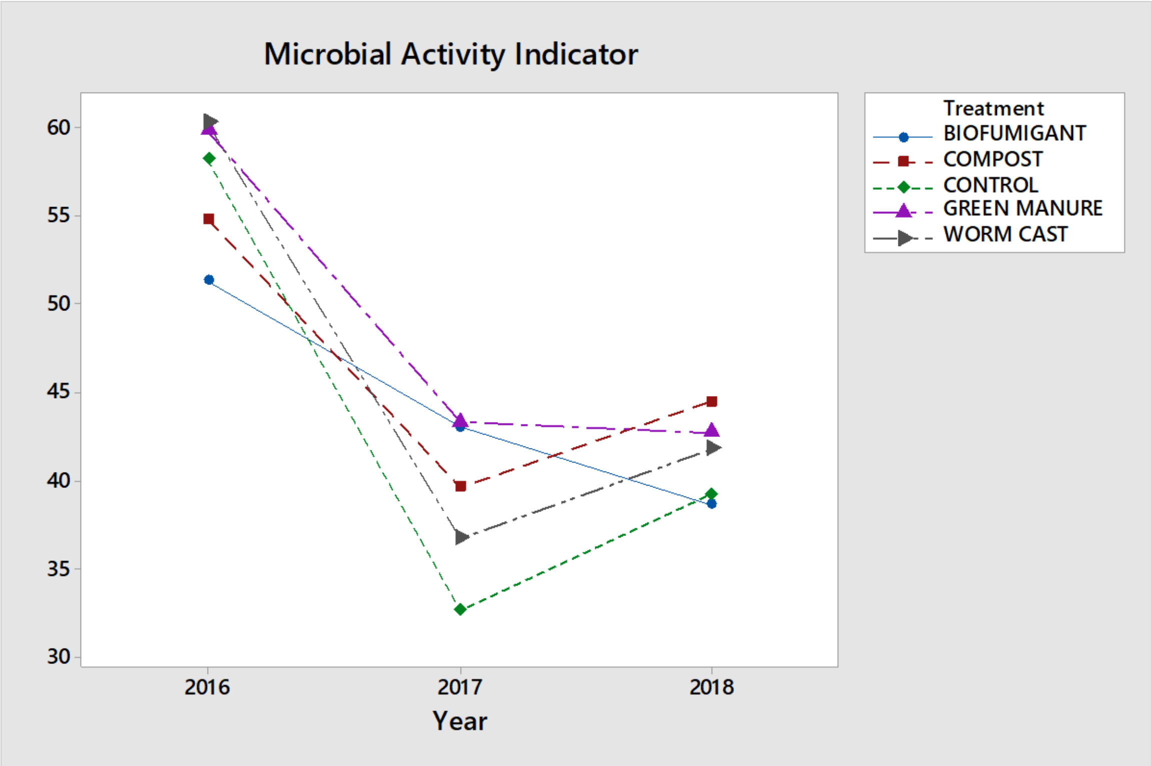

Soil Microbial Biomass
320
300
280
260
240
220
200
2016
2017
2018
Year
Treatment
BIOFUMIGANT
COMPOST
CONTROL
GREEN MANURE
WORM CAST

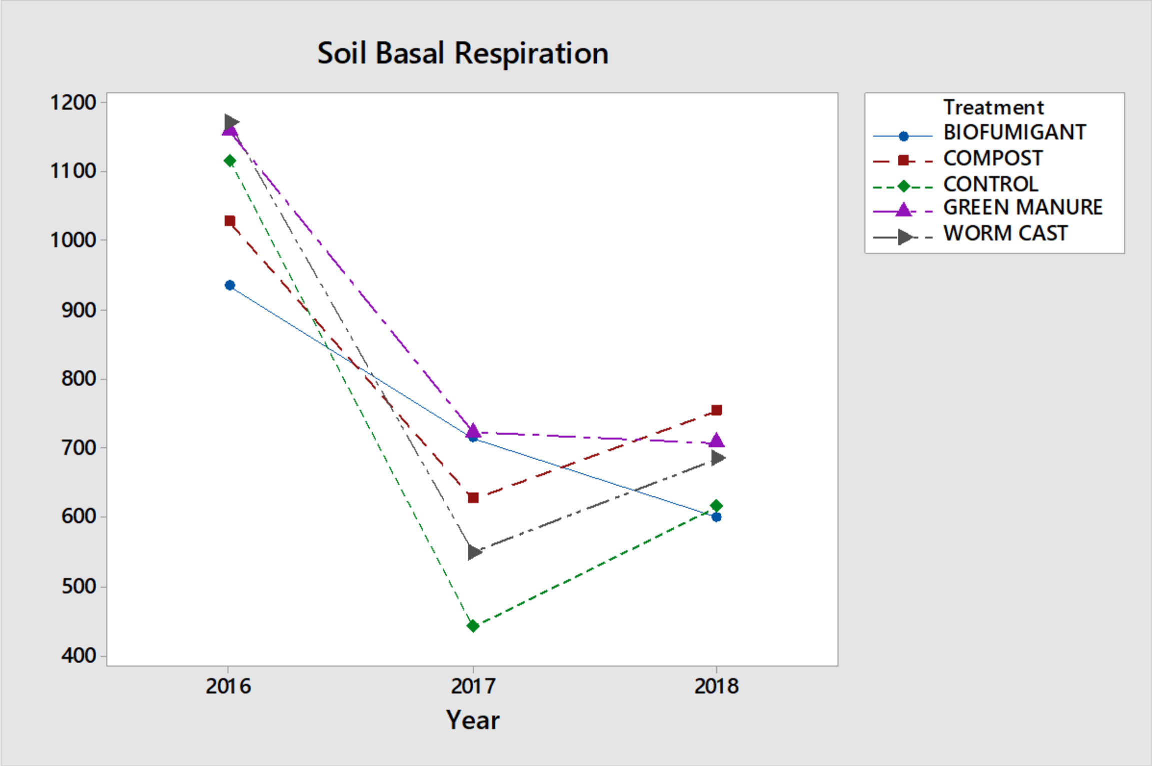
Appendix 2: Graphs of each variable vs year of measurement, Addison, Tasmania

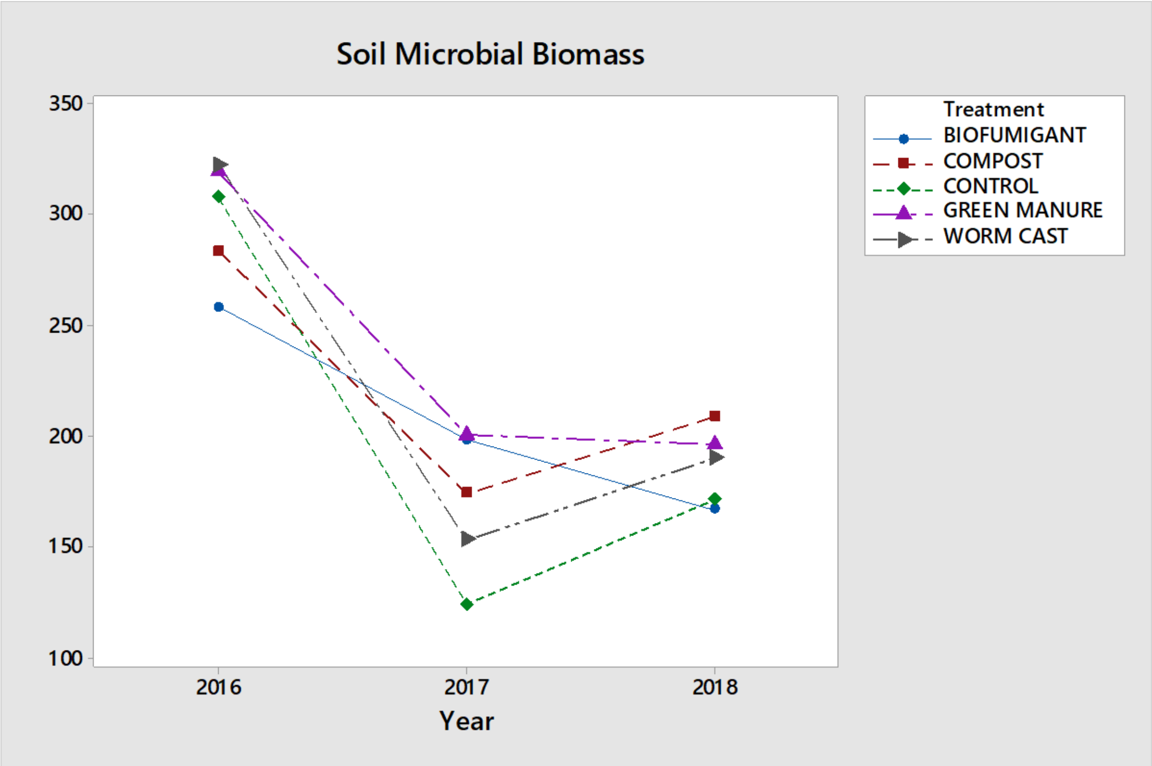





Total Organic Carbon
3.1
3.0
2.9
2.8
2.7
2.6
2.5
2.4
2.3
2016
2017
2018
Year
Treatment
BIOFUMIGANT
COMPOST
CONTROL
GREEN MANURE
WORM CAST


Microbial Activity Indicator
60
55
50
45
40
35
30
2016
2017
2018
Year
Treatment
BIOFUMIGANT
COMPOST
CONTROL
GREEN MANURE
WORM CAST


Soil Basal Respiration
1200
1100
1000
900
800
700
600
500
400
2016
2017
2018
Year
Treatment
BIOFUMIGANT
COMPOST
CONTROL
GREEN MANURE
WORM CAST


Soil Microbial Biomass
350
300
250
200
150
100
2016
2017
2018
Year
Treatment
BIOFUMIGANT
COMPOST
CONTROL
GREEN MANURE
WORM CAST

Working with earthworms – Boosting productivity with vermiculture

FACT SHEET #1: EARTHWORMS AND YOUR FARM

This fact sheet provides guidance about how to get the most benefit from earthworms in commercial growing systems.

In addition to being a good indicator of soil health, earthworms can play a vital role in improving soil structure and fertility. Earthworms can improve soil health and boost productivity by reducing input costs and improving yields. A healthy population of earthworms can 'turn over' and fertilise several tonnes of sub-soil per hectare each week.

Soil structure and health are improved by practices that increase soil organic matter and reduce the negative impacts of tillage and compaction. These practices also help earthworm activity, and the presence of at least two to four earthworms in each standard spade-full of soil tells you that a soil is healthy. The more earthworms found, the healthier the soil is.

Earthworms offer a free workforce that can further improve soil health, structure and fertility, and reduce the need for heavy tillage. This reduces bed preparation costs, produces deeper soils, helps to build soil carbon and fertility, and further improves conditions for earthworms to thrive and work and feed the soil.

Checking levels of earthworm activity

In a healthy soil, at least two to four worms should be found in nearly every sample taken. This is equivalent to 100-200 worms per square metre and is the minimum level to be considered 'healthy'.

To determine levels of earthworm activity dig for earthworms in cropped areas that have not been cultivated for at least two to three months when the soil is moist and the air temperature is less than 25°C.

Make a quick extraction of at least a spade-full of 150mm wide x 150mm long x 300mm deep soil and count the worms by sorting through it. Take samples at multiple sites across your farm, looking for an average of at least two to four earthworms per spade full.

Also look for evidence of earthworm burrows and casts in the soil. Soils with healthy earthworm populations have burrows and a less dense structure in the upper 300-400mm.

Building earthworm numbers

Factors that help to build and maintain healthy and agronomically useful earthworm populations include:

> **Soil organic matter.** Soil organic matter is essential for healthy earthworm activity. Earthworms feed on bacteria, fungi, other micro-flora and fauna, as well as decomposing organic matter. Healthy soils should have at least 2-4% by weight total organic carbon and healthy microbial populations. Cover crops, pasture phases, retention of organic residues and application of manures and composts can all improve conditions for earthworms as well as delivering other soil health benefits.

> **Green manures**. Green manures have been found to be most effective in promoting earthworm numbers and activity. They feed and protect the soil and earthworms during the growing 'cover crop' stage and add fresh organic matter to the soil that feeds earthworms as well as the bacteria and fungi that earthworms feed on. Legumes in the cover crop can boost soil nitrogen which also feeds earthworms, soil biology and plants. Deep rooted cover crop plants can improve soil depth and structure. Cover crops are also an opportunity for disease breaks and weed control that reduces the need for farm chemicals.

> **Less intensive and shallower tillage.** Conventional tillage, and particularly rotary hoeing, can reduce earthworm numbers by 80-90% with a single cultivation, and it could take over a year for earthworms to rebuild their numbers to pre-tillage levels. Tillage can also reduce soil organic matter, reducing earthworms' food supply. Earthworms are mainly active 100-400mm below the surface, so tillage to only 100-200mm can allow many earthworms to survive. Practices that reduce soil compaction such as controlled traffic management can allow less intensive tillage and allow earthworms to take on the sub-surface tillage role.

> **Moisture.** Earthworms need moisture but not waterlogged soils. Under dry conditions earthworms hibernate, but if dry conditions persist for more than three months many earthworms will die. As a rule of thumb, areas that receive less than 450mm of rainfall or irrigation per year will not sustain earthworm populations and ideally areas will receive at least 600mm or more rainfall or irrigation each year.

> **Sensitive chemical applications**. Nearly all fungicides, most insecticides and some herbicides will reduce earthworm activity. This includes some 'Certified Organic' products such as copper sprays and pyrethrin. However, if other conditions for earthworms are favourable and chemicals are used according to label advice, earthworm activity levels will survive and recover for most commonly used chemicals. Any form of soil fumigation – chemical, biological or thermal – will impact heavily on earthworm numbers and chemical fumigations will have greater and longer-lasting effect. Use of herbicides that reduce the need for tillage and build organic matter is generally beneficial to earthworm numbers. Fertilisers, lime and gypsum can reduce earthworm activity in the short term, but generally increase plant and root organic matter that feeds earthworms. Improving soil organic matter and health will make earthworm populations more resilient and able to recover more quickly after chemical use.

> **Integrated crop management**. The need for chemical use can be reduced using: disease and pest breaks in cropping rotations (including cover crops); beneficial biological agents that protect plants and attack diseases and pests; and insect baits and traps. ICM also can involve monitoring and responding to disease and pest risks rather than using scheduled chemical applications.

> **Reduced soil compaction**. Reduced tillage and controlled traffic management will reduce soil compaction.

> **Use of earthworm 'refuge' areas**. Earthworms can migrate through and over soil. Low-traffic and unworked areas next to beds, e.g. along permanent sprinkler lines, can be maintained as earthworm refuges (potentially with application of compost, mulch or straw to build soil carbon and converse soil moisture). The populations maintained in these areas can 're-colonise' worked areas.

What are the benefits?

The management practices that improve soil health and earthworm activity typically have productivity advantages associated with reduced input costs per unit of product.

Consider the various costs and benefits of different management options. The main benefits over time are likely to be:

> Reduced tillage costs
> Improved soil fertility and reduced fertiliser costs
> Increased and sustainable yields
> Reduced farm chemical costs

In many instances there will need to be a transition from existing practices, particularly if historic practices have resulted in poorly structured soils and hardpans down soil profiles.

Consideration should be given to what increases in yields or reduction in other inputs would be needed to justify the costs of changing practice. Depending on previous practices and conditions, average yield increases of 5-30% have been attributed to healthier soils, including higher levels of earthworm activity. However, the greatest productivity gains are likely to be associated with reduced costs of production over time.

Check earthworm numbers and soil health

Most farms will have a surviving population of earthworms that can recolonise areas if the conditions are right. Introduced and some native 'agronomic' worms are present in most agricultural soils, even if in very small numbers. However, earthworms need organic matter and a healthy soil biota (mainly bacteria and fungi, as well as other micro-organisms) to feed on. It is pointless to try to use earthworms without other work to build soil health. In particular, soil organic matter levels need to be increased and the intensity of tillage reduced to allow earthworms to maintain healthy populations. Cover crops, green manures and shallower and less intensive tillage have been found to be the most effective methods to increase earthworm activity.

Worm 'seeding'

Very low earthworm numbers can be artificially increased by bringing in worms from neighbouring worm-rich areas. Sods of soil containing worms and their eggs from worm-rich areas can be added at intervals of 10-20 metres across the paddock where higher worm numbers are needed. This should only be done where soil organic matter is greater the 2% and no heavy tillage is planned and at a time of the year where soil moisture is good and will be maintained for at least three months after seeding,

Worm-rich areas can often be found in uncultivated areas and near water channels.

Feedback

If you have questions or comments about earthworms or have found high earthworm numbers on your farm then we'd like to hear from you. Please contact Bill Grant on 0407 882 070.

This factsheet is part of a three-year research and demonstration project VG15037 *Optimising the benefits of vermiculture in commercial-scale vegetable farms*, funded by Horticulture Innovation Australia using the national research and development vegetable levy and funds from the Commonwealth. For further information about using earthworms to boost productivity and the project please contact Bill Grant on 0407 882070 or email bill.grant@blueenvironment.com.au.

Working with earthworms – Boosting productivity with vermiculture

FACT SHEET #2: ARE EARTHWORMS WORKING FOR YOU?

We all know that earthworms are a sign of healthy and functioning soil. But what is a 'healthy' earthworm population? This worksheet explains how vegetable growers can check whether they have a healthy population of earthworms working for them and the types of earthworm they are likely to find when they are checking.

How to estimate earthworm numbers

The figure below shows how to assess where earthworm numbers are healthy. Digging holes also allows assessment of how earthworms and other farm practices are affecting soil structure.

Mature worms are usually larger and have a distinct 'saddle' or thicker 'bulge' towards the more pointed 'head' or front end of the worm. Smaller earthworms are often immature versions of common species and do not yet have a saddle. The presence of adults in samples suggests established and healthy populations. A large number of immature earthworms but few adults suggests a recovering population.

How many earthworms should there be?

Previous studies suggest a healthy minimum number of earthworms is 100-200 per square metre, or average of at least two to four earthworms per 150mm x 150mm x 300mm deep spade full. This level of earthworms will continually work, aerate and fertilise the upper 300-500mm of topsoil, depending on the depth of the soil. An earthworm population of this size or more will start to have visible impact on the soil structure, with burrows and 'casts' or droppings resulting in improved water infiltration and aeration. This can reduce the need for deeper tillage. The higher the earthworm population, the more work they will do to improve soil structure and health, and this further improves conditions for earthworm activity.

Figure 1 How of check earthworm numbers

1. Use a normal garden spade in areas that have not been cultivated for at least two to three months and have had good soil moisture down the profile during that period. In the warmer months do this in the early to mid-morning before the temperature gets above 25°C.
2. Randomly pick a sample point. Use the spade to measure and cut out a spade sized sod of approximately 15cm x 15 cm wide x 30-40cm deep (i.e. the width and depth of most spade blades). Do this as quickly as possible – earthworms will retreat down the soil profile when they sense digging.
3. Place the sod on the ground or on a tarp and sort through it by hand. Extract and count adult and non-adult earthworms. Adult earthworms are typically larger and have a distinct collar or 'saddle'. If the earthworm population is healthy, there will be an average of at least two to four larger earthworms per spade-sized sod. You might not find this number in every sample, but you should find it in most. Repeat the sampling and worm counts at least 5-10 other sampling points to get a feel for the average number.

What types of earthworm are present?

Although Australia has over 700 identified different species of native earthworms, only a small number of 'agronomic' worms are commonly found under agricultural systems. Most of these are introduced species that can survive, and under the right conditions thrive, under cropping and modified pasture systems. Native worms are less common under cropping systems.

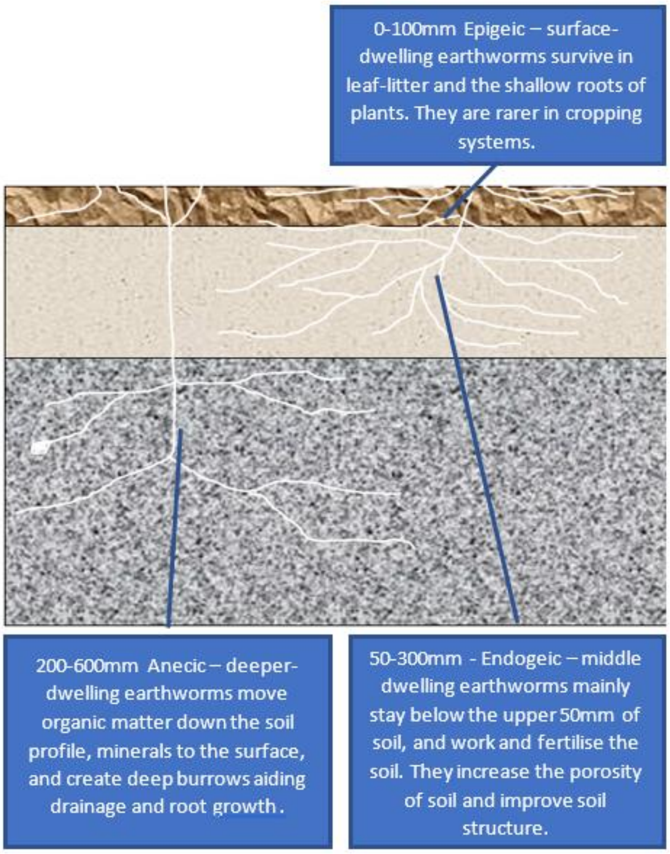
There are three main types of earthworms, shown in the figure below. They are:

> **Surface dwelling or 'Epigeic' earthworms.** These earthworms live in organic matter at the surface of the soil, and only penetrate the upper few centimetres of the soil. They can be found in leaf litter and pasture, or under organic mulches. These earthworms convert organic matter into nutrient-rich casts at the surface, but only work the upper few centimetres of soil. They are not common in cropping systems and vegetable farming where there is not much organic matter at the surface. These earthworms are often smaller and thinner than deeper dwelling species and are often dark red or yellow in colour. Some Epigeic species breed rapidly, including the 'compost' worms used in 'worm farms' to convert organic matter into vermiculture casts and liquid extracts. These earthworms are often bright red and banded/stripy.

> **Sub-surface, middle-dwelling, or 'Endogeic'.** earthworms that live mainly in the upper 50-300 mm of the soil profile, these earthworms are the main potential 'workers' on vegetable farms. They feed on organic matter, bacteria, fungi and other soil microorganisms, including disease-causing pathogens and nematodes. They produce casts in the root zone of plants. Some species will burrow deeper, especially as upper soil dries and when earthworms hibernate/aestivate in the soil. Commonly found varieties include Grey, Purple, Red, Rosy-tipped and Orange-saddled worms.

> **Anecic or deep-dwelling earthworms.** These earthworms live further down the soil profile, but mainly feed on organic matter at the surface. They are often larger than other types of earthworm and move organic matter and nutrients down the soil profile, creating deeper and freer draining soils. Tell-tale signs of these species are piles of casts around holes at the soil surface and deep vertical burrows when sods are dug. These earthworms are more common in pasture but are not common on the majority of vegetable farms due to the lower amounts of decaying organic matter at the surface on most farms. They are often longer and thicker than shallower dwelling species with darker red-brown heads and paler bodies.

Figure 2 ***Types of earthworm***



Earthworms differ from pathogenic 'worms' or nematodes. They will not target living root or other plant tissue, and instead feed on dead and degrading organic matter and the bacteria and fungi living on this matter. Earthworms will not damage roots or plant growth and will usually improve root growth. Earthworms excrete chemicals that stimulate root growth and aerate the soil. On denser soils, roots can often be seen growing along old earthworm burrows.

Most earthworms are not prolific breeders, and even under good conditions some key species can take over a year to re-establish populations after events that reduce worm numbers.

Heavy tillage, prolonged low moisture, and some chemical applications can greatly reduce worm numbers. Building levels of soil organic matter and reducing tillage will increase earthworm activity and are vital to a healthy earthworm population.

This factsheet is part of a three-year research and demonstration project VG15037 *Optimising the benefits of vermiculture in commercial-scale vegetable farms*, funded by Horticulture Innovation Australia using the national research and development vegetable levy and funds from the Commonwealth. For further information about using earthworms to boost productivity and the project please contact Bill Grant on 0407 882070 or email bill.grant@blueenvironment.com.au.

Hort Innovation Strategic levy investment
VEGETABLE FUND
SESL AUSTRALIA
blue environment pty ltd

Working with earthworms

Improving productivity using vermiculture in commercial vegetable growing

Project overview

This information sheet details the ***Optimising the benefits of vermiculture in commercial-scale vegetable farms*** project and tells how you can get more information about the project.

Horticulture Innovation Australia Ltd (Hort Innovation) has engaged Blue Environment and SESL Australia to undertake a three-year project working to investigate and demonstrate how vegetable growers can benefit from changing practices to boost earthworm activity.

The need for this project

In addition to being a sign of a healthy soil, earthworms can boost soil health and function, and improve the commercial and environmental sustainability of vegetable production. Many vegetable growers have adopted practices to promote soil health and productivity, but little specific work has been undertaken in Australia or internationally on how earthworms can boost productivity.

Although earthworms are known to be beneficial to soil and plant health, the magnitude of these benefits are not quantified for vegetable production, and growers interested in using vermiculture need to understand how to get the best results.

Vermiculture benefits

Earthworm activity, and potentially the use of vermiculture products such as vermi-casts and liquid extracts, can provide a range of agronomic benefits in farming such as:

> improving nutrient availability
> improving soil drainage and aeration
> breaking down organic residues and moving organic material down the soil profile
> spreading and stimulating other beneficial soil microbes
> stimulating and promoting root growth.

Earthworms could potentially reduce the need for deep tillage and fertiliser, as well as promote soil and plant health and productivity.

The project

A key component of the project is to promote awareness and understanding in vegetable producers, through demonstrations and 'communities of practice' for promoting earthworm populations on farm and for using vermiculture practices and products.

The project has reviewed existing research and has established field-based research and demonstration at sites across Australia to develop and promote commercially viable models using vermiculture and vermiculture products in conventional commercial vegetable production.

Two main field research sites have been established in Maffra, Victoria and Moriarty, Tasmania, looking at how different soil management practices impact on earthworm activity and soil health. A further eighteen other sites have been surveyed for levels of earthworm activity, and are being used as case studies and for field days.

Our team has also conducted an extensive literature review looking at how earthworm activity and vermiculture products can be expected to improve soil function and productivity, and how different farm management practices can favour or inhibit beneficial earthworm activity.

Project aims

The project seeks to identify:

> Factors that favour or inhibit worm numbers in growing systems. These include soil management, tillage, crop rotation, soil amendments, chemical use and moisture management practices.
> The agronomic benefits and 'services' worms can provide in commercial vegetable growing systems. These include nutrient availability, soil structure, root-growth stimulation, soil-biology stimulation and pathogen control.
> The potential benefit of vermiculture products such as worm castings, liquid extracts and other soil additives.

> Practical and cost-effective ways to optimise the benefits of earthworm activity in different production systems.

Key findings

A 'healthy' and beneficial level of earthworm activity is at least 100-200 earthworms per square metre. That means at least two to four earthworms should be found in every spade full – a sod of approximately 150mm x 150mm and 300mm deep - of soil dug.

> The best place to gauge whether earthworms are working for you is on land that has not been tilled/worked for at least two to three months and has had good soil moisture for all of that time.

> The best times to look for earthworms are early in the morning and when average daily top temperatures are less than 25°C.

> The most common earthworms under vegetable growing systems are species that live in the upper 100-400mm of soil. These earthworms produce mainly semi-permanent horizontal burrows and 'work' the soil.

> Earthworm-effected soils may have some visible burrows, but mainly display signs of small 'ball' or ped formation as well as aeration or 'fluffiness' where the earthworms have worked and manured the soil. Earthworm droppings or casts improve soil structure and contain plant-available nutrients and root-growth stimulants. The burrowing improves soil structure, aeration and drainage.

Our research suggests key factors and practices effecting earthworm activity are:

> **Soil organic matter and levels of bacterial and fungal activity.** Earthworms need organic matter and microorganisms to feed on. Practices such as retention of organic residue, cover crops, pasture phases, reduced tillage and organic additives such as manures and composts can be used to build and maintain soil organic matter.

> **Cover crops and green manures have greatest positive effect on earthworm numbers.** They protect and feed the soil microbes and earthworms.

> **Soil moisture.** Earthworms need the equivalent of at least 450-600mm of rainfall or irrigation per year, and numbers will fall dramatically if the soil dries out for more than three months.

> **The intensity of tillage.** Conventional deep and rotary hoe tillage can reduce earthworm numbers by 80-90% and they can take over a year to re-build numbers afterwards. Reduced, shallower and 'lighter' tillage practices allow earthworms to maintain healthy and beneficial populations.

> **Soil type and profile.** Earthworms will struggle to survive on shallow soils, low-carbon soils, coarse sands and soils with pH outside the 5.5-8.5 range.

> **Chemical use.** Most fungicides and insecticides, including some 'organic' treatments can reduce earthworm activity. Some herbicides can have short term negative effects, but can have benefit where they are used to reduce tillage and build soil organic matter. Most fertilisers, as well as lime and gypsum have a positive effect on soil biology including earthworms, but might have short term negative effects.

> **Soil fumigation practices** (chemical, steam, bio-fumigants). Chemical and steam soil fumigation will greatly reduce earthworm activity. The project is investigating the impact of bio-fumigation practices and these seem to reduce earthworm numbers.

> **Available 'refuge' areas.** Earthworms can migrate several metres per day and will move to where conditions are favourable. Untilled areas and areas kept fed and moist with organic mulch or compost can provide earthworm 'refuges' where earthworms survive and then re-colonise worked areas.

Vermiculture products

In addition to working to build and maintain useful earthworm populations, growers can apply 'vermi-composts' or 'liquid extracts' produced by composting worms. Commercial suppliers of these promote the products as fertiliser and soil and plant health stimulants. It is recommended growers trying these products ask suppliers for product specifications based on laboratory testing that demonstrate the products contain nutrients or plant growth stimulants.

Contact

For information or to discuss how you boost productivity by working with earthworms, please contact Bill Grant on 0407 882 070 or email bill.grant@blueenvironment.com.au.

This factsheet is part of a three-year research and demonstration project VG15037 Optimising the benefits of vermiculture in commercial-scale vegetable farms, funded by Horticulture Innovation Australia using the national research and development vegetable levy and funds from the Commonwealth. For further information about using earthworms to boost productivity and the project please contact Bill Grant on 0407 882070 or email bill.grant@blueenvironment.com.au

WORKING WITH EARTHWORMS INDUSTRY SURVEY

Horticulture Innovations has engaged Blue Environment and SESL to investigate and promote ways in which vegetable growers can benefit from improving soil health and earthworm activity in their cropping systems.

The purpose of this survey is to find out commercial vegetable growers' levels of knowledge about and interest in using earthworms to improve soil health. Most people know that earthworms are a sign of a healthy soil, and the Working with Earthworms project is about finding practical ways that vegetable growers can build and maintain beneficial earthworm numbers in their soils. Please complete the survey regardless of how much you think you know about earthworms. We want to hear from as many vegetable growers as possible.

Please complete the following questions about your location and growing system. Note that it is optional whether you provide personal contact information. If you do, this information will be treated as confidential and we will only contact you if you indicate that you want more information about earthworms and the project.

If you would like to discuss the survey, please call Bill Grant on 0407 882 070 between the hours of 8am-8pm or email him on bill.grant@blueenvironment.com.au.

PART ONE: FARM LOCATION AND CONTACT DETAILS

Please enter postcode or area name for property. If more than one property is farmed, please provide details.

If you would like to receive more information about soil health and earthworms, please provide the following details. This information will only be used to provide information to you and will not be made available to any other person or organisation for marketing or other purposes:

Name:

Email:

Phone (optional):

Mobile phone (optional):

PART TWO: EARTHWORMS ON YOUR FARM

How important do you think it is to have a healthy earthworm population in your soil?

- ☐ Not important
- ☐ Somewhat important
- ☐ Very important

If you were to dig sods of soil from vegetable growing beds when the ground is has good soil moisture, what would you consider to a 'good'/'useful' number of earthworms?

- ☐ One earthworm every 2-4 sods turned
- ☐ One earthworm in nearly every sod turned
- ☐ Two earthworms in nearly every sod turned
- ☐ 3-5 earthworms in nearly every sod turned
- ☐ 5-10 earthworms in nearly every sod turned
- ☐ More than 10 in nearly every sod turned

What do you think a high earthworm population indicates (tick more than one if needed)

- ☐ It is the time of the season where there are more earthworms about
- ☐ Soil moisture is good
- ☐ There are high levels of soil organic matter
- ☐ There is healthy soil biology
- ☐ The area has not been worked/tilled for a long time
- ☐ Other (please list)

What do you think a low earthworm population indicates (tick more than one if needed)

- ☐ It is just the wrong time of the year to see earthworms
- ☐ Less healthy soil
- ☐ Soil compaction
- ☐ Dry soil
- ☐ Low organic matter
- ☐ Earthworms just can't cope with modern vegetable farming
- ☐ Other (please list)

Do you think earthworms could improve productivity on your farm?

- ☐ Yes
- ☐ No
- ☐ Unsure

How would you describe current levels of earthworm activity on your farm?

- ☐ I haven't actively looked for earthworms, so I am not sure
- ☐ Never see earthworms
- ☐ Rarely see earthworms
- ☐ Sometimes notice earthworms
- ☐ Commonly notice earthworms when soil is moist
- ☐ Usually see earthworms when soil is disturbed
- ☐ Sometimes notice earthworms come to the surface after heavy rains or chemical application
- ☐ Would usually find 1-2 earthworms per spade-full of sod dug when soil is moist
- ☐ Would usually find more than 2 earth worms per spade-full of sod dug when soil is moist
- ☐ Would usually find more than 5 earth worms per spade-full of sod dug when soil is moist

Please tick the main benefits you would expect from increased earthworm activity on your farm (please tick up to five)

- ☐ I would not expect to see significant benefits
- ☐ I am unsure whether I would see any significant benefits
- ☐ Plant pathogen suppression
- ☐ Increased crop yield
- ☐ Increased soil fertility
- ☐ Increased soil biology
- ☐ Deeper more friable soil
- ☐ Improved soil drainage
- ☐ Improved soil aeration
- ☐ Reduced need to cultivate
- ☐ Disease suppression
- ☐ Improved plant root growth
- ☐ Neutralised soil pH
- ☐ Increased soil carbon
- ☐ Improved soil fertility
- ☐ Improved infiltration of rain and irrigation water
- ☐ Other (please provide details)

Please tick the main factors you think might prevent earthworms providing benefits on your farm (please tick up to five)

- ☐ Soil type
- ☐ Types of crops grown
- ☐ Availability of organic matter in the soil
- ☐ Annual rainfall
- ☐ pH
- ☐ Soil moisture
- ☐ Soil temperature
- ☐ Soil compaction
- ☐ Season/time of the year
- ☐ Frequency and intensity of tillage
- ☐ Use of cover crops in rotations
- ☐ Use of fallow in rotations
- ☐ Application of lime
- ☐ Application of gypsum
- ☐ Application of herbicides
- ☐ Application of fungicides
- ☐ Application of insecticides
- ☐ Other (please detail)

PART 3: ABOUT YOUR FARM AND SOIL

Which of the following best describes your growing system?

- ☐ Vegetable crops grown in a cropping rotation involving pasture and non-vegetable crops
- ☐ Vegetable crops grown close to continually, with short periods of fallow between crops
- ☐ Vegetable crops grown close to continually, with short periods of fallow and cover crops between crops
- ☐ Vegetable crops grown close to continually, with periods of cover crop between vegetable crops
- ☐ Other (please describe)

How would you describe your farming system?

- ☐ Conventional chemical use with scheduled chemical applications
- ☐ Lower-input farming, but still using chemicals to control weeds, disease and insects when needed
- ☐ Rarely using chemicals to control weeds, disease and insects when needed
- ☐ Soil management focused on building soil health through reduced tillage, reduced compaction, cover crops and the building of soil organic matter
- ☐ Certified or becoming certified organic,
- ☐ Certified of becoming certified biodynamic

How would you describe your soil?

- ☐ Deep (>600mm in depth before heavy clay, gravel, rock or other sub-soil type) sand or sandy loam
- ☐ Deep loam
- ☐ Deep clay-loam
- ☐ Deep clay
- ☐ Shallow (<600mm in depth before clay or other sub-soil type) sand or sandy loam
- ☐ Shallow loam
- ☐ Shallow clay-loam
- ☐ Shallow heavy clay

Does your soil have a hard-pan or heavy clay layer at 400mm or less?

- Yes
- No

How would you describe your soil pH?

- Strongly acidic
- Acidic
- Acidic-neutral
- Neutral
- Alkaline-neutral
- Alkaline
- Strongly alkaline
- Variable

Which of the following describes your tillage practices? (choose more than one where applicable)

- Heavy tillage prior to most crops using multiple workings and using ripping, disk or blade ploughing, or rotary hoes to depths of 300mm or more
- Deep ripping to greater than 300mm to break up hard pans before most crops
- Periodic deep ripping to break hard plans
- Lighter surface tillage, using tines and/or power hoes to a depth of less than 100mm, but no disk/blade ploughs or rotary hoeing
- Minimum or 'zero' tillage using direct drill or

What are the main vegetable crops raised? (pick more than one where appropriate)

- Artichokes
- Asparagus
- Beans
- Beetroot
- Broccoli /Baby Broccoli
- Brussels Sprouts
- Cabbage
- Capsicums
- Carrots
- Cauliflower
- Celery
- Chillies
- Cucumbers
- Eggplant
- English Spinach/Silverbeet/Kale
- Fresh Herbs
- Fennel
- Parsley
- Other Herbs
- Garlic
- Ginger
- Leafy Asian Vegetables
- Leafy Salad Vegetables
- Leeks
- Head Lettuce
- Onions
- Parsnips
- Peas
- Potatoes
- Pumpkins
- Sweet Corn
- Sweetpotatoes
- Tomatoes
- Zucchini
- Other Vegetables (please list)

Which of the following management practices do you use on your farm? (choose more than one where applicable)

- ☐ Cover crops
- ☐ Rotary hoeing
- ☐ Deep ripping
- ☐ Biofumigant crops
- ☐ Reduced tillage
- ☐ Disc or blade tillage
- ☐ Tine tillage
- ☐ Fallow
- ☐ Pasture breaks
- ☐ Rolling or crimping crop or cover crop residues
- ☐ Controlled traffic or permanent beds
- ☐ Chemical fumigation
- ☐ Steam fumigation
- ☐ Pre-emergent herbicides
- ☐ Synthetic fungicide use
- ☐ Synthetic insecticide use
- ☐ Compost application
- ☐ Biochar application
- ☐ Rotations containing legumes
- ☐ Manure application
- ☐ Use of vermi-compost or vermi-cast solid or liquid products
- ☐ Other (please provide details)

PART 3: INCREASING EARTHWORM ACTIVITY

Please rate how commercially viable the following practices would be to use on your farm to improve soil health and earthworm activity? (rank using score 0 = not commercially viable/practical; 1 = unlikely to be commercially viable/practical; 2 = possibly commercial viable/practical; 3= likely to be commercially viable/practical,4 = highly likely to be commercially viable/practical, 5 = already use this practice because it is commercially viable/practical.

Practice	Score					
	0	1	2	3	4	5
Cover crops						
Reduced intensity of tillage						
Compost application						
Permanent beds						
Controlled traffic to reduce soil compaction						
Pasture phases in the rotation						
Use of plastic mulch						
Use of straw or composted mulch						
Reduced use of fungicides						
Reduced use of insecticides						
Reduced use of herbicides						
Mulching or crimp rolling residues, cover crops or green manures						
Irrigation of cover crop, green manure or pasture phases in a rotation						
Application of vermi-cast products						
Other practices that you think would increase earthworm activity (please detail)						

If you were looking for information about earthworms, where would you expect to find it:

- ☐ Internet searches
- ☐ Friends and family
- ☐ Your agronomist
- ☐ Department of agriculture /primary industry personnel
- ☐ Department of agriculture/primary industry publications or on-line resources
- ☐ Specific webpages, facebook or other social media sites (please list any you use)

Thank you for your participation in this survey. If you have not already provided contact details but would like more information about earthworms and the working with earthworms project, please provide details below. This information will only be used to provide information to you and will not be made available to any other person or organisation for marketing or other purposes:

Name:

Email:

Phone (optional)

Mobile phone (optional)

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Hort Innovation Strategic levy investment | VEGETABLE FUND | blue environment pty ltd

Working with earthworms

Bill Grant, Blue Environment

Declan McDonald, SESL Australia

SESL AUSTRALIA Environment & Soil Sciences

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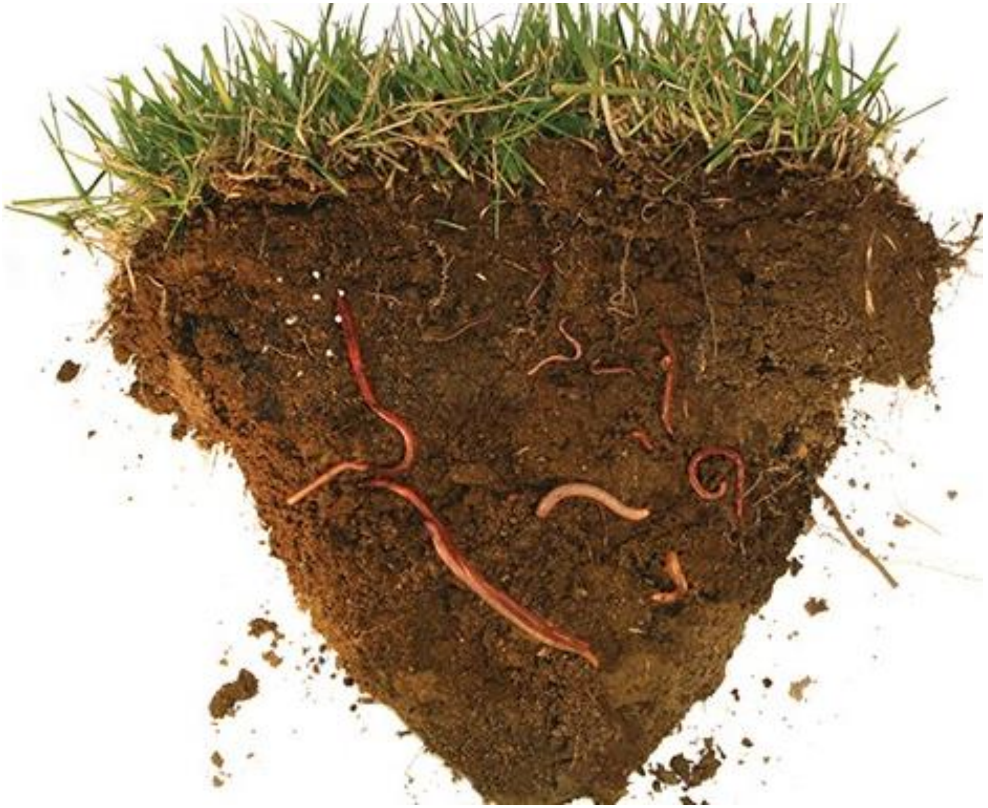
Horticulture Innovation Australia



Three-year project looking at how earthworms can boost soil health and productivity in commercial vegetable growing.

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Introduction

1. About earthworms
2. Building and maintaining agronomically beneficial earthworm populations
3. Research results.

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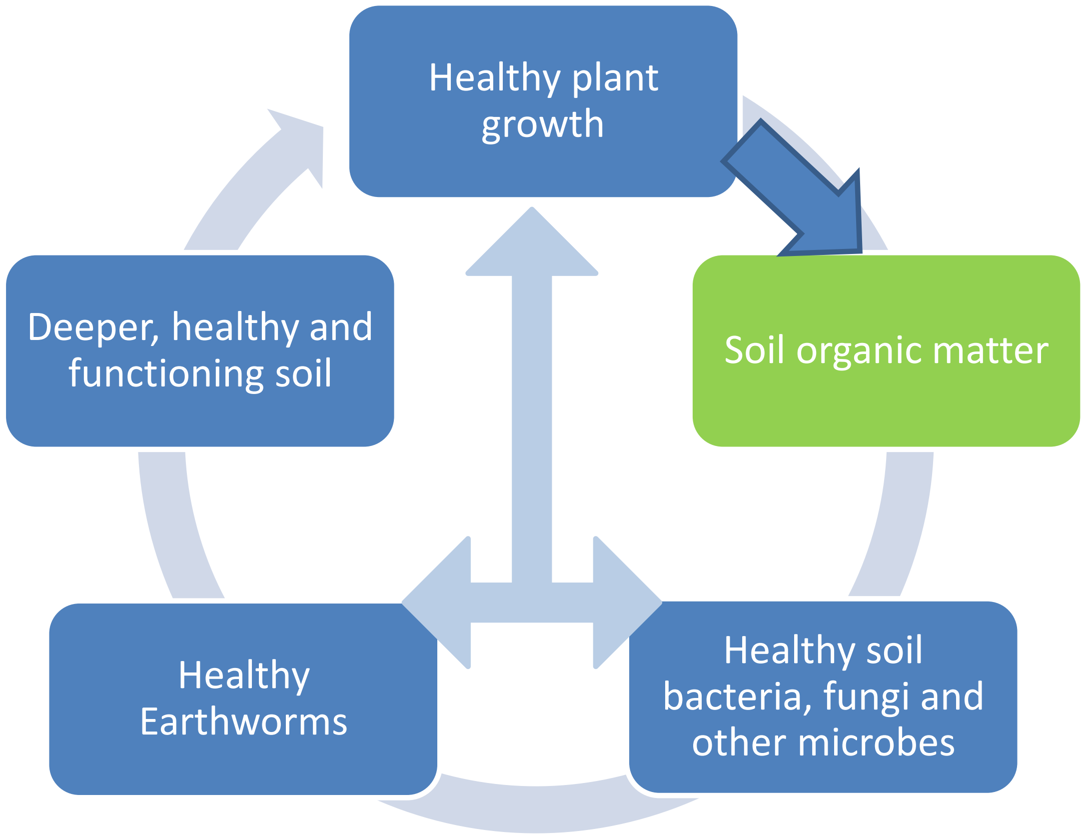
"Workers of the earth"

"Nothing can be compared with earthworms in their positive influence on the whole living Nature. They create soil and everything that lives in it."

- Charles Darwin



Spoilers/Key points

- Earthworms can help to restore soils and reduce the need for tillage and fertiliser
- In order the thrive earthworms need:
  - increased soil organic matter and active bacterial and fungal populations, labile/‘fresh’ organic material from green manure crops has the most benefit
  - reduced tillage
  - moisture management
  - considered/sensitive chemical use/integrated crop management
- Intense and deep tillage/cultivation and fallow are the great enemies of earthworms.

Working earthworms

- Worm activity aerates the soil, improving drainage and root growth
- Worms 'cultivate' the soil to produce more food for earthworms
- They can eat and excrete their body weight every day when they are active
- A 'healthy' population of 200 earthworms per sq m = 200g/m^2/day = 2 tonnes/ha/day tillage and spreading of nutrient rich casts
- Higher populations can undertake more work
- When earthworms are working, you will see burrows and peds/casts indicating an aerated and fertilised soil.

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What earthworms want

- Organic matter
- Active soil biology
- Available nitrogen/nitrates
- Moisture (a minimum equivalent to >450mm per year, and preferably >600mm). Dry periods of more than 3 months will see rapid and even catastrophic losses on worm numbers
- Less dense soil to depth of at least 300-400mm
- Neutral soils (in 5.5-8.5 range)
- To be left alone (less disruptive tillage and chemicals).

Types of earthworms

- There are over 700 species of earthworms in Australia playing a diversity of roles in soil ecosystems
- There are three main types:

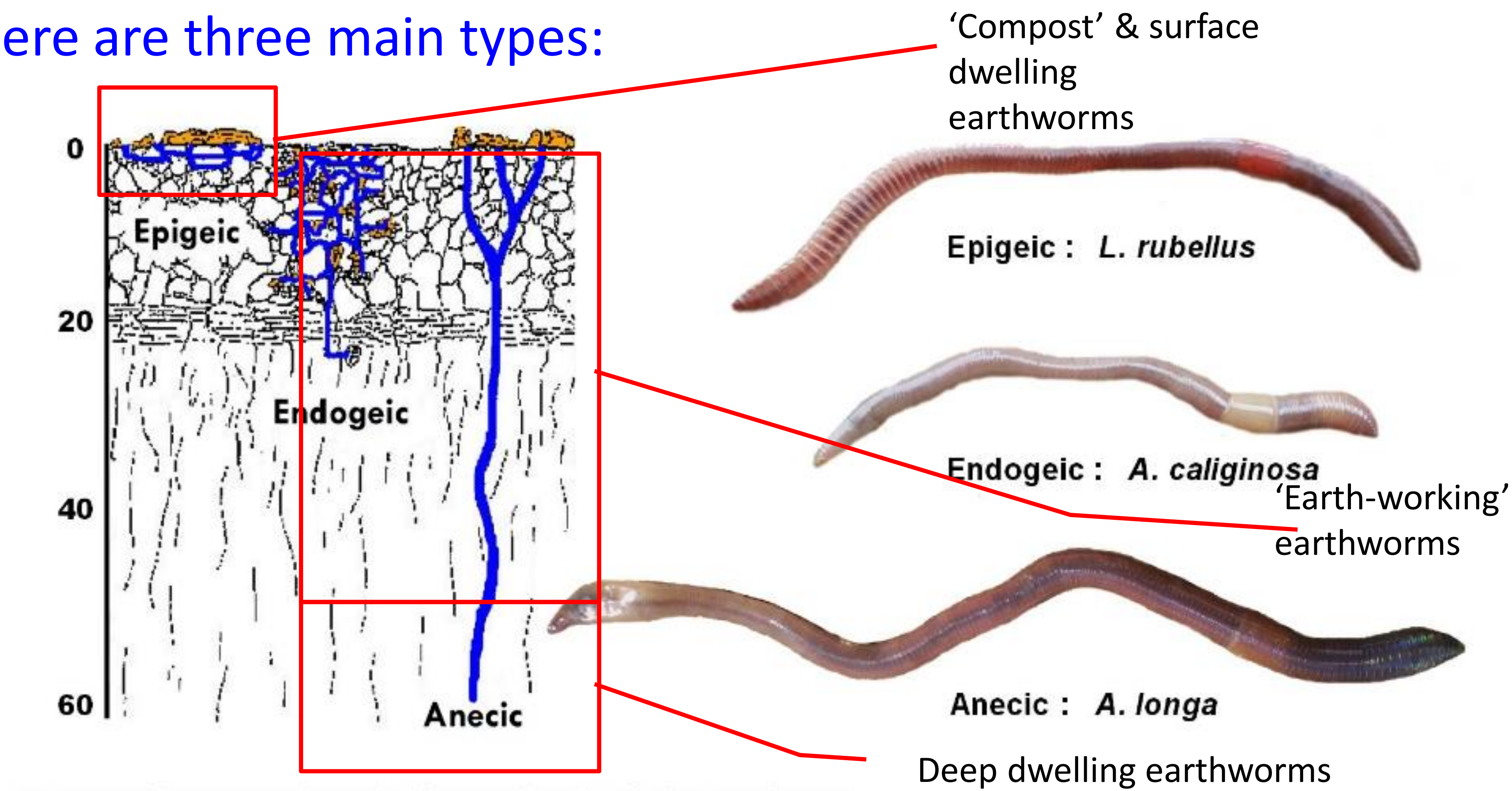

Diagram courtesy of the Science Learning Hub. Figure adapted from Fraser and Boag, photos of earthworms copyright Ross Gray.

Types of earthworms

- >700 species in Australia - native and introduced
- Mature
  - generally larger
  - usually a distinct saddle/collar
  - reproductive pores often more visible
- Juvenile/immature
  - no saddle/collar
  - reproductive pores undeveloped
- Hatchlings/eggs.

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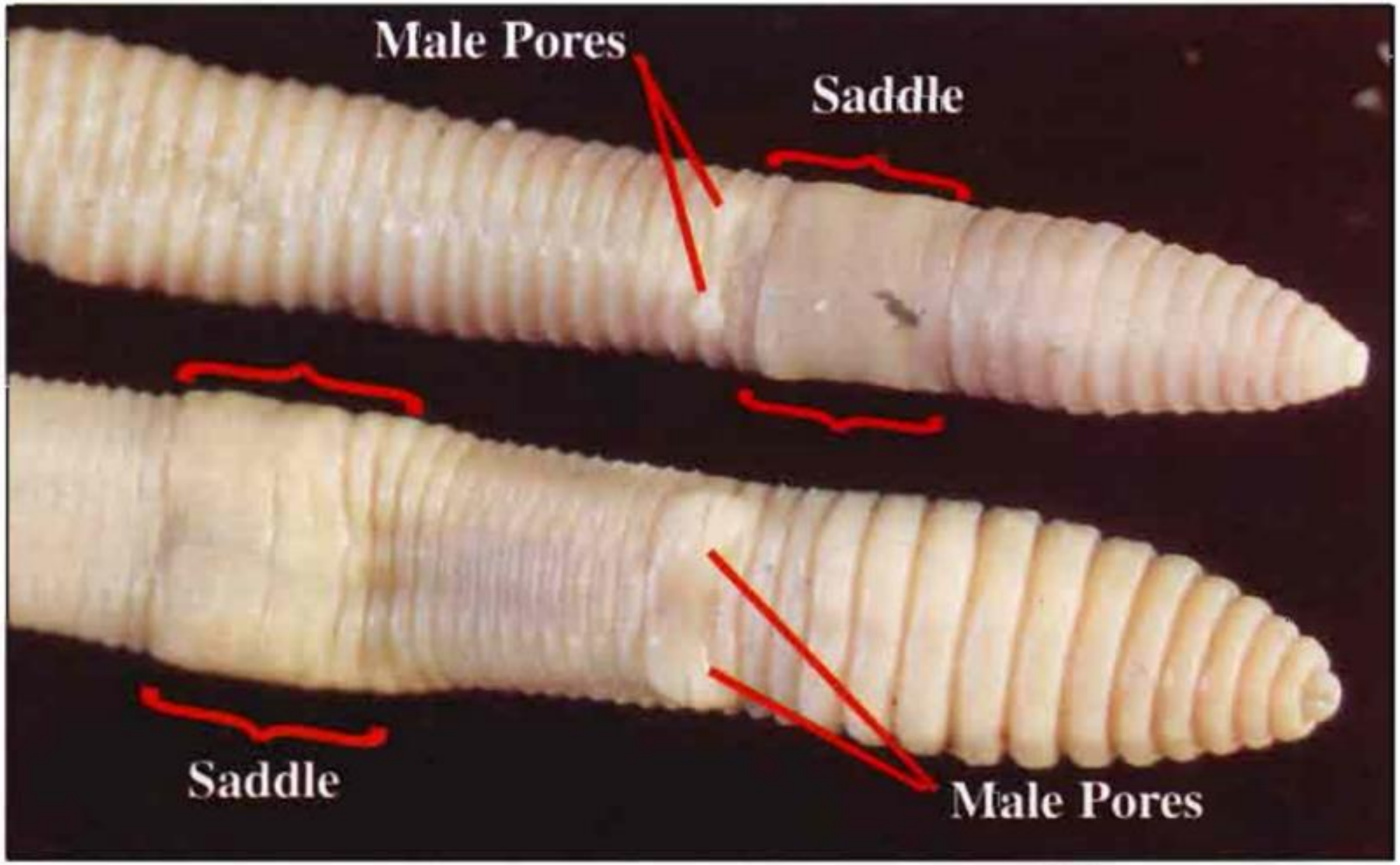
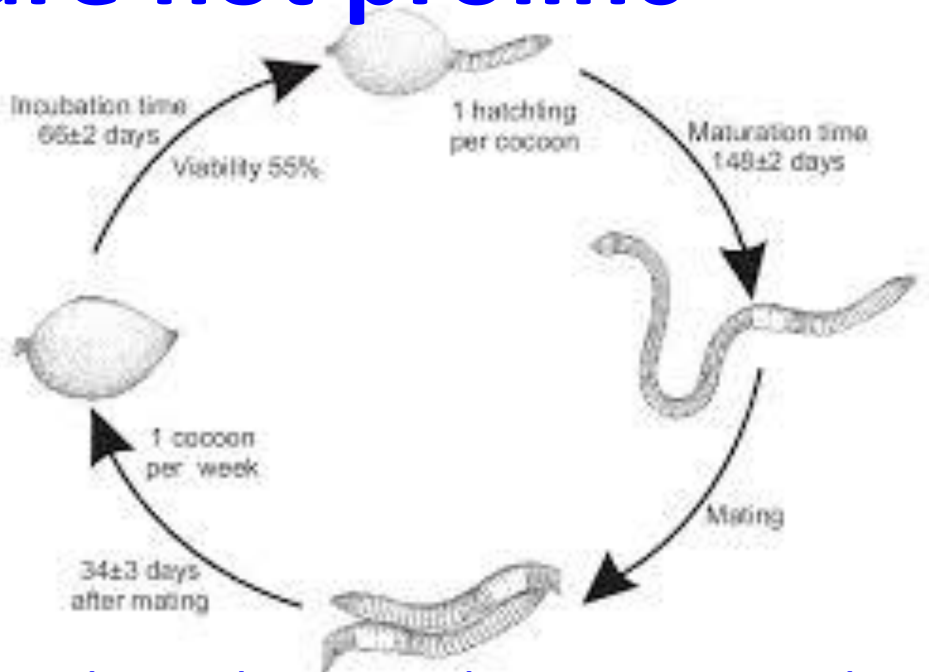
Types of earthworms



Underside of Native (above) and Introduced (below) Earthworms (x4).

Worker earthworms are not prolific



- Earth working earthworms can take 90-100+ days to initially double their numbers under good conditions
- Conventional tillage and fumigation use can reduce numbers by >80-90%, and it takes over a year to get back to original numbers.

Aestivation/hibernation

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Aestivation/hibernation

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About earthworms

- Earthworms feed on decaying organic matter, bacteria, fungi and other micro-organisms (including disease /pest organisms) and are a good indicator that soil biology is healthy
- They are not the same as ‘nematodes’, earthworms do not attack living roots or plants
- Excretion or ‘casts’ contain concentrated and plant- available nutrients, as well as containing plant growth hormones/stimulants
- Earthworms also produce calcium carbonate, which improves soil structure
- ‘Compost’ worms will not colonise cropping land
- If their population is damaged they could take a year to recover their numbers.

Research outcomes

c

Research

- Survey of levels of earthworm activity and types of earthworms in different states and under different practices
- 2 main research sites to investigate if earthworms can enhance soil health and productivity – Maffra, Victoria and Moriarty, Tasmania
- 16 other demonstration/observation sites studied
  - X4 in NSW and Qld
  - X3 in SA and WA
  - X2 in Victoria and Tasmania
- Sites selected on the basis of organic inputs and other soil health measures being part of current operations plus commitment
- Practices include use of compost, green manures, biofumigants, worm casts, and strip tillage; site history captures chemical use, tillage, crop rotation and other relevant soil management practices

Sites

Victoria	Middle Tarwin **Maffra** Werribee South	**Tasmania**	**Moriarty** Hagley Forthside
NSW	Theresa Park Agnes Banks Hobartville Wildes Meadow	**Western Australia**	Brookhampton Manjimup Donnybrook
Queensland	Thornton Lockyer Valley Lowood Mulgowie	**South Australia**	Hay Valley Mount Barker Hillier

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Data collected:

- Worm counts – mature/immature, type
- Cropping history
- Field observations – soil moisture, temperature
- Soil chemistry - TOC, oxidisable C, Total N, macro and micro nutrients, pH
- Soil texture
- Microbial biomass carbon.

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Variables

- Soil temperature
- Soil moisture
- Soil texture
- Climate (not rainfall)
- Tillage practices
- Crop rotation
- Spray regime

- Soil properties such as temperature, moisture and texture were recorded
- All site were irrigated, but some were drying at times of sampling
- Tillage and harvest times (soil disturbances) varied
- Crop rotation and associated spray/chemical regime varied.

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Issues

- Multiple variables across and between sites and years
- Soil moisture variability a significant factor in earthworm activity levels at the time of sampling
- Odd/'Inexplicable' results.

Main research sites: Treatments and randomised block design

		Victoria		
Compost	Biofumigant crop	Green manure	Worm casts	Control
Worm casts	Control	Compost	Biofumigant crop	Green manure
Biofumigant crop	Green manure	Worm casts	Control	Compost

		Tasmania		
Green manure	Worm casts	Control	Compost	Biofumigant crop
Control	Compost	Biofumigant crop	Green manure	Worm casts
Biofumigant crop	Green manure	Worm casts	Control	Compost

Trial treatments

- Plots were randomly assigned across the trial areas
- Treatments:
  - Compost applied at 6t/ha
  - Worm casts applied at 500kg/ha
  - Biofumigant crop – Caliente crimp rolled
  - Green manure crop (rye, rye and clover, pea regrowth)
  - Control – continuous cropping or standard rotation
- Treatments re-applied each year.

Maffra, Victoria

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Maffra, Victoria

- Converted dairy pasture – ~10 years ago
- Leafy green /salad mix production
- Well-managed soil and integrated cropping
  - Cover crops and green manuring
  - Disease-breaking rotations
  - Controlled traffic
  - Reduced and shallower tillage
  - Beneficial biologicals used
  - Sensitive chemical use
- Usually high rainfall
- Clay-loam, with slight hardpan at 350-400mm

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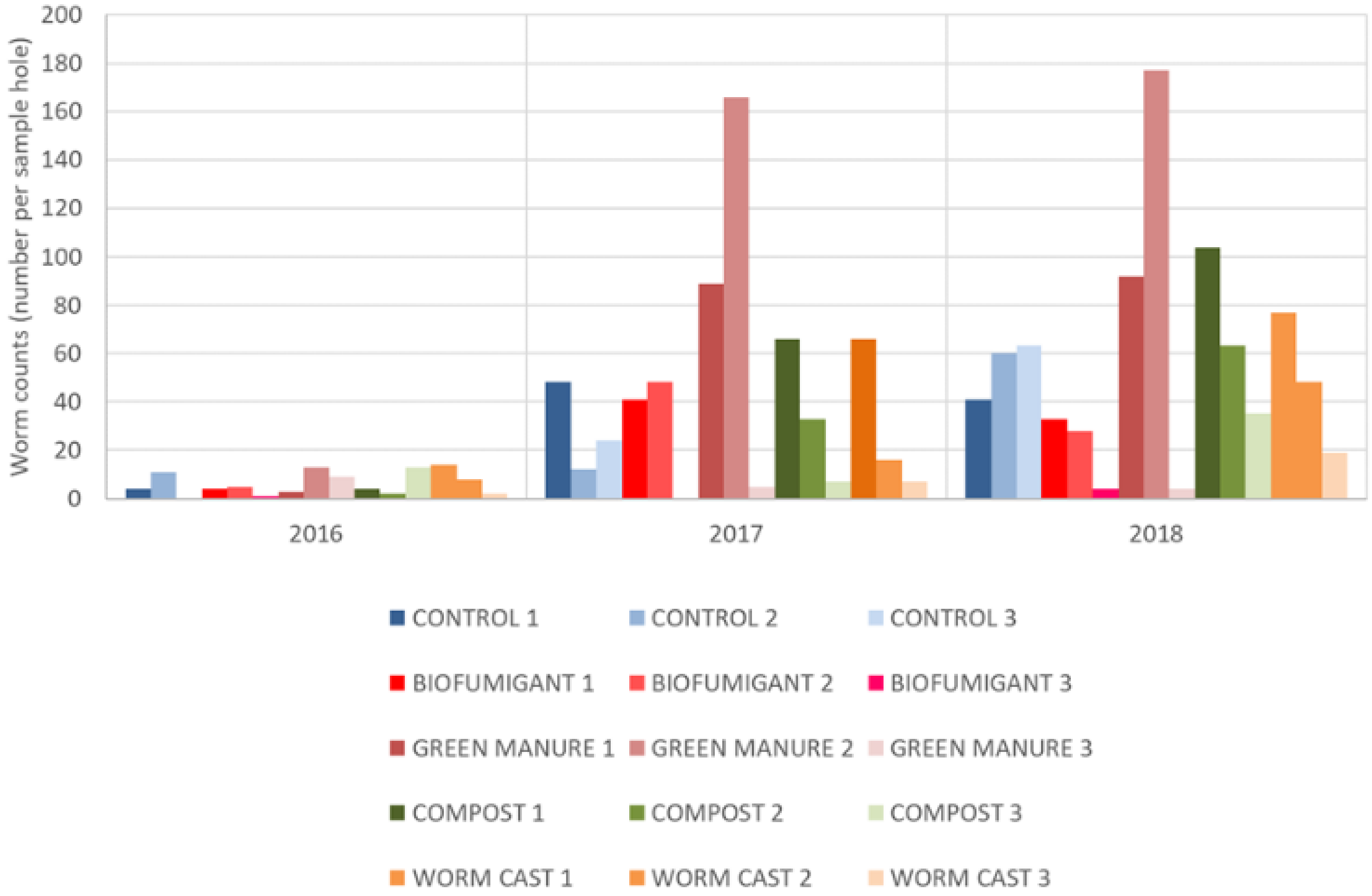
Results Maffra, Victoria



- Biofumigation prior to site establishment in 2016
- Variability – with Bay 3 receiving less irrigation water in parts of the site.

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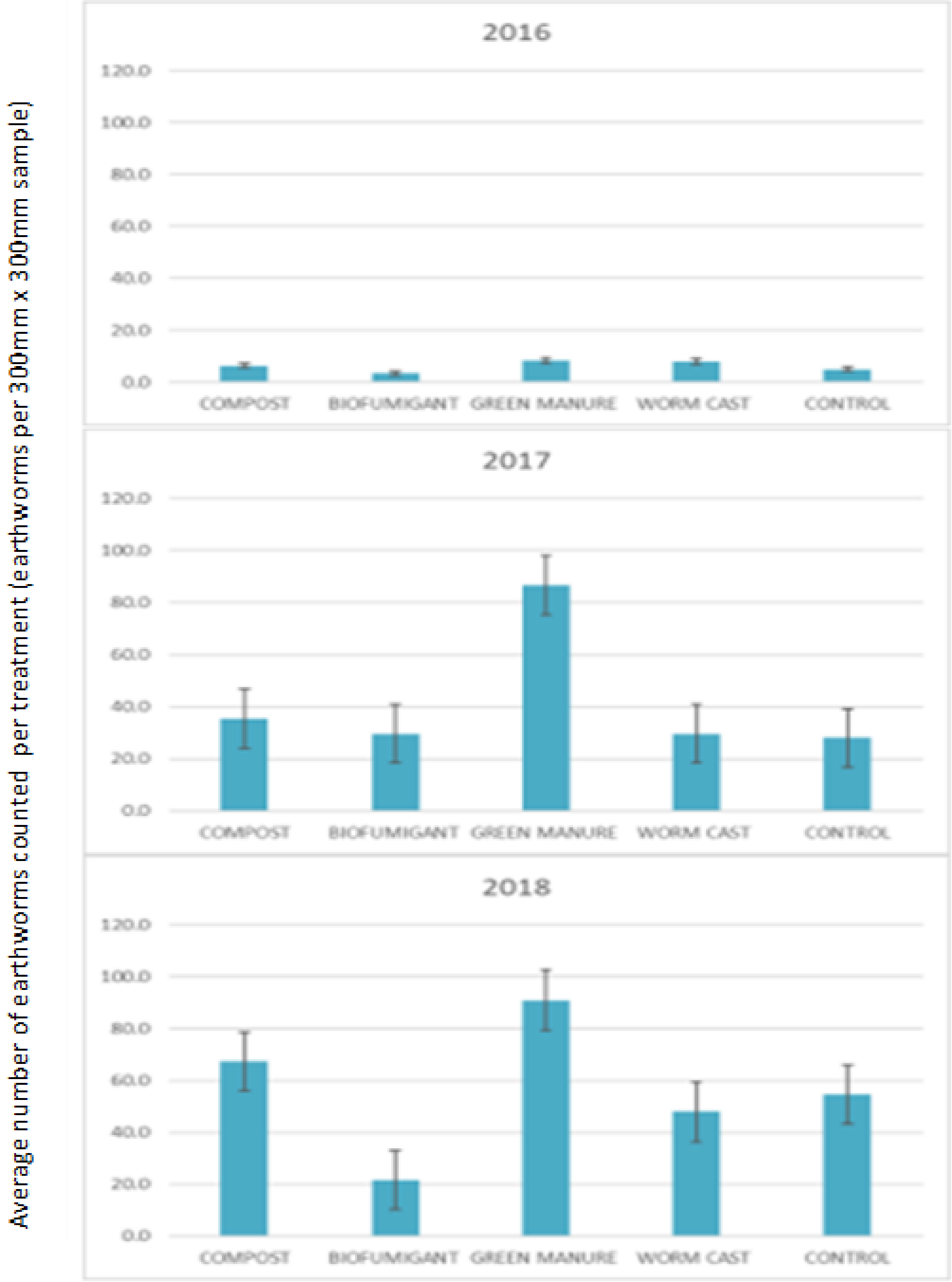

- Biofumigant used prior to 2016 sampling
- Control was continuously cropped with winter fallow.

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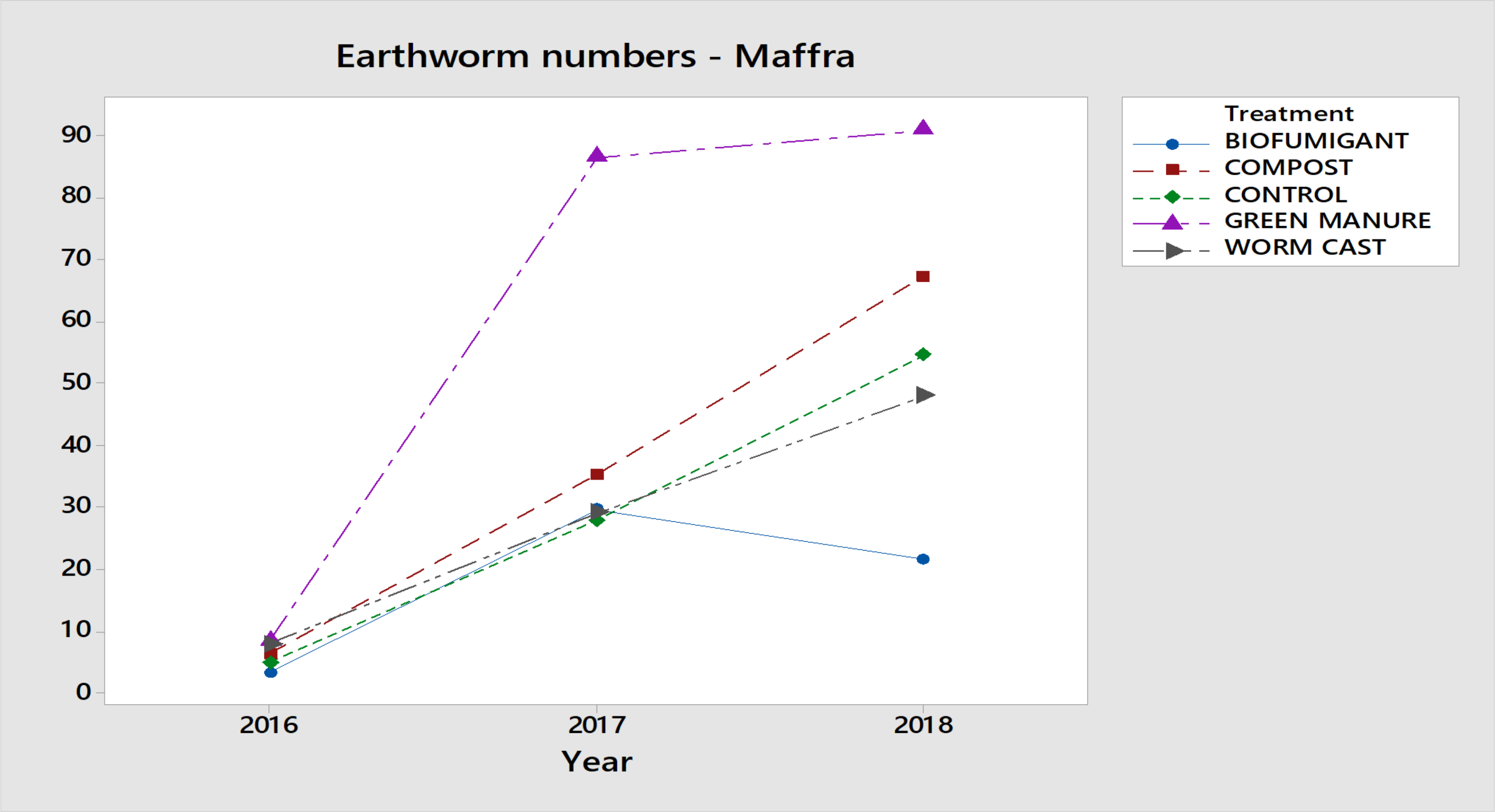
Results Maffra, Victoria



Results Maffra, Victoria

- Green manure > compost > control > worm cast > biofumigant
- Covariate analysis sought to identify relationships between treatments and soil properties that may influence earthworm numbers, e.g. TOC, TN, ppoxC, microbial biomass C
- Potassium permanganate oxidisable carbon (ppoxC) - indicating presence of labile carbon - was identified as a significant predictor of earthworm numbers in both 2017 and 2018.

Maffra

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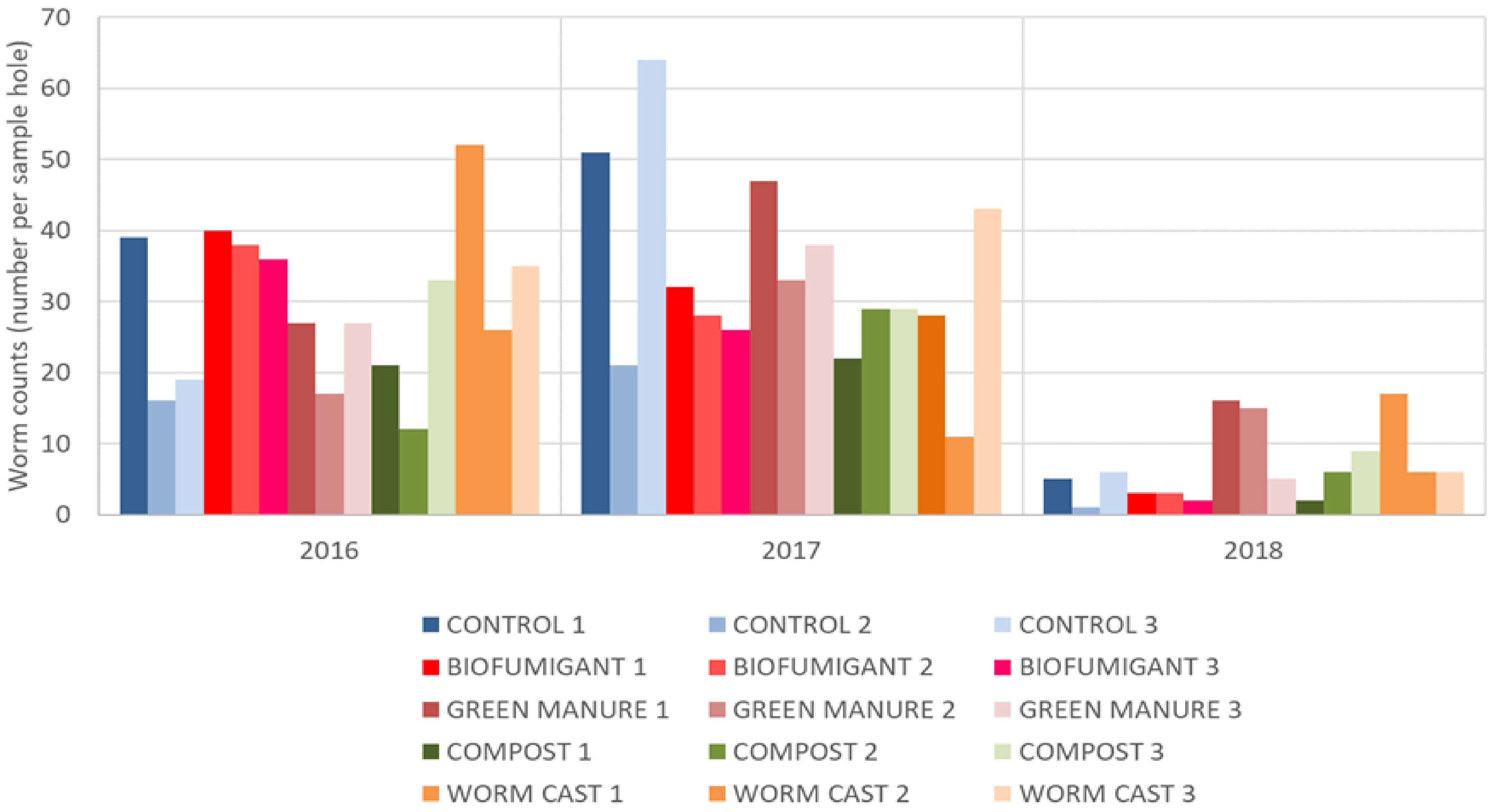
Moriarty, Tasmania

Moriarty, Tasmania

- Onions, Carrots, potatoes in a mixed cropping /grazing rotation
- Green manures and legume crops are routinely used in the rotation
- Clay loam overlying a heavier gravelly clay at 250-400mm
- Usually high rainfall.

Results - Moriarty, Tasmania



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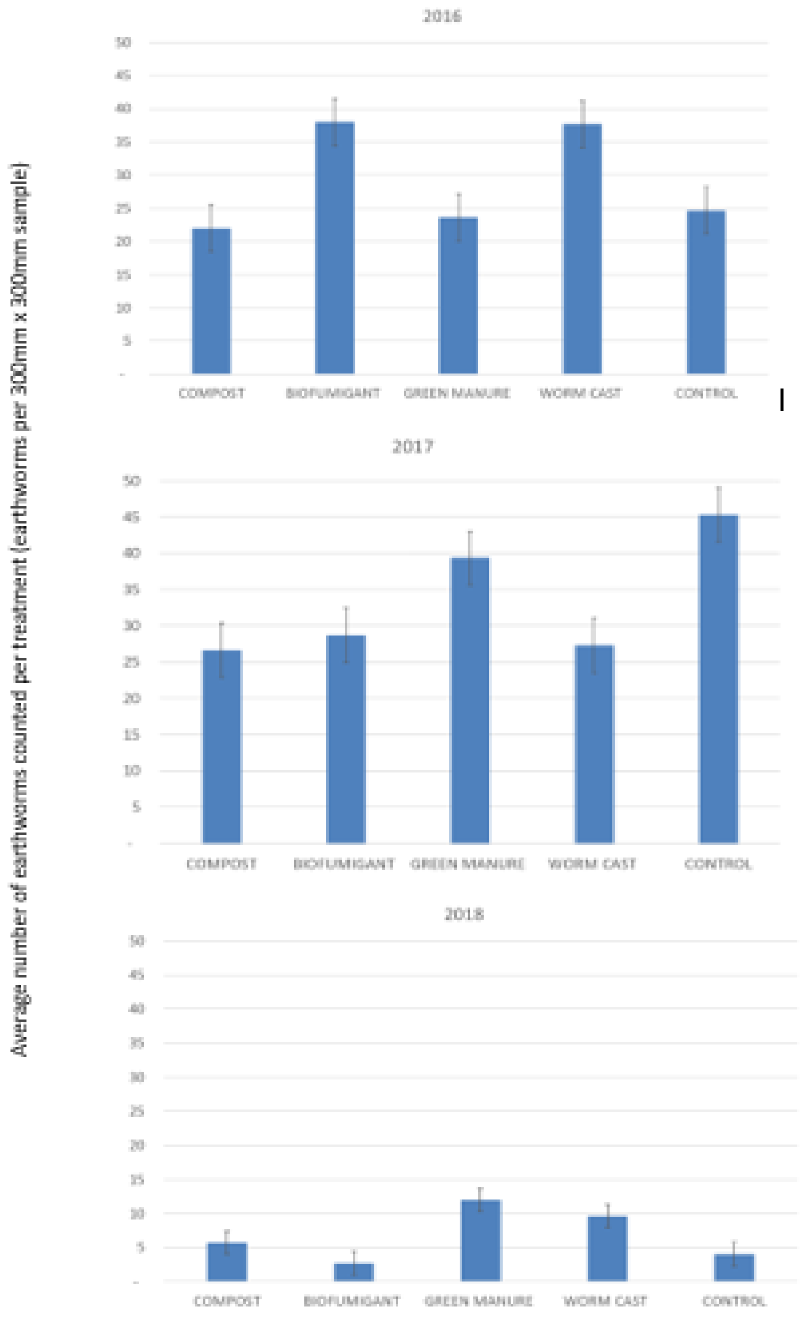

- Control in 2016/17 included a broad bean crop/green manure
- In 2018, soil had been worked for a recently sown potato crop and was drying.

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Results Moriarty, Tasmania

- Green manure ≥ worm cast> compost ≥ control > biofumigant
- Oxidisable carbon and soil microbial biomass were shown to be a moderately significant predictors of earthworm numbers in both 2017 and 2018.

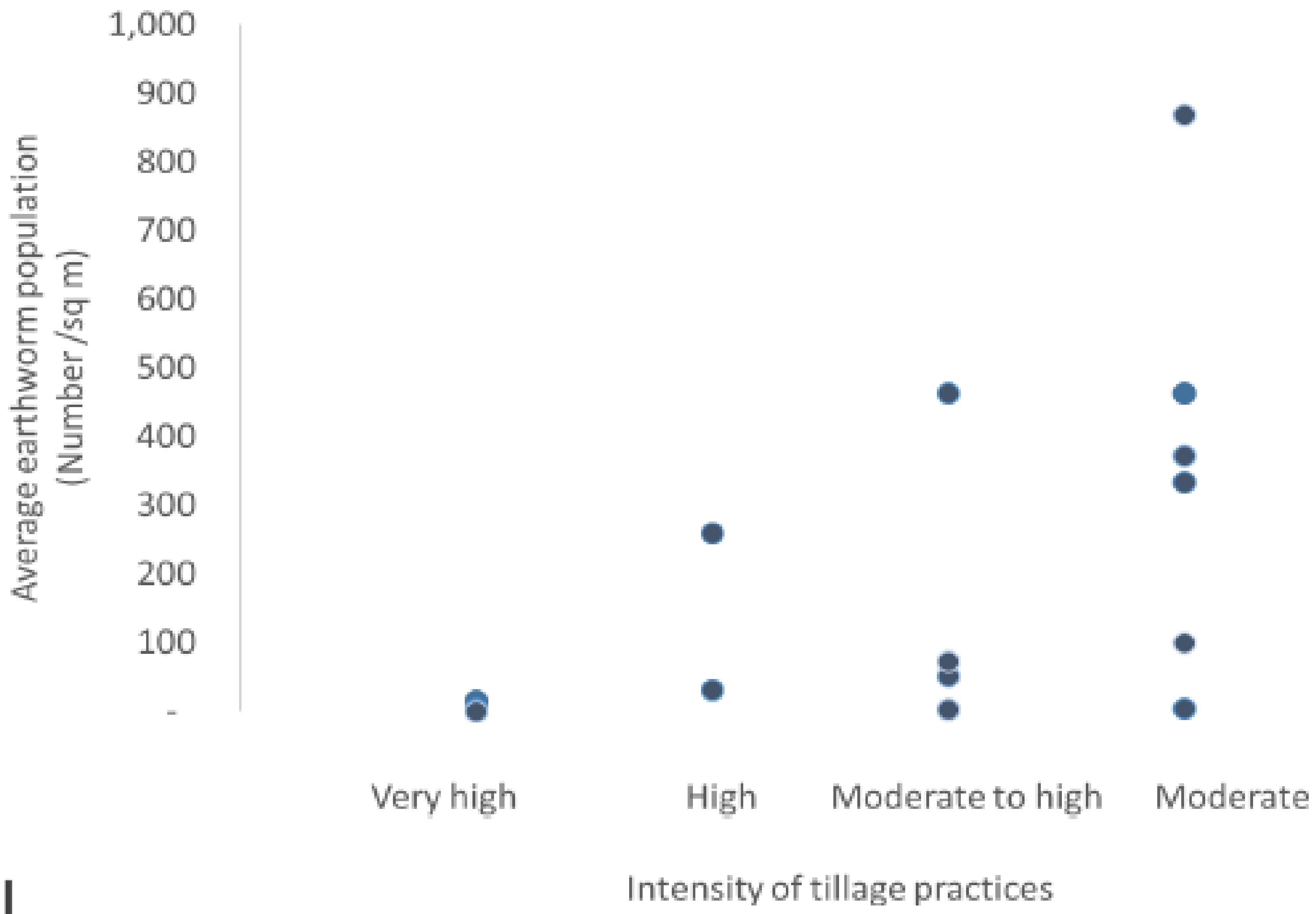
Key findings

- Green manures promoted highest earthworm populations in Victoria and Tasmania, suggesting cover crops and labile carbon is more important than simply soil carbon content
- Benefits of treatments may have been muted because the ‘control’ treatment also represented good soil management
- Timing of sampling (time of year, soil moisture and temperature) influenced results.

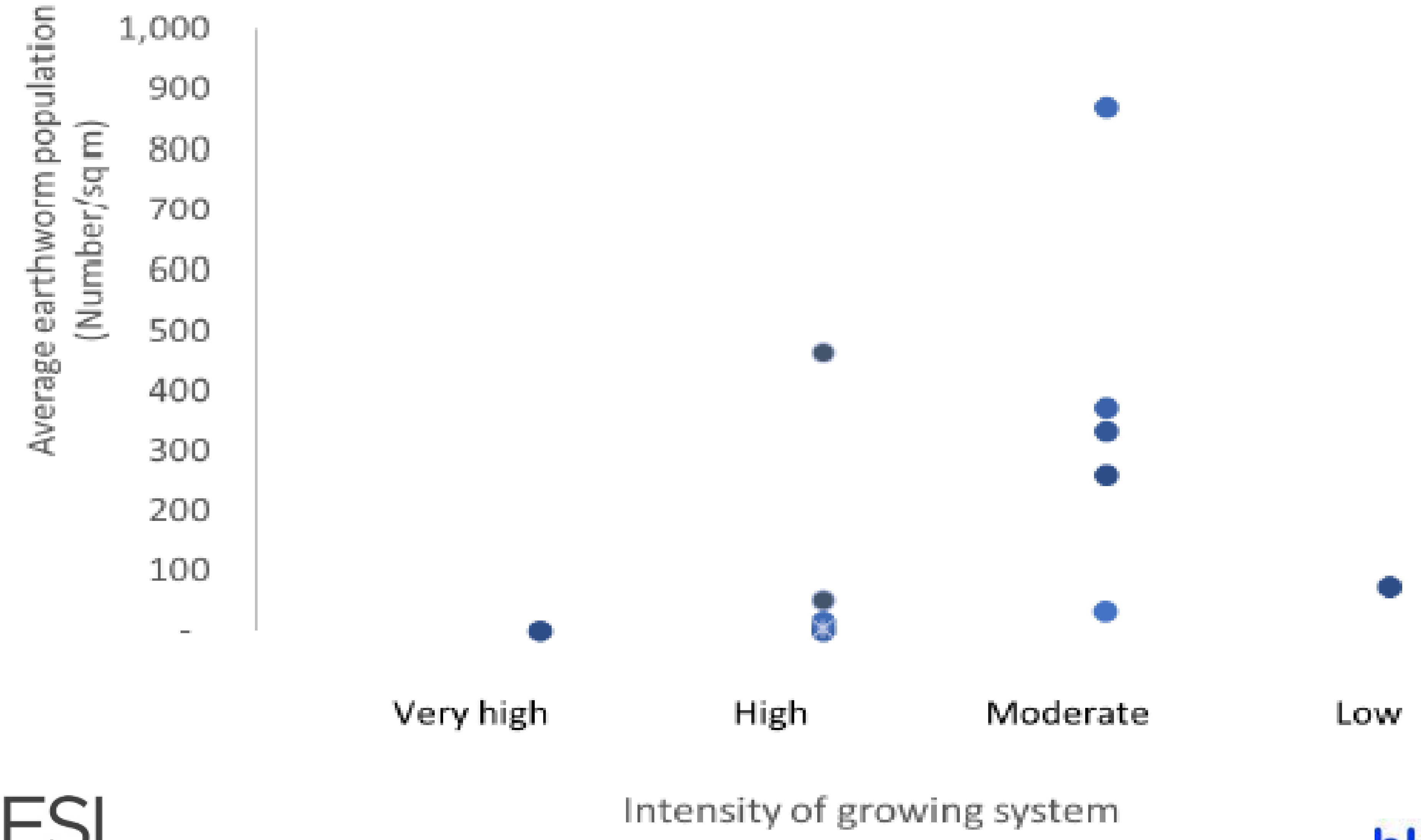
Other sites and findings

- Smaller observational sites were also sampled across Australia
- These had different levels of intensity of tillage and production
- Earthworm counts and soil testing were conducted in 2016 and 2017.

Intensity of tillage



Intensity of production



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Observations

- Intensity and depth of tillage relative to the depth of the sub-soil has significant impact
- Bio-fumigation significantly reduces earthworm numbers, but the residue then feeds soil carbon
- Earthworms will migrate to favourable conditions
- It might be possible to 'seed'/re-populate areas with earthworm-rich sods or 'worm bombs'.

Getting earthworms to work

- Build organic matter in soils
  - Use cover crops/green manures
  - Manage residues
  - Reduce tillage and practices that ‘burn off’ organic matter
  - Use composts and vermi-composts
- Reduce intensity of tillage
  - Strip tillage
  - Tines and discs rather than rotary hoe
  - Shallower tillage
  - Ripping of hard pans if they form and management to avoid reformation.

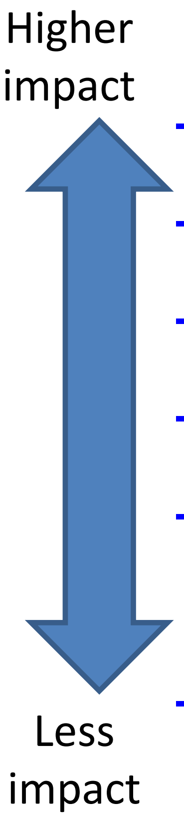
Getting earthworms to work

Other factors

- Manage moisture to avoid prolonged drying
- Rethink chemical use
  - what chemicals are used and how
  - integrated crop management
  - if other factors (soil carbon, tillage, moisture) are well managed, then chemical use will have less impact
- Create earthworm ‘refuges’ (e.g. along permanent irrigation lines)
- If earthworm numbers are very low, consider reintroducing earthworm-rich sods from other areas.

Farm chemicals

- **If other conditions are favourable for earthworms and chemicals are used according to label advice, then earthworm activity levels will generally survive/recover**



- Nematicides and soil fumigants
- Fungicides (mostly kill earthworms and worm food)
- Insecticides (most will have some impact on worm activity)
- Some 'Certified Organic' products are more toxic than some synthetics
- Some herbicides (but if these reduce tillage and build organics matter they can also help earthworm numbers)
- Fertilisers generally have a positive overall effect on earthworm activity.

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Advantages of working with earthworms

- Reduced input costs
  - Fuel, equipment and labour
  - Farm chemicals
  - Fertiliser
- Potential yield and quality gains, particularly when soils are initially poor and climate conditions are more extreme
- Sustainable soil health.

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Conclusions

- Earthworms are a sign of healthy soil, but also do useful work
- Most of the useful earthworms are introduced 'agronomic' species adapted to cropping
- On average, each spade-full should contain at least 2-4 earthworms
- Earthworms need at least 2-4% soil organic matter
- Green manure/labile organic carbon is the most effective way to build earthworm numbers
- Intensity of tillage is also a key factor
- Soil moisture is vital to earthworm activity.

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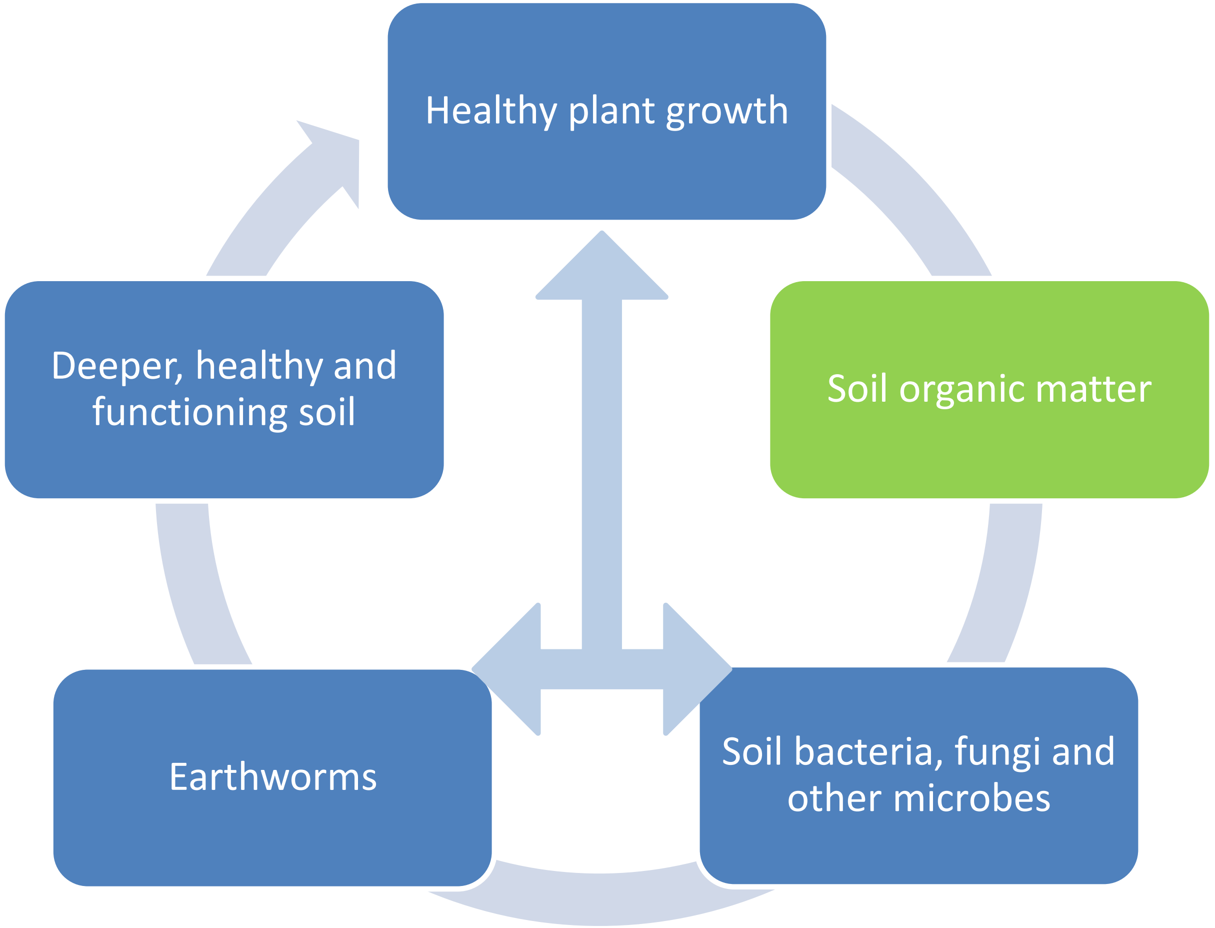
What earthworms need



Integrated crop management/ sensitive chemical use

Soil moisture management

Reduced tillage

For more information

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Working with earthworms – ongoing communications and engagement plan

Introduction

This plan outlines suggested ways to raise grower awareness about the potential benefits of earthworms in commercial vegetable growing and to promote earthworm friendly farming practices to improve productivity.

Situation analysis

Our work has found limited levels of grower interest in using earthworms as contributors to soil health management. However, there is growing awareness of the need to improve and maintain soil health through a range of practices and some recognition that earthworms are an indicator of health soil conditions. Blue Environment suggests that engagement and extension programs focused on practice change to promote soil health are likely to gain a wider audience than a program focused on earthworms.

Our work suggests many growers respond to information they receive about soil and other farm management practices from their agronomists and peers rather than many of the industry extension programs. Some growers also rely on their own independent on-line research to obtain information and national extension work is one 'voice' competing for their attention. Because few farmers are focused on deliberately using earthworm activity in the farming systems, it will be more difficult to run extension programs that promote industry leaders and 'champions' as influencers. A few of the growers we worked with have practices that mostly promote earthworm activity, but none of these felt that earthworm activity was essential to the management of their soil or crop productivity. Prior to our work with them, earthworms were seen mostly as an indicator that their efforts to improve soil health were working rather than a significant contributor to soil porosity and health. However, earthworms can greatly improve soil porosity and function in the upper 50-400mm of soil and have a key but unrecognised role to play in reducing growers' dependence on more intensive and deeper tillage.

Many of the practices promoted to improve soil health, such as increasing soil organic matter, using cover crops and green manures and working to reduce the intensity of tillage, will also promote earthworm activity. Similarly, integrated crop management practices that reduce disruption to soil micro-biology through more sensitive chemical use and biological controls are also mostly complementary with the aims of building and maintaining an agronomically useful population of earthworms. The exception to this is use of biofumigant crops, steam soil fumigation and to a lesser extent solarisation.

Proposed promotions

The project has produced:

- a detailed research report providing a review of literature and details of research undertaken
- information sheets about earthworms, earthworm-friendly farming practices and project outcomes
- articles about the benefits of earthworm-friendly farming and how to monitor earthworm numbers.

It is anticipated these will be made available via Hort Innovations and Blue Environment web pages and potentially via the national extension network.

It is recommended that promotions about earthworms and earthworm-friendly practices are incorporated in ongoing promotions of soil health management practices such as reduced tillage, increasing SOM, green manures and cover crops, controlled traffic management, sensitive chemical use and integrated crop management. The role of endogeic earthworms, and particularly larger and more mature earthworms, in improving soil porosity, bulk density and fertility in the upper 50-400mm should be included as one of the benefits of moving to lower intensity tillage systems and work to assess the effect of earthworm activity on the need for tillage could be included in future research work.

Key messages

The key messages are:

- Earthworms can greatly add to the benefits being achieved through practices to build soil organic matter and reduce the intensity of tillage.
- A healthy earthworm population is at least 100-200 earthworms per square metre (or two to four earthworms per 150mm x 150mm spade full/sod) to a depth of 300-400mm.
- Growers can monitor the health of earthworms by walking across an area that has not been worked for at least three to four months and checking spadeful sods every 10-20m. This should be done when soil moisture conditions are good and ideally in the morning when ambient temperatures are 15-25^{o}C.
- A healthy population of earthworms will aerate and fertiliser the upper 50-400mm, improving porosity and promoting healthier root growth.
- This can reduce the need for deeper and intense tillage and will favour earthworm populations that can be devastated by deep and intense tillage.
- Key factors in promoting healthy earthworm populations are:
  - building soil organic matter and particularly labile carbon levels
  - reducing the intensity of deeper tillage
  - using cover crops and green manures to build SOM and feed the soil microbiota that earthworms feed on
  - managing soil moisture to avoid drying down the soil profile for periods greater than three months.
- Other factors include: sensitive chemical use; maintenance of earthworm refuges of uncultivated strips such as permanent buried irrigation lines; recolonising areas with earthworms using sods of soil from earthworm-rich areas after major cultivation, soil fumigation or drying events.

Communication channels

Our work found generally low levels of interest in the potential for earthworms to boost soil productivity, but higher levels of interest in practices that are compatible with building and maintaining agronomically useful populations of earthworms. It is proposed that the benefits of earthworms and earthworm-friendly farm practice are promoted through complementary work focused on soil health management, such as the SoilWealth and National Extension Network. Materials prepared as part of this project can be used. Periodic field day events promoting soil health management could include presentation regarding earthworms.

Our work also found that many growers reply on private sector agronomists – as employees or contractors, or those employed by agricultural supplies businesses. It is recommended that agronomists are targeted with information about earthworms and earthworm-friendly practices.

Industry media can also be used to direct growers to information available via the national extension network and Hort Innovations.