Final Report

Improved Australian apple and pear orchard soil health and plant nutrition

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Improved Australian apple and pear orchard soil health and plant nutrition (AP19006)

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Public summary

The objective of this project was to provide targeted research to optimise soil health, thus driving productivity through enhanced nutrient availability and uptake and resilience to climate variability. The desired outcome was an apple and pear orchard production system that maximises quality and yield with high nutrient use efficiency under increasingly variable climates.

Two intensive research trials were established in Tasmania, demonstration sites with limited data collection were established in New South Wales, South Australia and Western Australia. A further site in Victorian was established and shared as part of project *AP19002.* All sites were used as demonstration sites for field walks in conjunction with Future Orchards to facilitate communication and adoption of research findings.

This project has shown that it is possible to move towards a more regenerative approach in orchards by working with natural systems and processes to build optimum soil and plant health, without the need to discard the best of conventional farming methods, to maintain or improve production levels and quality. Natural systems allow for an increase in biodiversity, providing natural control of pests, and building soil health. It is evident that biodiversity, both above and below ground, is the key in the development of ecosystem services that enable a move away from reliance on synthetic fertilisers and pesticides.

The orchard floor is a complex environment that has a major influence on crop productivity and quality. The plants of the orchard floor provide a home and food source for pollinators, predators, and other beneficial insects above ground, and strongly influence the diversity of arthropods (insects, millipedes, spiders, and earth worms) and microbes at the soil boundary and below. Soil biology (macro- and meso-arthropods and micro-organisms) is the key to nutrient cycling, in addition to influencing soil physical properties such as aggregation and water infiltration. A diverse orchard floor can give the orchard resilience and balance both above and below ground, allowing the orchard to resist or rebound rapidly from disturbances or the impact of climatic events such as high rainfall or drought.

Species selected for the orchard floor, whether in the inter-row or tree-line, need to be robust and resilient to traffic, but not invasive or competitive, and provide shelter and a food source for beneficial arthropods without creating an environment conducive to pest species and disease. Understanding the importance and complexity of the interrelationships that occur within the orchard floor, both above and below ground, and nurturing these relationships will increase orchard resilience and long-term productivity.

The timing of irrigation and nitrogen application, and the amounts applied, are key determinants of fruit quality and yield in apple production. We partnered with SWAN Systems (Scheduling Water and Nutrients) who provide a web-based irrigation and nutrient management program that includes water and nutrients pre-season planning tools, and live data collection from in-field devices to track in-season weather, soil moisture, water use, and drainage. We investigated the synergies between SWAN Systems and the SINATA tool (developed in PIPS 2, AP14023) by installing the SWAN platform in five trial orchards, one in each growing region. Each grower reported that SWAN represented an accurate model of the irrigation requirements for their blocks and that seeing SWAN's outputs gave them confidence in the decisions they were making.

Technical summary

Four components of work were undertaken for this project. These included:

1. Literature review (Appendix 1)
2. Intensive research trials in Tasmania (full report Appendix 2)
3. Regional research and demonstration trials (full report Appendix 3)
4. Integration of SINATA with Swan Systems platform (full report Appendix 4)

The report is structured according to these four components of work.

Literature Review

A desktop literature review was undertaken to explore the impact of soil and orchard floor management practices on soil biology, nutrient availability, organic carbon capture, and potential reduction to the environmental footprint in apple and pear production. A total of 206 scientific journal publications and reports were reviewed, and the knowledge gained used to inform species selection for treatments in research and demonstration sites established as part of this project.

The review showed that it is possible to move away from conventional agriculture with its heavy reliance on pesticides and synthetic fertilisers to a natural system that increases biodiversity, provides natural control of pests, and builds soil health. The common misconception that sustainable agriculture means a return to old farming methods needs to be addressed; use of the term biological or regenerative, rather than sustainable, brings the emphasis back to where farmers need to be looking in the future. Regenerative farming works with natural systems and processes to build optimum soil and plant health, while also incorporating the best of conventional farming methods to maintain production levels and quality. Not all regenerative practices are suitable for perennial tree production, particularly in established orchards, but lessons can be learnt from practices such as permaculture food forests and by referring back to natural ecosystems. Biodiversity, both above and below ground, is the key in the development of ecosystem services that enable a move away from reliance on synthetic fertilisers and pesticides.

Many orchardists in Australia have planted permanent grass swards in the inter-rows, but these can be improved by increasing species diversity. Use of biocontrol methods for pest control is becoming increasingly common along with the incorporation of compost into soil prior to planting new blocks. These practices are a good start to reinstating a healthy ecosystem, but to become truly regenerative a paradigm shift is needed to enable a return to complex systems with strong food webs and beneficial trophic interactions. There is the opportunity to design new plantings to include more ecological functions that result in increased system self-regulation and decreased costs and environmental impacts.

Intensive research trials in Tasmania

Two research trial sites were established in Spring 2020 on a commercial orchard at Ranelagh in the Huon Valley (R&R Smith Rookwood orchard). Trial 1 was established in a 12-year-old 'Jazz' block and Trial 2 in a newly planted block of 'Morgana' ('Kazari')/M26. Each trial block consisted of three inter-row treatments (grower standard grass/clover swards, flowering meadow mix and a native seed mix) and three tree-line treatments (Trial 1 - herbicide strip, compost and a grass/legume mix; Trial 2 – mow & throw, compost, hemp straw)). A range of soil physical, biological and chemistry measurements were undertaken as well as fruit quality and tree growth assessments over a three-year period.

There was an overall trend towards an improvement in soil physical properties over the trial period under the orchard floor management treatments. Bulk densities in the inter-row treatments were all lowered during the study period, falling into the desirable range of 1.1-1.4 g/cm^3 for sandy loams. Even the tractor ruts that started with high bulk density were brought into the desirable range. Bulk densities in the tree-line were all lower than in the inter-row, with very little variation in bulk density values for differing tree-line treatments. There was an improvement in hydraulic conductivity in all inter-row treatments in both trial blocks. In the tree-line treatments there was no significant difference between treatments for hydraulic conductivity (K_{60}), but over time all treatments showed a slight improvement in hydraulic conductivity. All soils in the trial blocks were well structured/highly stable in the 1-2mm aggregates range. In the inter-rows aggregate stability varied from 0-10% between treatments, and improved significantly over time, from moderate to high in all but 'Morgana' Meadow mix and 'Jazz' Native mix treatments. There was 0-5% variation between the tree-line treatments, and aggregate stability improved significantly over time in all but the Hemp straw and Mow & Throw treatments.

Fungal and bacterial communities were affected by both inter-row and tree-line treatments, though no increase in soil microbial carbon was as yet detectable. The increased soil microbial carbon and bacterial species richness in wetter plots with compost treatments indicates that water may be a limiting factor that reduced potential effects of the applied treatments. Additional sampling under wetter conditions may provide some clarification. Significant changes to microbial biomass carbon may take longer than the time elapsed between application of treatments and sampling, particularly where other factors may be limiting.

Over the three years of field trials, although the differences between treatments were small, the grass/legume treatment in the tree-line was not detrimental to fruit quality in the first season (2022), but rather improved most fruit quality parameters compared with the standard bare-earth herbicide treatment. Fruit from the grass/legume treatment showed slightly more redness than the other treatments, and fruit from the compost treatment had the least redness. The difference in fruit soluble solids content in the grass/legume treatment in the second season may be due to competition as growth of the grass/legume plots was left unchecked. There were no significant differences observed between the tree-line treatments for blossom density or crop load. There was no difference in mean fruit weight between the tree-line treatments in 2022, but in the 2023 season fruit in the grass/legume tree-line plots was 11g lighter than in the herbicide plots. One explanation for this difference is that the grass in this season was well established and growing vigorously and hence was competing with the trees for water and nutrients – potentially if these plots had been mown regularly there may have been no effect.

Regional Research and Demonstration sites

Regional demonstration sites were established in different growing regions across Australia to support the intensive trial work undertaken in Tasmania. It also provided the opportunity for local examples accessible to growers that showcased how different orchard floor management practices influenced soil health, tree health and nutrition, fruit yield and quality, The demonstration sites, with limited data collection, were established in New South Wales, South Australia and Western Australia, the Victorian site was part of the PIPS3 project *AP19002 – Strengthening cultural and biological management of pests and diseases on apple and pear.* Key learnings from these trials were:

- It is extremely difficult to establish natives in the orchard without a long lead in time (at least two years of intensive work to remove the seed bank) as their slow growth rate makes it difficult for them to compete. Ensuring adequate irrigation in the establishment phase is critical.
- Autumn is preferable for sowing of both inter-row and tree-line treatments as access in Spring can be difficult due to wet soil conditions, and growers cannot avoid tractor traffic in the inter-rows in Spring.
- The compost and grass/legume treatments in the tree-line provided a physical addition of organic material, which breaks down to organic carbon in the system. Soil carbon can improve the activity and biodiversity of microorganisms in the soil.
- The tree-line grass/legume treatment showed the highest microbial respiration rate. Keeping the soil bare exposes organisms to temperature fluctuations and soil erosion; ground cover in the tree-line is important to protect soil microbes.
- Herbicide needs to be applied regularly throughout the season to maintain a bare strip in the tree-line - constant chemical application is a large expense for the grower, a health risk for workers and herbicide resistance can occur.
- Compost/mulch is effective in suppressing weeds, but success of this treatment was dependant on the amount of coverage and 'thickness' of application - in areas that didn't get an even coverage, weeds and grasses were able to establish under the trees.

Integration of SINATA with Swan Systems platform

Apple crop yield and quality depend on irrigation and fertiliser application. A Strategic Irrigation & Nitrogen Assessment Tool for Apples (SINATA) was developed in Microsoft Excel by TIA to aid with pre-season planning of these inputs for key apple growing regions in Australia. SWAN Systems is a web-based application that facilitates fertiliser and irrigation planning for any crop. SWAN also ingests live data feeds from a wide range of devices and analyses the data based on crop water usage models, soil type and irrigation system characteristics to provide daily recommendations of irrigation requirements. SWAN tracks key metrics such as soil moisture status and drainage. SWAN systems has a crop library that includes industry-standard crop coefficient models for apples, and these can readily be customised for different season lengths and locations.

The goal was to investigate whether the SINATA pre-season planning tool could be implemented via SWAN to provide growers with the added benefit of current season, real time tools for irrigation and nutrient management of apples. This project represents a first step to incorporating the SINATA planning tool into SWAN. Both systems incorporate the irrigation design, local weather, water budgeting, crop water use models and fertiliser planning based on plant nutrient uptake curves. Five orchards in different apple-growing regions were selected for the project and provided complete irrigation records either by feeds collected automatically by SWAN from irrigation controllers or by manual upload of flow data to SWAN. All the orchards had soil moisture probes installed in two or more blocks and onsite rainfall records were obtained via existing manually read gauges or automatic weather stations. Each grower reported that SWAN represented an accurate model of the irrigation requirements for their blocks and that seeing SWAN's outputs gave them confidence in the decisions they were making. SWAN still requires the apple nutrient uptake model to be added to its library for full planning functionality.

Keywords

Apples, soil health, soil physical properties, soil biology, compost, nitrogen, irrigation, SINATA, SWAN Systems, cover crops

Introduction

Soil health and sustainable apple production

Apples and pears are grown in all Australian states and production has been relatively stable over the last three years, with approximately 310,000 tonnes of apples and 110,000 tonnes pears produced annually. The industry is looking to develop environmentally sound and sustainable production practices that will continue to meet consumer demands and inspire public confidence, ensuring that the apple and pear industry has social license to continue production in the future. There is a growing appreciation of the integral importance of soil life and plant-symbiotic interactions in agricultural sustainability and healthy soils.

We now have a strong physiological understanding of apple tree seasonal nitrogen (and other macro nutrients) and water use dynamics and its influence on fruit quality. We needed to incorporate this understanding with better knowledge of the factors that drive soil health, nutrient and water availability for resilient ecosystem services, especially under climate variability and drought scenarios. Research into sustainable orchard management practices will improve our understanding of the impact of fertiliser application, soil amendments and orchard floor management on soil health indicators such as physical structure, biology, chemistry, and consequences for tree health, growth, productivity and fruit quality.

Sustainable orchard management aims to meet the production goals of the grower/industry without compromising the ability to meet these goals in the future. This strategic approach requires methods to improve soil health, maximise water and nutrient use efficiency, minimise pest and disease incursion and reduce the overall environmental footprint of the orchard. Methods for sustainable orchard management can include inter-row sward and tree-line cultivation with easy to grow nectar-rich native plant species, legumes, grasses and green manures, as well as adding soil amendments such as manuring and composting. These methods, when implemented correctly and integrated into the grower tool kit, aim to reduce the chemical inputs required for apple orcharding from synthetic fertilisers, pest and disease sprays and weed control.

Many growers are already successfully implementing sustainable orchard management practices that include the application of soil amendments and inter-row sward and tree-line cultivation. Whilst these management practices may help mitigate variation within and between orchard blocks, the benefits (above and below ground) of various approaches are not well understood, are difficult to demonstrate and will vary substantially between seasons, soil types and regions. There is a substantial knowledge gap on how the presence and function of beneficial organisms are promoted (or inhibited) by orchard management practices and how they interact with trees to increase tree water and nutrient-uptake, especially under drought conditions. Consequently, there is uncertainty on which management practice might be best suited to particular soils, sites and site histories and how best to implement the approach.

The research undertaken in this project will assist with determining how and which sustainable orchard management methods best achieve soil health and resilience outcomes whilst maintaining high yields and fruit quality standards in commercial orchard production. This research will identify the biological, structural and chemical indicators for soil health and determine how these relate in distinct regions and soil types.

Biological indicators may include: (i) increasing the presence and abundance of mycorrhizal fungi inoculating tree roots that directly facilitate tree water and nutrient uptake; (ii) increased microbial diversity and activity that improves soil mineralisation and nutrient availability for root uptake; (iii) increased abundance of soil and understorey meso/macro invertebrates; (iv) increased presence of predatory invertebrates to reduce invasive pest incursion and (v) nectar providing species that support native and feral insects acting as potential pollinators.

Structural indicators may include (i) increased soil organic carbon providing greater water holding and cation-exchange capacity of the soil and to support mineralisation and the presence and abundance of mycorrhizal fungi; (ii) reduced aggregation and crusting and improved infiltration, drainable porosity and readily available soil water.

Chemical indicators may include (i) increased plant available nutrient content of the soils; (ii) altered ratios of bound versus plant-available nutrients to enable plant uptake through increased mycorrhizal activity and (iii) improved electrical conductivity (EC), pH, cation exchange capacity (CEC), nutrient ratios and reduced Al content characteristics, all of which can act as nutrient uptake inhibitors.

With these indicators, it is important to recognise that there is a difference between changed and improved soil properties due to a treatment. We must be able to demonstrate to growers and advisors that this management approach can be used to mitigate spatial and temporal variability in orchard blocks and that changes to these indicators lead, at a minimum, to maintenance of, but preferably quantifiable improvements in, resource use efficiency, tree heath, fruit yield and quality outcomes. This project has adopted a systems approach with consideration given to how outputs can be integrated with other aspects of orchard management. Specifically, project outcomes integrate industry growing system practices with new knowledge of management for soil health and resilience. Given the increasing evidence of the devasting impacts of climate and weather extremes, the research activities are considered within the context of a changing climate and increased climate variability.

Integration of SINATA with SWAN Systems.

The timing of irrigation and nitrogen application, and the amounts applied, are key determinants of fruit quality and yield in apple production. The University of Tasmania, along with leading industry bodies, developed SINATA (Strategic Irrigation & Nitrogen Assessment Tool for Apples) to help apple growers with irrigation and nitrogen planning. SINATA is an Excel-based tool that considers apple cultivar, age, orchard layout, and irrigation strategy to provide estimates of weekly irrigation requirements for major apple growing regions based on historical climatic data. It also provides a nitrogen balance calculation for a range of local soil types based on inputs (fertiliser, leaf fall, mineralisation, etc.) and outputs (off-take in fruit, leaching, and volatilisation).

SWAN Systems (Scheduling Water and Nutrients) is a web-based irrigation and nutrient management program that includes water and nutrient pre-season planning tools, and live data collection from in-field devices to track in-season weather, soil moisture, water use, and drainage.

SINATA and SWAN are complementary and share some similar models. Like SINATA, SWAN is fully configurable for soil type, irrigation system, and crop characteristics. SWAN is generally applicable to all crop types, including apples. On the irrigation side, the primary difference is that SINATA is a pre-season planning tool based on seasonal averages, while SWAN uses live data to calculate daily soil moisture balance and provides a soil moisture forecast to facilitate irrigation decision support for the week ahead. For nutrients, SWAN allows full nutrient program planning based on targets for each element and users can record actual nutrient applications for comparison and reporting against the budgets. SINATA is unique in providing an estimate of likely annual Nitrogen-balance via models based on climatic averages and intended irrigation strategies.

SWAN partnered with the University of Tasmania to investigate the synergies between the two platforms and investigate options for implementing SINATA via SWAN to make the apple-specific SINATA planning tools accessible via SWAN's universal interface and provide growers with current season, real time tools for irrigation and nutrient management of apples.

Methodology

Intensive research trials in Tasmania

Two research trial sites were established in Spring 2020 on a commercial orchard at Ranelagh in the Huon Valley (R&R Smith Rookwood orchard. Trial 1 was established in a 12-year-old 'Jazz' block and Trial 2 in a newly planted block of 'Morgana' ('Kazari')/M26. Both blocks were on sandy loam soils, with a north-south row orientation. Inter-row spacing in both blocks was 3.5 m with 1.0 m tree spacing within the row. Each trial block consisted of three inter-row treatments and three tree-line treatments with five replicates per treatment. Trial design was a randomised complete block. Treatments are shown in Table 1.

Table 1*: Inter-row and tree-line treatments in the intensive trial blocks*

Trial 1 -Mature 'Jazz' block	Trial 2 – Newly planted 'Morgana' block
Inter-row treatments	
1. Grower sward	1. Grower sward
2. Flowering meadow mix	2. Flowering meadow mix
3. Native flowering mix	3. Legume/grass mix
Tree-line treatments	
1. Herbicide strip	1. Mow & throw
2. Compost	2. Compost
3. Legume/grass mix	3. Hemp straw

A bare earth / herbicide strip in the tree line was adopted as the control in the established 'Jazz' block as it is normal practice in most orchards. In the newly planted 'Morgana' block the grass/legume tree-line treatment was replaced with hemp straw to avoid root competition. The flowering meadow and native flowering mixes were aimed at providing habitat and a food source for bees and beneficial insects (Refer to Appendix 2, Table 2 for details).

Treatment establishment

Planting of trial treatments were delayed due to wet conditions in August/September and challenges in obtaining seed, as most suppliers were either out of stock or had limited supplies. As the ground in Trial 2 was already worked up from planting the trees in this block in July 2020, Trial 2 was sown first. The inter-rows in the trial section were harrowed on 27th October 2020 and seed was broadcast by hand 29th October 2020 followed by a light harrow. The inter-rows and tree-lines in the established 'Jazz' trial block were sprayed with knockdown herbicide on 2nd November 2020 and inter-rows cultivated on 10th November. Seed was sown by hand broadcasting and the inter-rows harrowed on 10th November. Due to dry conditions during late spring and summer, seed germination and establishment was very patchy, so inter-row treatments were reseeded in August 2021.

Except for the *Microleana stipoides* native grass, the native species in the native flowering mix treatment were planted out as plugs in June 2021 after starting from seed in the greenhouse. Seed of *Microleana stipoide* was on backorder and not received until August 2021, so was broadcast by hand once it was received.

The tree-line grass/legume plots were prepared by raking, seed was broadcast by hand and lightly incorporated into the soil by raking to encourage germination. The tree-line grass/legume treatment established well, however was accidently sprayed off with herbicide in January 2021 during routine orchard weed control by orchard staff, so was resown in autumn 2021. The remaining tree-line treatments were set up in early 2021. Compost was provided by Nic Hansen from Cherries Tasmania. Hemp straw was donated by Andi Lucas at X-Hemp Pty Ltd. As the 'Jazz' block went into conversion from conventional to organic six months after trial establishment, the organic approved herbicide Slasher (525 g/L nonanoic acid, Organic Crop Protectants Pty Ltd) was applied in the herbicide tree-line treatment plots. Organic matter for the mow & throw treatments was gathered whenever the orchard was mown and distributed across the relevant plots.

Sampling and monitoring

Soil sampling

Soil sampling was undertaken at periods throughout the project to enable determination of soil physical parameters, soil chemistry, soil microbiology, arthropod populations, pest damage, tree growth and fruit quality (refer to Appendix 2,

Table 3 for details). Soil samples were collected from both trial blocks in May 2021 and 2023. A total of six cores were collected from each plot, vegetation removed and cores thoroughly mixed for each plot before oven drying. Inter-row and tree-line treatments were sampled separately. In 2021 all samples were pooled for each treatment, while in 2023 samples were kept separate for each plot. Samples were forwarded to CSBP Soil and Plant Analysis Laboratory for analysis. Soil samples were collected from each of the tree-line and inter-row plots in early September 2022 and in May 2023 and returned to the soil physics laboratory for analysis of bulk density, moisture content, aggregate stability, infiltration rate, hydraulic conductivity, mean pore size and contribution of pore size to maximum flow.

Samples were also taken from tree-line and inter-row soil in January 2022 and separated into the upper and lower halves of 150mm cores. Subsamples were taken for soil moisture content, microbial biomass carbon (extractable in K_2SO_4) and estimated by Microbiometer^{TM}, volatile organic compounds, fungal biomass, bacterial and arbuscular mycorrhizal fungal biomass (estimated by qPCR) and fungal and bacterial community composition. Worm counts of both tree-line and inter-row plots were undertaken in September 2022 in both the 15-year-old ‘Jazz and 2-year-old ‘Morgana’ blocks.

Detailed methodology and data analysis of soil sampling is described in Appendix 2.

Arthropod sampling

Arthropod assessments were completed in the ‘Jazz’ trial block in collaboration with the PIPS3 project AP19002. Earwig traps, sticky cards, and Delta (pheromone) traps for codling moth and Light Brown Apple Moth were set up in the trees. Pitfall traps were installed in both the tree-line and inter-row. Traps were monitored for one week every month during the growing season.

Fruit quality assessments

The ‘Morgana’ trees were in second leaf in the 2021/22 season and hence were not cropping; these trees carried a small crop in the 2022/23 season, but there was insufficient fruit for fruit quality assessments. Trees in the established ‘Jazz’ block were harvested at normal commercial fruit maturity in early April 2022 (2021/22 season) and 2023 (2022/23 season); fruit numbers were counted prior to harvest on two tagged trees in the centre of each trial plot (90 trees in total) and a sample of 40 fruit collected from the eastern side of these trees.

Fruit samples were returned to the laboratory, weighed and mean fruit weight determined for each sample tree. A subsample of 25 defect-free fruit was randomly selected from each tree for laboratory analysis of fruit quality and maturity. Parameters assessed included weight, diameter (D), length (L), skin chlorophyll content (DA Index), flesh firmness, total soluble solids (TSS) content, starch pattern index (SPI) and percentage dry matter content (DMC) (detailed methods described in Appendix 2).

Regional trial and demonstration sites

Regional demonstration sites were established in different growing regions across Australia to support the intensive trial work undertaken in Tasmania. It also provided the opportunity for local examples accessible to growers that showcased how different orchard floor management practices influenced soil health, tree health and nutrition, fruit yield and quality, The demonstration sites, with limited data collection, were established in New South Wales, South Australia and Western Australia, the Victorian site was part of the PIPS3 project *AP19002 – Strengthening cultural and biological management of pests and diseases on apple and pear*.

The treatments established in each region included a range of tree-line cover crops, composts, mulches and herbicide bare-earth strip; inter-row plantings included native herbaceous and/or grass mix, flowering meadow mix, and grass/legume mixes.

Treatments and species used reflected regional priorities and soil, climatic and management system differences to assist with:

- identification of the biological, structural and chemical indicators for soil health, including relationship to regional and soil type differences, and assessment methods;
- improving understanding of the interaction between management practices, soil health, nutrient availability, water availability, pest and disease control and fruit productivity/quality;
- measuring the impact of sustainable orchard floor management on the presence and function of mycorrhizal fungi and the organic carbon content of the soil;
- providing a better understanding of the relationships between soil health, tree health, growth and fruit yield, productivity and quality; and

- addressing grower perceived impediments to adoption including water requirements, herbicide and fungicide use, tractor movements and fire risk.

Further details for the establishment and monitoring of each regional trial site is presented in Appendix 3

Integration of SINATA with Swan Systems platform

Five orchards in different apple-growing regions were selected for the project (Table 2). The Shepparton farm (Plunkett) was devastated by hail in December 2022 and will not be analysed further. The remaining orchards provided complete irrigation records either by feeds collected automatically by SWAN from irrigation controllers (Fontanini and Oakleigh) or by manual upload of flow data to SWAN (Squibb and Tingira). All the orchards had soil moisture probes installed in two or more blocks and onsite rainfall records were obtained via existing manually read gauges or automatic weather stations.

Table 2. Orchards participating in the SWAN trial for PIPS3.

State, Region	Orchard	Blocks	Ha	Irrigation data	Devices
WA, Manjimup	Fontanini	8	11.8	Controller (MAIT)	2 probes, rain gauge
SA, Lenswood	Oakleigh	14	8.6	Controller (Netafim)	2 probes, AWS
Tas, Spreyton	RW Squibb	19	19.5	Manual records	3 probes, rain gauge
NSW, Batlow	Tingira	23*	22.3	Manual records	2 probes, rain gauge, AWS
Vic, Shepparton	Plunkett	10	30.5	n/a	n/a

Growers followed their normal nutrient programs. The nutrient applications were recorded in SWAN. SWAN was used to compare the timing of nutrient application with irrigation, rainfall, and predicted drainage. SWAN's outputs were derived from live data for the current season. The actual Nitrogen applications and crop yields were added into the SINATA sheet at the end of the season. SINATA was configured to match the blocks being analysed (location, weather source, soil type, crop age, irrigation system details, spacings). The SINATA output was thus based on inputs of actual yields and fertiliser applications analysed against long-term weather averages. Further details provided in Appendix 4.

Results and discussion

Literature Review

The literature revealed that it is possible to move away from conventional agriculture with its heavy reliance on pesticides and synthetic fertilisers to a natural system that increases biodiversity, provides natural control of pests, and builds soil health (Appendix 1). The common misconception that sustainable agriculture means a return to old farming methods needs to be addressed; use of the term biological or regenerative, rather than sustainable, brings the emphasis back to where farmers need to be looking in the future. Regenerative farming works with natural systems and processes to build optimum soil and plant health, while also incorporating the best of conventional farming methods to maintain production levels and quality. Not all regenerative practices are suitable for perennial tree production, particularly in established orchards, but lessons can be learnt from practices such as permaculture food forests and by referring back to natural ecosystems. Biodiversity, both above and below ground, is the key in the development of ecosystem services that enable a move away from reliance on synthetic fertilisers and pesticides.

Many orchardists in Australia have planted permanent grass swards in the inter-rows, but these can be improved by increasing species diversity. Use of biocontrol methods for pest control is becoming increasingly common along with the incorporation of compost into soil prior to planting new blocks. These practices are a good start to reinstating a healthy ecosystem, but to become truly regenerative a paradigm shift is needed to enable a return to complex systems with strong food webs and beneficial trophic interactions. The starting point is to increase biodiversity within the orchard, and simple methods for achieving this include:

- increasing soil organic matter
- diversifying orchard floor vegetation
- use of cover crops
- mulching in the tree row
- mow and blow inter-row vegetation into the tree row
- reducing frequency of mowing
- planting hedgerows around the orchard and/or between blocks
- planting of multiple tree species
- use of biocontrol strategies rather than pesticides

There is the opportunity to design new plantings to include more ecological functions that result in increased system self-regulation and decreased costs and environmental impacts. Redesign is a difficult change to make it yields the most sustainability improvement per unit of change; we need to "connect the dots" to maximise the benefits of existing knowledge and to determine what future research needs to be undertaken for specific situations.

Intensive research trials in Tasmania

Soil physical properties

Soil physical results demonstrate an overall trend towards an improvement in soil physical properties. Detailed results for each of the soil parameters measured are described in Appendix 2.

Bulk densities in the inter-row treatments were all lowered during the study period, falling into the desirable range of 1.1-1.4 g/cm^3 for sandy loams. Even the tractor ruts that started with high bulk density were brought into the desirable range. Bulk densities in the tree-line were all lower than in the inter-row, with very little variation in bulk density values for differing tree-line treatments. There were reductions in K_{60} in all inter-row treatments in both the 'Morgana' and 'Jazz' blocks – a reduction represents an improvement in hydraulic conductivity. A significant large improvement was observed in K_{10} in the inter-rows in both the 'Morgana' and 'Jazz' blocks (Table 3). In the tree-line treatments there was no significant difference between treatments for K_{60}, but over time all treatments showed a slight improvement (decrease). As for the inter-row treatments, there were significant large improvements to K_{10} in all three tree-line treatments in both blocks between 2022 and 2023 – this is a desirable finding. All soils in the trial blocks were well structured/highly stable in the 1-2mm aggregate size range. In the inter-rows variation between treatments for aggregate stability was 0-10%, with a significant improvement over time, from moderate to high in all but the 'Morgana' Meadow mix and 'Jazz' Native mix treatments. There was 0-5% variation between the tree-line treatments, and aggregate stability improved significantly over time in all but the Hemp straw and Mow & Throw treatments.

Table 3 The impact of tree-line treatments on soil water infiltration, hydraulic conductivity and worm numbers in a 15-year-old 'Jazz' apple block

Tree-line treatment	Infiltration -10 (mm/hr)	Hydraulic conductivity -10 (mm/hr)	Hydraulic conductivity -60 (mm/hr)	Worm #
Herbicide	52.2 ^{a}	13.4 ^{a}	5.3 ^{a}	2.1 ^{b}
Compost	22.4 ^{b}	4.5 ^{b}	2.0 ^{b}	2.1 ^{b}
Grass/Legume	46.7 ^{ab}	11.3 ^{a}	4.8 ^{a}	9.3 ^{a}
Fprob	*0.055*	*0.028*	*0.041*	*<0.001*
Lsd (p≤0.05)	*25.68*	*6.74*	*2.7*	*2.99*

Soil biology

No significant effects of tree-line or inter-row treatments were detected on soil moisture or microbial biomass carbon, though microbial biomass carbon was elevated under compost treatments with higher moisture levels. PERMANOVA main test indicated that bacterial community composition differed among the soil treatments (P=0.0001), but pairwise tests did not differentiate bacterial community composition under different cover crops in the inter-row. In the 'Jazz' block, the two tree-line treatments, compost and grass/legume, supported different bacterial communities to the bare treatment but were not significantly different from each other. In the 'Morgana' block, the compost treatment differed significantly from the other two treatments. All tree-line treatments were significantly different from all inter-row treatments.

Fungal communities differed significantly among treatments. Both grower and meadow mix treatments differed from the control treatment in the 'Jazz' inter-rows, but not from each other. Similarly, meadow mix differed significantly from both grower mix and fescue/legume, but the latter two were not significantly different from each other in the 'Morgana' inter-rows. Among the tree-line treatments, the bare-earth treatment was significantly different from both the compost and grass/legume treatments, but these two were not significantly different. All but two of the tree-line treatments in the 'Morgana' block were significantly different from each other at p<0.05. In addition, the fungal communities under compost differed between inter-row treatments, but hemp straw and mow & throw did not. All inter-row fungal communities were distinct from tree-line fungal communities. Fungal and bacterial communities were affected by both inter-row and tree-line treatments, though no increase in soil microbial carbon was as yet detectable. The increased soil microbial carbon and bacterial species richness in wetter plots with compost treatments indicates that water may be a limiting factor that reduced potential effects of the applied treatments. Additional sampling under wetter conditions may provide some clarification. Significant changes to microbial biomass carbon may take longer than the time elapsed between application of treatments and sampling, particularly where other factors may be limiting.

In the older 'Jazz' block, the number of worms found in the living grass/legume mulch was 440% higher than in the compost mulch or herbicide treatments. In the 'Morgana' block there was no significant difference in worm number between the compost mulch, hemp straw mulch or mow & throw mulch tree-line treatments. There was no difference in worm numbers between any of the inter-row treatments in either the 'Jazz' or 'Morgana' blocks.

Tree growth

There were no significant differences between the tree-line treatments in initial tree size (measured as trunk cross-sectional area in September 2021) in either the 'Jazz' or 'Morgan' trees. Tree-line treatments had no effect on tree growth, measured as increase in trunk circumference and trunk area, in either cultivar. These results were not unexpected as this was the first full season following application of treatments, and it can take several years for the impact of soil treatments to carry through to tree growth.

Fruit quality

There were no significant differences observed between the tree-line treatments for blossom density or crop load (measured as number of fruit per 100 blossom clusters and number of fruit per cm^2 trunk cross-sectional area. These results were not unexpected as this is the first full season following application of treatments, and as noted above, it can take several years for the impact of soil treatments to carry through to tree growth and yield. There was no difference in mean fruit weight between the tree-line treatments in 2022, but in the 2023 season fruit in the grass/legume tree-line plots was 11g lighter than in the herbicide plots (Table 4). One explanation for this difference is that the grass in this season was well established and growing vigorously and hence was competing with the trees for water and nutrients –

potentially if these plots had been mown regularly there may have been no effect. This is worth exploring in future studies.

There was no difference between treatments in fruit shape, represented by L/D ratio, in either season. There were, however, small but significant differences in other fruit quality parameters, although these differences were not always consistent across the two seasons (Table 4). Both fruit TSS and DMC were higher in the grass/legume treatments than in the compost or herbicide treated plots in the 2022 season, but in the 2023 season TSS was lower while there was no difference in DMC. Fruit firmness was higher in the grass/legume treatment compared with the herbicide treatment in both seasons, while fruit in the compost treatment showed the lowest firmness in the 2022 season and the highest firmness in the 2023 season. Fruit chlorophyll content (DA Index) was lower in the grass/legume treatment in the 2022 season, but in the 2023 season this was higher in the grass/legume treatment compared to the herbicide control. SPI showed a slower rate of conversion of starch to sugar in the grass/legume treatment across both seasons.

Although the differences between treatments were small, it is interesting to note that grass/legume in the tree-line was not detrimental to fruit quality in the first season (2022), but rather improved most fruit quality parameters compared with the standard bare-earth herbicide treatment. The difference in fruit soluble solids content in this treatment in the second season may be due to competition as growth of the grass/legume plots was left unchecked (noted above for tree growth).

Table 4: The effect of different tree-line treatments on fruit quality parameters in Trial 1 ('Jazz' apple)

Treeline treatment	Mean fruit wight (g) 2022	2023	Soluble solids (°Brix) 2022	2023	Dry matter content (%) 2022	2023
Herbicide	134	136.9 a	12.04 ^{b}	12.9 ^{a}	14.59 ^{b}	15.06
Compost	137	139.4 a	12.10 ^{b}	12.8 ^{ab}	14.63 ^{b}	15.07
Grass/Legume	132	125.9 b	12.39 ^{a}	12.7 ^{b}	14.93 ^{a}	15.02
Fprob	*0.362*	*0.001*	*<0.001*	*0.003*	*0.006*	*0.953*
Lsd (p≤0.05)	*ns*	*7.56*	*0.087*	*0.13*	*0.227*	*ns*
	Firmness (kg) 2022	**2023**	**DA Index 2022**	**2023**	**Starch pattern index 2022**	**2023**
Herbicide	9.41 ^{b}	9.24 ^{c}	0.47 ^{b}	0.29 ^{b}	4.44 ^{a}	5.39 ^{a}
Compost	9.28 ^{c}	9.38 ^{a}	0.59 ^{a}	0.24 ^{c}	4.23 ^{b}	5.45 ^{a}
Grass/Legume	9.66 ^{a}	9.36 ^{b}	0.38 ^{c}	0.43 ^{a}	4.02 ^{c}	5.25 ^{b}
Fprob	*<0.001*	*0.028*	*<0.001*	*<0.001*	*<0.001*	*<0.001*
Lsd (p≤0.05)	*0.107*	*0.112*	*0.027*	*0.035*	*0.113*	*0.075*

Within each column, means followed by different letters are significantly different according to the LSD means comparison test at p = 0.05.
DA = delta absorbance

For fruit colour (Table 5), the L* values are in the mid-range for all treatments. Fruit from the grass/legume treatment showed slightly more redness (a* and hue angle) than the other treatments, and fruit from the compost treatments had the least redness.

Table 5: The effect of different tree-line treatments on fruit skin colour in Trial 1 ('Jazz' apple) *in the intensive research trial at Ranelagh, Tasmania*

	L*	a*	b*	Chroma	Hue angle
Herbicide	42.29 ^{b}	32.53 ^{b}	22.12 ^{b}	40.1 ^{b}	0.6 ^{b}
Compost	43.98 ^{a}	28.84 ^{c}	23.91 ^{a}	38.3 ^{c}	0.7 ^{a}
Grass/Legume	40.64 ^{c}	34.79 ^{a}	20.58 ^{c}	40.7 ^{a}	0.5 ^{c}
Fprob	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*
Lsd (p≤0.05)	*0.637*	*0.816*	*0.442*	*0.51*	*0.02*

Within each column, means followed by different letters are significantly different according to the LSD means comparison test at p = 0.05.

Fruit damage

Fruit damage assessments were completed in Trial 1 ('Jazz') on 4th April 2022, approximately two days prior to harvest. Overall, fruit damage was relatively low across the block (mean ± SEM, 4.48 ± 0.3%). The observed damage was largely caused by weevils, apple scab (*Venturia inaequalis*), and codling moth (*Cydia pomonella*) stings with very low levels of thrip damage observed. Weevil damage was the predominant damage type (54.9%) followed by codling moth (20.5%) and apple scab (11.9%). No codling moth larvae were observed in any of the fruit assessed indicating the efficacy of the repeated organic insecticide applications (*Bacillus thuringiensis* & *Cydia pomonella granulovirus*) used in early December in preventing larval tunnelling but not fruit damage. The weevil damage is believed to have been initiated by garden weevils (*Phlyctinus callosus*) as this was the only species - all be it in relatively low numbers - observed during the production season at the 'Rookwood' conservation biocontrol field site.

Although preliminary analysis of fruit damage indicated no significant difference in the total damage observed between the three interrow treatments (H = 11.780, P = 0.203), differences in damage type were significant. Significant differences in the levels of codling moth stings (H = 5.897, P = 0.024) and apple scab lesions (H = 9.000, P = 0.028) differed between the three inter-row treatments, with higher levels of damage observed within the exotic flowering meadow inter-row treatment. No difference was observed between the standard grower sward and the native species mix.

No significant difference was observed in total damage (H = 5.048, P = 0.080), weevil damage (H = 3.140, P = 0.208) or codling moth stings (H = 3.849, P = 0.146) between the three tree-line treatments. However, a difference was observed in apple scab incidence (H = 11.083, P = 0.004) with greater scab incidence in the compost tree-line treatments. No significant interaction was observed between the interrow and tree-line treatments in any of the damage types observed or total damage occurrence.

Regional trial and demonstration sites

Changes to soil properties and detailed fruit quality outcomes across the three regional trial sites are presented in Appendix 3. The demonstration sites in each region have provided growers with a basic understanding of the impact of different soil ameliorants on soil health and nutrition. Further investigation into the establishment of these treatments and how they may impact growers economically would be beneficial. There is a definite improvement in soil when introducing mulch, compost and cover crops, but it is unknown how viable they are in a grower's bottom line. A summary of key learnings from the regional trial sites is presented below:

- It is extremely difficult to establish natives in the orchard without a long lead in time (at least two years of intensive work to remove the seed bank) as their slow growth rate makes it difficult for them to compete. Ensuring adequate irrigation in the establishment phase is critical.
- Autumn is preferable for sowing of both inter-row and tree-line treatments as access in Spring can be difficult due to wet soil conditions, and growers cannot avoid tractor traffic in the inter-rows in Spring.
- The compost and grass/legume treatments in the tree-line were a physical addition of organic material, which break down to organic carbon in the system. Soil carbon can improve the activity and biodiversity of microorganisms in the soil.
- The tree-line grass/legume treatments showed the highest microbial respiration rate. Keeping the soil bare exposes organisms to temperature fluctuations and soil erosion; ground cover in the tree-line is important to protect soil microbes.
- Herbicide needs to be applied regularly throughout the season to maintain a bare strip in the tree-line - constant chemical application is a large expense for the grower, a health risk for workers and herbicide resistance can occur.
- Compost/mulch treatment is effective in suppressing weeds, but success of this treatment was dependant on the amount of coverage and 'thickness' of application - in areas that didn't get an even coverage, weeds and grasses were able to establish under the trees.
- One drawback of compost is the rapid break down and need to re-apply each season, which is costly for the grower.
- Tall tree-line cover crops that grow to heights reaching the bottom branches of the tree can create an easy access for pests, create a more humid environment for trees and can pose a significant bushfire risk.
- Growers found it difficult to allow the inter-row to grow freely and allow plants to flower and seed. This meant that it was difficult to see the full benefits of the inter-row sward treatments. A key learning from this is that it is a change in mind-set for growers to allow the inter-row sward to grow to a height without mowing, and an informative process will need to happen to support growers to adapt in practice change in this regard.

Integration of SINATA with Swan Systems platform

SWAN set up and training

Full results and discussion of the integration of SWAN with SINATA is provided in Appendix 4. SWAN maintained regular contact with growers. This involved calls with the growers to discuss the data and recommendations produced by the system, and at least three detailed reviews with each grower during the season. SWAN support was available at any time to answer questions or check data feeds. The detailed reviews were conducted at strategic times in the season via Teams conference calls and used screen-sharing. The first detailed review was in December and was conducted to discuss and review the setup of the sites, irrigation system parameters, data feeds, etc. This review was to ensure the account was calibrated and "ground-truthed" against probes, grower feedback, etc. This first session was also the first training session, familiarising the grower in the key aspects of the SWAN program, namely SWAN's soil moisture modelling principles, interpreting the soil moisture charts, and using SWAN for daily scheduling. This session occurred prior to commencement of irrigation in 3 of the 4 orchards.

The second review was timed to occur 2-3 weeks after irrigation-proper had begun. The session reinforced the subjects and training provided in the first and was also used to cover more advanced questions from the growers, and for SWAN to fine tune crop water use modelling to fit the timings of cultivars in each block. The final session was a post-season wrap-up with the Tasmanian Institute of Agriculture represented by Nigel Swarts. This session took in a detailed analysis of the season's data, reviewed water usage, timing of fertiliser application, drainage and the SINATA predictions for the N-balance of selected sites, as shown in the report. It included a discussion about the usage of SWAN during the season, which is covered below. A full review of the season's data and settings typically forms the basis for rolling over the SWAN setup for the next season. The initial season thus forms the blueprint, and subsequent seasons require much less direct support.

Usage patterns

All the growers regularly logged into and reviewed their accounts in SWAN, though the frequency of logins varied. SWAN's login data (anonymised below, and in no particular order), shows the number of distinct days on which each of the growers logged into the platform. Logins were concentrated in the irrigation months. There were different approaches to using the system. A common theme was that the growers reported they were keen to see how the system worked and to be sure they trusted it before directly following the irrigation recommendations. All reported that SWAN represented an accurate model of the irrigation requirements for their blocks and that seeing SWAN's outputs gave them confidence in the decisions they were making. Likewise, they stated that they would have greater confidence to use the system to guide irrigation in subsequent seasons.

Grower 1 logged into SWAN almost daily and reported great confidence in the SWAN dashboard, and that it provided good guidance and confirmation that he was on the right track for his irrigation practice. Grower 2 ran his standard approach for the season and reported being happy to monitor progress with SWAN and see how it compared with the standard approach. He logged into SWAN about once per week during the irrigation period and regretted being especially time-poor this season due to various infrastructure issues. He was very interested to run SWAN for another year and use SWAN more fully to inform irrigation decisions.

Grower 3 reported being satisfied with the accuracy of SWAN's soil moisture predictions and regularly accessed the system to confirm moisture status. Irrigation requests were communicated to staff via the app. His aim would be to follow SWAN's recommendations fully next season. Similarly, Grower 4 acknowledged the confidence that SWAN Systems gave him in irrigation decisions.

Water use

Due to rainfall, there was no significant irrigation at any of the properties before December 2022. Irrigation had typically finished by late March or early April 2023. Water use and rainfall during the period of irrigation is shown in Table 5.

Table 5. Water use and rainfall during period of irrigation (Dec 2022 – Apr 2023)

State, Region	Orchard	Rain (mm)	Irrig (kL/ha)	Min (kL/ha)	Max (kL/ha)
WA, Manjimup	Fontanini	187	3600	3225	3730
SA, Lenswood	Oakleigh	189	2950	1935	3553
Tas, Spreyton	RW Squibb	257	1650	1300	2020
NSW, Batlow	Tingira	418	540	80	1400

Drainage

Understanding drainage plays a key role in ensuring that fertiliser (nitrogen in particular) and irrigation are applied at appropriate times. Excessive drainage following fertiliser application may result in environmental discharge of nutrients which is both an unnecessary cost and not in keeping with best-practice environmental stewardship. Rainfall and irrigation both potentially contribute to drainage. However, the timing of irrigation was appropriate for all the orchards. Only rainfall potentially contributed to drainage. The SINATA tool provides an annual estimate of drainage for each location based on historical weather data, soil types and other variables. This can help to inform planning of the timing and quantity of fertiliser application, but actual timing will depend on the specific season. SWAN calculates drainage daily based on actual weather, irrigation, crop water use and daily soil moisture balance. Table 6 summarises the drainage data estimated or calculated by the different methods. This data highlights the variability of rainfall (and resultant drainage) from season to season.

Table 6. Average drainage (mm) for each location estimated by SINATA (long term annual average) and calculated by SWAN for the 2022-23 season, and for the period of fertilizer application during the 2022-23 season

State, Region	Orchard	SINATA (annual)	SWAN (season)	SWAN (fert app.)	Fert apply Period
WA, Manjimup	Fontanini*	277	700	300	Aug – Apr
SA, Lenswood	Oakleigh	300	130	0	Dec – Apr
Tas, Launceston	RW Squibb	175	130	79	Sep – Apr
NSW, Batlow	Tingira	315	1150	315	Oct – Apr

Nitrogen fertiliser applications

The N applications were recorded in SWAN on a weekly basis, either from fertigation system records, or manually from grower-reported records. Two of the four farms provided fertiliser records after the season had concluded. N applications were then aggregated into five main periods of application to conform to the SINATA input requirement, which allows five applications for planning purposes. In some cases, this meant that continuously or frequently applied fertiliser was aggregated to a date corresponding to the middle of an interval of application. The amount of nitrogen applied varied greatly between orchards and cultivars. This was presumably driven by agronomic recommendations (tree age, cultivar, yield targets, soil type, etc.), historical practice, and capacity to apply the fertiliser under the conditions. All the orchards were irrigated appropriately given the weather and evaporative demand. The timing of rainfall cannot be predicted but the SWAN's soil moisture forecast can give some indication of whether irrigation will be required, and whether drainage may occur following specific rain forecasts. This in turn might guide the timing of N application, particularly where large quantities of N were applied during or prior to periods that are typically wet.

Outputs

A summary of the project's outputs (extension events and Australian Fruit Grower magazine articles) can be found In Table 7 below. A more detailed summary of project outputs including monitoring data collected to provide evidence of outputs as per the project's M&E Plan (where applicable) can be found in Appendix 5.

Table 7. Output summary

Output	Description	Detail
TIA web page	**Audience:** Apple & Pear industry; **Content:** general project information & targeted apple grower information (soil your undies) & news	4 Web pages General project page & Soil your Undies campaign pages
Web	**Audience:** Apple & Pear industry; **Content:** Resources for growers	26 web page articles & resources hosted by APAL website on PIPS pages and news pages
YouTube Videos	**Audience:** Apple & Pear industry; **Content:** Project updates; Grower interviews; Events;	13 YouTube videos produced by Project Coordinator in conjunction with APAL and TIA. 2 YouTube videos produced by Susie Murphy-White (WA)
Social Media	**Audience:** General audience; apple & pear growers, researchers, advisors, peak industry bodies, allied commercial businesses **Content:** Project updates; Events; Links to articles & videos;	65 posts by APAL, Project coordinator & TIA. Content from AP19006. Output on main social media platforms: Facebook, Twitter, LinkedIn. Instagram
APAL Industry Juice *(E-news)*	**Audience:** Apple & Pear industry **Content:** Project activities, highlights, events.	22 articles in collaboration with APAL & Project coordinator. Content from AP19006. Output as E-news to apple & pear growers, researchers, advisors, peak industry bodies, allied commercial businesses
Printed /online Media & Industry E-News	**Audience:** National and Regional Apple & Pear Industry; Regional general audience; Irrigation industry **Content:** Project activities, highlights, events.	8 articles published in Australian Fruit Grower with content provided by TIA in collaboration with Project Coordinator 9 articles in other Industry Journals; Regional publications; Industry E-news
Events *(Field days, conferences, workshops, forums, open day, community event)*	**Audience:** Majority of events targeted at apple & pear growers, advisors & agribusiness; Other events for general audience; research community. **Content:** Technical & general information on project outcomes	22 events • 15 Field walks/field days; • 5 Conferences, forums, technical days • 2 Community events
Apps	**Audience:** Apple & pear growers, advisors & agribusiness, researchers **Content:** SINATA app by SWAN systems	
Grower Guide	**Audience:** Apple & pear growers, advisors & agribusiness, researchers **Content: Grower guide to orchard**	Appendix 7

	floor management		

Outcomes

A summary of the project's outcomes can be found in Table 8 below. A description of outcome achievement and evidence to support the achievement is detailed against the outcomes identified in the project's M&E Plan. More detailed statistics of reach and evaluation against each outcome are provided in Appendices 5 and 6 respectively.

Table 8. Outcome summary

Outcome	Alignment to fund outcome, strategy and KPI	Description	Evidence
Short term: Orchardists & advisors with increased knowledge of key soil health indicators for apple and pear orchards	**Outcome 1 Industry and global competitiveness is improved by reducing the average cost per carton,** Strategy 1.3 Improve soil health & increase knowledge of beneficial microbes in orchard management. Primary research project: AP19006	Progress was made through as much industry engagement as possible (see list of outputs above and in Appendix 5) leading to increased knowledge on sustainable orchard management practices & soil health Using trial sites across Australia's main apple growing regions as demonstration sites for orchard walks proved successful for engaging industry. One of the key outcomes of the Future Orchards Spring Walk (Southern Loop) was to demonstrate the value of the www.applesoils.com website whilst in the orchard.	Soil your undies campaign, multiple orchard walks including the Southern Loop (Spring 2022, presented by Nigel Swarts), magazine articles, start of project survey, literature review. Outreach activities listed above
Short term: Orchardists & advisors with increased knowledge of sustainable orchard management practices and their impact on soil health, resilience, orchard productivity and fruit quality	**Outcome 1 Industry and global competitiveness is improved by reducing the average cost per carton,** Strategy 1.3 Improve soil health & increase knowledge of beneficial microbes in orchard management. Primary research project: AP19006	Developed recommendations for cultural practices that support orchard biodiversity for low input nutrient requirements and pest & disease management. Recommendations made here and provided through various platforms on orchard floor management practices will improve resilience and have an immediate productivity/quality impact.	Outreach activities listed above
Short-term: Orchardists & advisors with increased awareness and skills in utilising the web based SINATA tool to manage water and nutrients in the orchard	**Outcome 3 The value of the average bin has risen, resulting in improved industry profitability** Strategy 3.1 Improve quality consistency and percentage of Class 1 fruit per hectare	Decision support tools developed, trialled & training of advisors/ grower conducted for improved decision-making & monitoring of orchard precision and sustainable management practice recommendations and implementation. SWAN Systems platform was installed on five growers' farms representing each of the major apple growing regions. SWAN integrates all existing hardware such as soil moisture sensors,	SINATA tool published on APAL and Hort Innovation websites, early presentations on SINATA were completed within this project. Integration with Swan Systems software on five farms allowed comparison of outputs between SWAN and SINATA. Presentations made to each growing region on the SWAN platform (from final evaluation, Appendix 6) Integration of SINATA into the

		weather stations and historical data into their platform for each grower's farm. The crop factor model to provide advice on irrigation management was compared to information from the SINATA tool.	Swan Systems online platform has been well received by the trial farmers for it's ease of use, accuracy (alignment with "what I thought") and support provided by the company.
Medium Term: Orchardists implementing sustainable orchard management practices	**Outcome 1 Industry and global competitiveness is improved by reducing the average cost per carton,** Strategy 1.3 Improve soil health & increase knowledge of beneficial microbes in orchard management. Primary research project: AP19006 **Outcome 3 The value of the average bin has risen, resulting in improved industry profitability** Strategy 3.1 Improve quality consistency and percentage of Class 1 fruit per hectare	Informed understanding of interactions between cultural/biological/chemical IPDM & soil health practices leading to implementation of recommended sustainable orchard practices. Advisors & consultants are confident in providing sustainable management practice advice to apple and pear growers developed from PIPS3. Growers have adopted recommendations and tools of the PIPS3 Program and are able to demonstrate benefit through yield/quality, profitability and resilience gains.	Soil your undies campaign, multiple orchard walks, magazine articles, start of project survey (from final evaluation) A shift in thinking about soil health and chemical use. How we can do things more beneficial for the environment, and then how this links to the consumer experience
Medium term: Orchardists confident in using the web-based SINATA tool to help manage orchard irrigation and nutrition	**Outcome 3 The value of the average bin has risen, resulting in improved industry profitability** Strategy 3.1 Improve quality consistency and percentage of Class 1 fruit per hectare	Industry platforms for greater collaboration on productivity, irrigation, pests and soils are valued by industry growers/advisors as trusted sources of scientifically robust information & recommendations. Decision support tools adopted by industry: Pear irrigation scheduling, SINATA for apples irrigation scheduling & nutrient budgeting & Apple crop-load tool. Farms with the Swan Systems platform installed were used as demonstration farms for extension at the end of the project.	Grower hosts of Swan Systems will facilitate uptake and adoption. (from final evaluation) SINATA trial farmers see the value proposition of the tool, however, there is concern amongst some respondents that growers may not be willing to pay a subscription to SWAN Systems to access the tool. The benefits and economic value need to be clearly articulated and promoted. All growers are looking forward to trialing the tool again over the next season to evaluate the benefits of varying seasonal conditions. All are enthusiastic about being local ambassadors for the tool.
Long-term: A sustainable Australian apple and pear industry with an improved environmental footprint: This project supports Pillar 3 (Industry	**Outcome 1 Industry and global competitiveness is improved by reducing the average cost per carton,** Strategy 1.3 Improve soil health & increase knowledge of	**The apple and pear industry has adopted tools and management practices required to operate orchards that:** Are resilient to climate variability and weather extremes; Use resources efficiently and sustainably; Apply biological and	(from final evaluation) AP19006 has raised awareness on the concepts of soil health and its relationship with nutrient availability and water management, however, it has not necessarily provided confidence to growers that making orchard floor management changes will be

sustainability) of the Apple & Pear Industry Strategy 2018-2023, as well as Pillar 4 (Capability and capacity) and the Hort Innovation investment priorities “Support industry efficiency and sustainability” and “Improve productivity of the supply chain through innovative technologies	beneficial microbes in orchard management. Primary research project: AP19006 **Outcome 3 The value of the average bin has risen, resulting in improved industry profitability** Strategy 3.1 Improve quality consistency and percentage of Class 1 fruit per hectare	cultural solutions in the management of pests, disease and nutrients; Drive product quality and business profitability through use of automated/ mechanised advanced technologies along the supply chain; and Produce a low environmental footprint and sustainable product that meets consumer preference and expectations.	beneficial to their business (yield, quality, or profitability). There remains a need for economic analysis of the value proposition of the trialed interrow and tree line managements in their farming system. There is agreement across the board that soil health takes time to respond to changes in management and therefore evaluate, but commencing the conversation and having focal points in the regional demonstration sites has facilitated this foundational process.

Monitoring and evaluation

The PIPS3 Program Final Evaluation interview process was conducted in June and July 2023 by the PIPS3 Program Coordinator. The full report can be found in Appendix 6, and a summary is presented below.

For AP19006, Overall, 24 telephone interviews were undertaken (Researcher (n =2), Grower (n = 13), Service Provider (n = 9)) each interview averaging a 20 minute in duration. Eleven questions were asked, seven of these structured with a rating response required between 1 (most negative) and 5 (highly positive), with an opportunity to provide an extended comment to support the rating response. Most often, the respondents were highly motivated to expand upon the ratings provided. Four questions were open-ended to gain feedback and insight in a less formal and structured approach. The interviews conducted for this project ensured good representation across the regional areas in which both trial and demonstration activities were being conducted.

The interview process of both quantifiable and qualitative questions was used to evaluate effectiveness, relevance, process appropriateness, efficiency and legacy KEQ of the PIPS3 Program, and the specific program/project questions underpinning these (refer to the table below for questions that were specifically developed by the AP19006 project). The design of the questions enables analysis of responses at both a program and project level so that all users of the evaluation report can apply findings to both program and individual project level questions.

AP19006 achieved a “Strong” performance rating across all KEQ from the final evaluation interview process, although the long-term legacy rating was borderline at an overall rating of 3.8, with a moderate rating for likelihood of adoption in the next ten years rated as medium (3.7).

Table 9. Key Evaluation Questions

Key Evaluation Question	Project performance
EFFECTIVENESS: *To what extent has the PIPS3 Program addressed the objectives, research agreement achievement criteria and identified outcomes/ outputs?*	Respondents were confident that the project achieved its objectives and activities were executed as expected, however the delayed establishment of the soil health sites in season one had an impact upon the overall outcomes of the project. There was substantial caution expressed on the practicalities of certain interrow (native species) treatments and cost of tree line (mulch/compost) treatments trialed, and an underling belief that other industries had already conducted extensive research into these strategies, and these needed to be looked at more thoroughly.
RELEVANCE: *How relevant were the research outcomes/ outputs to the needs of apple and pear growers, advisors, and industry stakeholders?*	The project was considered strongly relevant to both growers and advisors who support them. There was certainly interest expressed on the desire to be more sustainable and having demonstratable evidence to show consumers. It was evident that growers and advisors appreciated the “theoretical” information extended by the project on the importance and likely benefits of good soil health. However, the project did not provide tangible information to growers on how the soil health treatments benefited fruit yield and quality, some respondents expressing that the project needs to concentrate on the soil, nutrient, water, and insect/pollinator benefits, and leave fruit parameters out. Many respondents acknowledged that soil health is an area of research requiring a much longer timeframe than three years. The SINATA tool integrated into Swan Systems was immediately relevant to the irrigators who trialed the tool.
APPROPRIATENESS: *How well have intended audiences been engaged in the project?* *To what extent was the PIPS3 Program Communications and Extension Plan appropriate and had*	The project was considered strong in developing materials and engaging with the industry, especially through local demonstration and the final roadshow events, or where programmed in Future Orchards® walks. However, respondents expressed that the general information on soil health and likely benefits now needs to be underpinned by resources and extension that is backed by data relevant to them, including the economics.

an impact upon the target audience?	In Tasmania, there is acknowledgement that the local TIA team is very accessible to the industry, and many will "pick-up the phone" to ask a question when the need arises. Ongoing contacts list restriction for *Industry Juice* prevail. There are growers and advisors who do not receive IJ, but they receive local organizational materials (i.e., FGT, FGV, Pomewest). While the volume and content of information was regarded as high quality, issues with grower time pressures to read and engage is a concern, primarily raised by advisors.
EFFICIENCY: ***What efforts did the PIPS3 Program partners make to improve efficiency?***	The AP19006 respondents rated the PIPS3 Program as strong on its performance to deliver an efficient approach to research, and communication and extension of the research. Issues were raised that need to be addressed for PIPS4. These are the development of standard protocols and processes for demonstration sites in trial design and the collection and management of data. Regional coordinators suggest that standard templates and a schedule of delivery expectations is needed at commencement to ensure that the integrated requirements across projects (in PIPS3 this was AP19006 & AP19002) are clear, and they know what has to be done and when it needs to be done.
LEGACY: ***Are there signs that the PIPS3 Program will influence apple and pear growers in the future?***	AP19006 has raised awareness on the concepts of soil health and its relationship with nutrient availability and water management, however, it has not necessarily provided confidence to growers that making orchard floor management changes will be beneficial to their business (yield, quality, or profitability). Most respondents are waiting for data-driven evidence and economic analysis of the value proposition of the trialed interrow and tree line managements in their farming system. There is agreement across the board that soil health takes time to respond to changes in management and therefore evaluate, but commencing the conversation and having focal points in the regional demonstration sites has facilitated this foundational process. Improvements in grower and advisor consultation to inform trial design were suggested by a number of respondents. They believed this would provide a more practical and realistic element to the treatments applied, and also increase confidence in the concept of orchard floor management longer-term. Both are seeking more information on long-term management of the treatments, especially to better evaluate the labour, water, and nutrient input implications, both positive and negative. SINATA trial farmers see the value proposition of the tool, however, there is concern amongst some respondents that growers may not be willing to pay a subscription to SWAN Systems to access the tool. The benefits and economic value need to be clearly articulated and promoted. All growers are looking forward to trialing the tool again over the next season to evaluate the benefits of varying seasonal conditions. All are enthusiastic about being local ambassadors for the tool. The idea of extending more of the 'known' research and experiences from other industries was raised by respondents who saw a gap in industry extension. While they know the research has been undertaken, they believe there is a gap in apple and pear extension of the outcomes of R&D over the past 5-10 years but acknowledge this is not the ongoing role of PIPS as an R&D program.

Recommendations

Soil health and sustainable apple production

The knowledge gained from the intensive research trials and regional demonstration sites as well as the review of the literature has shown that it is possible to move towards a more regenerative approach in orchards by working with natural systems and processes to build optimum soil and plant health, without the need to discard the best of conventional farming methods, to maintain or improve production levels and quality. Natural systems allow for an increase in biodiversity, providing natural control of pests, and building soil health. It is evident that biodiversity, both above and below ground, is the key in the development of ecosystem services that enable a move away from reliance on synthetic fertilisers and pesticides.

The orchard floor is a complex environment that has a major influence on crop productivity and quality. The plants of the orchard floor provide a home and food source for pollinators, predators, and other beneficial insects above ground, and strongly influence the diversity of arthropods (insects, millipedes, spiders, and earth worms) and microbes at the soil boundary and below. Soil biology (macro- and meso-arthropods and micro-organisms) is the key to nutrient cycling, in addition to influencing soil physical properties such as aggregation and water infiltration. A diverse orchard floor can give the orchard resilience and balance both above and below ground, allowing the orchard to resist or rebound rapidly from disturbances or the impact of climatic events such as high rainfall or drought.

Species selected for the orchard floor, whether in the inter-row or tree-line, need to be robust and resilient to traffic, but not invasive or competitive, and provide shelter and a food source for beneficial arthropods without creating an environment conducive to pest species and disease. Understanding the importance and complexity of the interrelationships that occur within the orchard floor, both above and below ground (Figure 1), and nurturing these relationships will increase orchard resilience and long-term productivity.

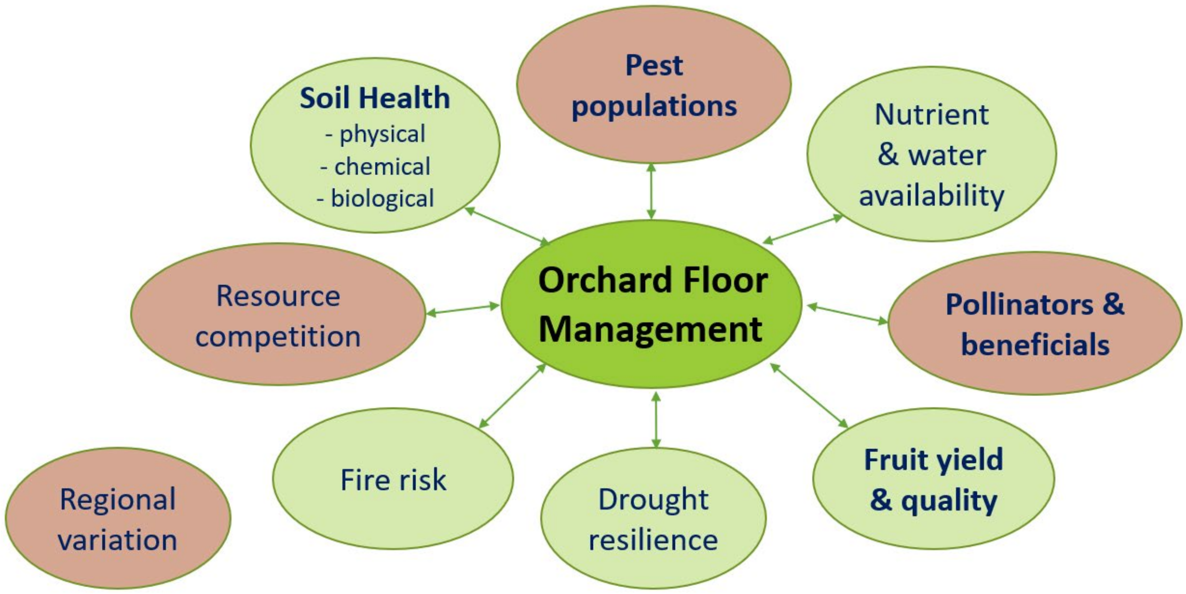

Figure 1: Bringing it all together – the complex inter-relation*ships involved in orchard floor management*

Competition

Many orchardists are concerned about competition for water and nutrients from ground cover plants on the orchard floor, particularly in the tree-line, reducing yield and fruit quality. However, the results from both the intensive research site and the regional demonstration sites suggest that the impact of cover crops in the tree-line is not necessarily detrimental to fruit quality. Further studies examining tree-line cover crop mixes and their vigour will alleviate this concern. Another option is the use of summer dormant species, however in an irrigated orchard these species do not always become dormant.

There is also concern that a vegetated tree-line provides habitat for pest species and tall vegetation growing up into the lower branches of the trees can create a humid microclimate, thus increasing disease pressure. Managing the tree-line vegetation by mowing, or even an occasional herbicide application, can ameliorate these problems.

Managing pests

Several lessons arose from this project in relation to management of pests within the orchard. These are reported in the final report for project AP19002, but include:

- arthropod species change with plant species,
- insect numbers can be altered by manipulating ground covers,
- costs and benefits for pest management can be quantified but may be site specific,
- pesticide applications can undo any improvements in numbers of beneficial insects.

Selection of orchard floor species

Any ground cover, even weeds, as a living mulch is better than bare soil, but the more diverse the plant species on the orchard floor, the greater the diversity of root architecture (fibrous, spreading and tap roots). There is evidence that the more diverse the plant species, the greater the diversity in soil organisms.

A living mulch dominated by perennials is logical in an orchard situation, and many growers have adopted a version of living mulches with a permanent sward, normally grasses or a grass/clover mix, in the inter-row, even though a bare strip under the tree row is normally still maintained. This enables the inter-row sward to be maintained without the need for reseeding each year. Use of annuals requires either reseeding every season, which adds to the costs of maintaining the orchard floor, or allowing the annuals to flower and seed. However, growers are used to maintaining a 'tidy' orchard with regular mowing and find it difficult to leave the inter-row to grow freely so plants are able to flower and seed. For a practice change such as this to succeed, a change in mind-set will be required for growers to allow the inter-row sward to grow to a height without mowing, and growers will require support to adapt.

There are multiple criteria to be considered when selecting species for planting in the orchard inter-row and/or tree-line, and these are listed in Table 10.

Table 10: considerations when selecting plant species for living mulches in the orchard inter-row and/or tree-line.

Inter-row	Tree-line
- easy and fast to implement	- easy and fast to implement
- rapid establishment of sward	- established rapidly
- ease of maintenance after establishment	- longevity and maintenance
- longevity	- organic matter source
- range of root architecture	- food source/habitat for beneficials
- traffic resilience	- improved soil structure & water infiltration
- provide sufficient grip for tractors	- improved water & nutrient availability
- aids in reducing soil compaction	(no competition with tree crop)
- improves water infiltration	- increased soil biology
- nutrient recycling	- maintain/improve fruit quality
- food source / habitat for beneficial arthropods	- sustainability

In this project, native species failed to establish successfully in the inter-row in all regions. One problem was the inability of native species to compete with weeds and pasture grasses due to their slow growth rate. For native grasses and herbaceous species to have any chance of success in orchard inter-rows a long lead in time of at least two years with intensive herbicide application would be required to remove the seed bank from the soil. Apart from the intensive labour requirements, this would be impractical for most orchards.

Although impractical in the orchard inter-row, there is still potential to introduce the benefits of native flowering plants in relation to habitat and food source for beneficial insects, particularly native insect species. Potential methods for introducing native flowering species include hedge rows around the orchard and/or between blocks, or in high-density orchards planting every 10th row to native species.

Increasing soil organic matter and biology

Organic matter is a vital component of healthy soils, and the amount of organic matter in a soil is determined by the balance between accumulation and loss through decomposition or oxidation. The rate of decomposition and accumulation of soil organic matter is dependent on multiple factors including soil type, temperature, moisture content, aeration, and biological activity; but conversely, soil organic matter can modify many of these soil properties.

It is well recognised that soil fertility can be improved by regular additions of organic matter and that microbial biomass is central to organic matter cycling in soils - the higher the level of microbial activity the higher the rate of mineralisation of organic matter.

As well as providing a food source for soil microbes, organic matter acts a sponge, aiding in water infiltration and increasing drought resilience. Incorporation/addition of organic matter is a proven method of building the soil.

In new orchards the process of increasing soil organic matter can be started by incorporation of a high-quality compost prior to planting. In established orchards the following practices can aid in increasing soil organic matter levels:

- Addition of composts in both the inter-row and tree-line. Specialised spreaders for application to the tree-line will aid in minimising labour input.
- Application of coarse mulches or straw in the tree-line.
- Cover crops in the inter-row.
- Permanent sward in the inter-row – perennial species avoid the need for annual resowing.
- Living mulches, ideally a mix of grasses and legumes in the tree-line.
- Throwing the mowing clippings onto the tree-line.

As root exudates from actively growing plants provide a food source for soil microbes, the abundance and diversity of the soil microbial community is likely to be increased by ensuring full ground cover with a range of plant species. There is normally a decline in carbon availability with increasing soil depth, and this has been attributed to the vertical soil distribution of microbial communities. The dominant factor influencing microbial biomass and activity at different depths appears to be plant root distribution, with the presence of deeper rooting species resulting in higher microbial populations and diversity deeper in the soil profile.

In the short two years that our treatments were established in this project, differences were observed in both fungal and bacterial communities between the inter-row and tree-line treatments. While there were no measurable treatment effects on soil microbial carbon, there was an increase in soil microbial carbon and bacterial species richness in the wetter compost plots, indicating that water may be a limiting factor that reduced potential effects of the applied treatments.

The different components of this project are all in agreement that soil life can be increased by increasing organic matter in soil. Practices such as reducing herbicide use and adding organic matter to the soil will aid in increasing soil life. While addition of compost and/or mulches such as straw or mower clippings plays an important role, actively growing plants are critical to healthy microbial populations and an active food web within the soil that provides a high level of nutrient cycling and an adequate supply of plant available nutrients.

<u>Have we seen an improvement in soil health?</u>

While there is no set definition of what constitutes the optimum 'healthy soil,' we know that soil health is related to factors such as physical structure, aggregate size, water retention and infiltration, soil chemistry and availability of nutrients, and biodiversity including microbe and invertebrate (arthropod) populations.

Building up good soil health is a gradual process. Depending on the soil type and initial state of 'health', some benefits to any management changes aimed at improving soil health and resilience may be observed within the first 12 months, but it often takes several years before noticeable improvements can be observed. Healthy soil attributes to work towards include:

- good levels of organic matter,
- good populations of earthworms, macro- and meso-arthropods,
- thriving populations of micro-organisms - bacteria, fungi, protozoa, and nematodes,
- nutrient cycling to provide plant available nutrients,
- 100% ground cover with a diverse mix of species,
- small & large pore spaces for air & water,
- good soil aggregation,
- good water infiltration rates (>100 mm/hr),
- absence of a compaction or crusting layer.

In spite of the relatively short time frame that treatments were implemented, there were differences in soil microbiology observed between treatments, and soil physical characteristics such as soil bulk density, hydraulic conductivity and aggregate stability improved. There were also increases in level of several nutrients observed in some of the tree-line treatments, with the compost and grass/legume treatments appearing to be the most beneficial. However more time is needed to quantify these changes.

What can growers do to check the state of their soils ?

Whatever the state of your soil, there are many simple ways of keeping track of your soil health, from commercially available soil test kits to simple tests using everyday equipment. What you are looking for is change (hopefully positive!) over time. Remember that if you change the way you manage your orchard floor, results won't be seen immediately – so to know whether the change was beneficial you need to monitor what is happening over time.

Make sure that you are consistent in the time of year that you take your samples, the way you take a soil sample and the lab you use if you are sending samples for laboratory analysis. But there are multiple tests that you can do yourself, including looking at biological activity using simple field kits, such as Solvita, that measure soil respiration or carbon dioxide production.

And most importantly, remember that a spade is one of your most valuable tools to see what is happening in your soil - dig a hole so you can see the subsoil:

- Are old inactive roots decomposing (evidence of bacteria and fungi);
- Does the soil smell earthy (actinomycetes);
- Is the soil dark in colour (soil organic carbon);
- Is the soil well structured (soil aggregation);
- Is there evidence of bioturbation (macrofauna – earthworms and beetles);
- store a representative sample of soil in an ice cream container – do the same in subsequent seasons to see how the physical character of your soil changes.

Look for evidence of organisms

- Count earthworms – 10-12 per spadeful indicates good soil health;
- Set pitfall traps for macro and mesofauna;
- Examine nodules on legume (clover) roots – a bright pink/red colour indicates active nitrogen fixing bacteria;
- Rapid deterioration of wooden stakes is a good indicator of fungal activity (the cellulose in the wood provides a food source for fungi), or bury some cotton undies and check for decomposition after 8-10 weeks.

Recommendations for future studies

1. Continue monitoring the existing PIPS3 intensive trial sites, with a focus on tree-line treatments.
2. Examine tree-line cover crops and their vigour for effective on tree growth, crop yield and fruit quality.
3. Examine inter-row mixes that support a self-sustaining population of flowering annual and perennial species that encourage insect guilds that provide pollination and predatory services.
4. Identify optimal mowing times / methods (e.g. alternate rows) to support beneficial insect guilds.
5. How do we shift the orchard from a bacteria dominated environment (changes to bacterial populations) to a mycorrhiza dominated environment (what species, rates of colonisation?).
6. What influence do changes to soil health have on fruit quality?

- What are the influences beyond simple and traditional fruit quality measures?
- Apply research tools such as e tongue and e nose to fruit quality evaluation.

7. Tree physiological impacts:

- Cover crops and compost addition should improve tree water availability over time due to increased soil carbon/organic matter and benefits to soil structure and water infiltration/retention.
- Potential effects of orchard floor treatments on fruit and leaf tissue carbon isotope ratios may indicate improved resilience of the growing system to tree water deficit.

8. Develop a soil health tool kit for growers:

- Advance the BMPs for cover crops to growers determining benefits/changes simply and cost effectively
- Easy to adopt methods and how to monitor benefits/changes.

9. Form distinctions between the functional purposes of cover crops in the tree-line vs inter-row

- Tree-line: tree health, accessibility to water, soil water holding capacity, nutrient recycling, mycorrhizal activity;
- Interrow: attract beneficials, alterative food source for pollinators, habitat for predatory insects, overcoming soil compaction issues, holding soil together on slopes.

10. Economic analysis: cost benefits of cover cropping, modelling of soil carbon changes and benefits, determining resilience and economic benefit of a more resilient orchard.

Integration of SINATA with SWAN Systems

SWAN would require the apple nutrient uptake model to be added to its library for full planning functionality. There are two fundamental differences between SINATA and SWAN:

1. SINATA is a pre-season planning and scenario-testing tool, whereas SWAN covers some planning functions, but is intended to be used daily (or frequently) for live monitoring and decision support.

2. SINATA has a model for calculating soil nitrogen balance; SWAN does not.

The first difference is just a matter of purpose – essentially planning can only be done based on averages. Growers must then adapt to each season's unique challenges (weather events, water availability etc.). SWAN potentially covers both sides of the divide here. The second difference is that SWAN does not currently provide for soil nutrient analysis or modelling of soil nitrogen balance. SWAN's estimates of drainage may be sufficient to give an indication of the timing of fertiliser application relative to actual drainage events, and thus also of environmental costs of N-application. SWAN is already developing a data hub to collect, store and analyse a wide range of data feeds and facilitate custom display options. With this tool in place, it will be relatively straightforward for SWAN to provide a native overlay of nutrient applications on the annual soil moisture history chart.

To include the full SINATA functionality in SWAN would require dedicated human resources to increase the capacity of SWAN's development pipeline. The models for N-balance calculations would need to be built into SWAN (e.g. N in crop offtake, leaf-fall, mineralisation and volatilisation dynamics of specific soils, the leached N fraction, etc.) Development on SWAN's side would need to consider the system architecture to house the data, including soil nutrient analysis, and the ability to add base data for new regions. The combination of planning tools and calculation of N-balance models based on current season live data would be a unique and powerful tool for the management of pome orchard soil health and plant nutrition.

Refereed scientific publications

Journal article

Tan BZ, Swarts ND, Close DC. **Decomposition of Apple (Malus domestica) Plant Residue and Uptake of Residue-Derived N** JOURNAL OF SOIL SCIENCE AND PLANT NUTRITION **22**(3):3033-3044 Sep 2022 (Journal Article)

Hardie M, Green S, Oliver G, Swarts N, Clothier B, Gentile R, Close D. **Measuring and modelling nitrate fluxes in a mature commercial apple orchard** AGRICULTURAL WATER MANAGEMENT **263**:12 pages Article Number ARTN 107410 01 Apr 2022 (Journal Article)

Tan BZ, Swarts ND, Close DC. **Interactions of nitrogen, phosphorus and potassium fertilization on 'Gala' apple tree nutrition, fruit yield and quality** Acta Horticulturae. International Society for Horticultural Science (ISHS). 261-268. Jan 2022 (Academic Conference)

Tan BZ, Close DC, Quin PR, Swarts ND. **Nitrogen use efficiency, allocation, and remobilization in apple trees: uptake Is optimized with pre-harvest N supply** Frontiers in Plant Science **12**:1-15 Article Number 657070 2021 (Journal Article)

Chapter in a book or paper in conference proceedings

Swarts N, Green S, Hardie M, Tan BZ, Close D. **Apple tree nutrition for improved productivity - SINATA** Future Orchards National Tour, 24 Jun 2020 - 24 Jun 2020. Future Orchards National Tour. Apple Pear Australia Limited. 2020 (Academic Conference)

Intellectual property

No project IP or commercialisation to report

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We want to particularly express our gratitude to SWAN Systems and each of the growers hosting the SWAN Systems platform on their orchards. We are grateful for their engagement and willingness to participate in the sharing and scrutinizing of their irrigation and nutrition practices.

Appendices

Appendix 1: Literature Review

Appendix 2: MS190 Technical report for Research Intensive sites in Tasmania

Appendix 3: Regional trial sites summary

Appendix 4: Integration of SWAN Systems with SINATA final report

Appendix 5: List of outputs (not available)

Appendix 6: Final Report Monitoring and Evaluation

Appendix 7: Grower guide to orchard floor management

AP19006 – Literature Review

Impact of orchard floor management practices on soil health, tree growth, yield and fruit quality

Prepared by Sally Bound, Tasmanian Institute of Agriculture, University of Tasmania

Draft 1: 10/12/2021

Contents

Introduction

Although they can be highly productive, current perennial fruit production systems contain practices that are unsustainable in the long term and orchardists are becoming increasingly aware that an ecologically balanced system is essential for maintaining healthy crops and optimising fruit quality The goal of a sustainable agricultural system is to adopt methods that depend primarily on renewable inputs for maintaining current levels of crop productivity (Sainju and Singh 1997). Agricultural production is highly dependent on ecosystem services provided by natural ecosystems, those that are readily quantified include biological pest control, pollination, nutrient cycling, soil structure and fertility, and provision of water (Power, 2010). Agriculture can also be the source of numerous disservices (Power 2010), including loss of wildlife habitat and biodiversity, nutrient runoff, sedimentation of waterways, greenhouse gas emissions, and pesticide poisoning of non-target species

High-input agricultural practices such as monoculture cropping and increased use of agrochemicals have led to habitat destruction and landscape-wide structural simplification. Jones (2020) points out that a simplified system is a disfunctional system and notes that susceptibility to pests and diseases, low nutrient status and poor plant productivity are linked to low diversity in the soil microbiome. Unlike high-input agriculture, low-input agriculture relies strongly on biodiversity and associated ecological processes (beneficial trophic interactions, soil food webs, stress-adapted crop genotype (Tscharntke *et al*. 2012).

Soil degradation occurs as part of natural cycles in the ecosystem, but human abuse of this valuable resource contributes greatly to its rate of decline. On a global scale, approximately 12,000,000 hectares of arable land is destroyed and abandoned annually due to non-sustainable farming practices (Pimental *et al.* 1995). The importance of soil in relation to human populations is illustrated very strongly in history, as soil degradation has been instrumental in the fall of some ancient civilisations; the degradation of these fertile soils is largely due to the past actions of primary producers (Hillel 1991). Contemporary farmers are experiencing the same problems that plagued our predecessors, but we are now farming more intensively and on a larger scale. We have also added to these issues with chemical fertilisers and pesticides, the production of more waste and air pollution (Hillel 1991) and contamination of waterways by chemicals and silt from agricultural runoff (Miller 1999). In simple economic terms the result of soil degradation is reduced soil productivity, leading to increased cost of production which, in turn, can affect the state of the agricultural industries (LMTF 1995).

The advent of synthetic inorganic fertilisers enabled the nutrient enhancement of soil such that crop production and yield could be increased with suitable application of supplemental nutrients. Despite many texts focussing on holistic agriculture and the complex interactions within farming systems, coupled with evidence from Asia of fields being worked for 4,000 years without depleting soil fertility, by the 1950s, the beginning of the 'green revolution', the shift in mainstream agriculture resulting from technological advances created a system relying on agrichemicals (chemical fertilisers, pesticides, and herbicides), new crop varieties and labour-saving energy-intensive machinery (Reganold *et al.* 1990; Zeunert 2018). This system is today known as conventional industrial agriculture (Code 2018), or mechanical farming Massy (2020) – the term conventional will be used throughout this review. While this system initially contributed to the preservation of the natural resource base and biodiversity through replacement of nutrients removed in harvested crops and erosion, increased biomass production, adoption of high yield varieties and use of otherwise non-productive land (Byrnes and Bumb 1998), it has now led to a decline in the yield potential of agricultural soils as the biological processes that maintained their health and quality became overtaxed (Welbaum *et al.* 2004). These authors note that *During the 1970s, 1980s, and 1990s the scientific literature became filled with reports of 'soil fatigue', 'soil degradation' and 'soil loss'* (Welbaum *et al.* 2004).

During the 20th century, the increase in intensification, specialisation, mechanisation, use of artificial fertilisers and pest control, and replacement of native ecosystems has led to the separation of agriculture from ecology (Granatstein 2021). There is growing concern worldwide with regard to the resulting undesirable environmental outcomes which include, but are not limited to, soil erosion, salinisation, compaction, loss of biodiversity, loss of genetic diversity, contamination of ground and surface waters, and increased toxins in the food chain (Karlen *et al*. 2003; Granatstein 2021), and many farmers are seeking alternative practices to ensure the long term sustainability of agriculture. There are numerous names given to these alternative or non-conventional practices/systems that come under the guise of sustainable agriculture, including organic, alternative, low-input, biological, regenerative, ecological, or agro-ecology. However Reganold *et al*. (1990) point out that just because a farm is organic or alternative does not mean that it is sustainable. To be truly sustainable, farmers need to understand the complex interactions within agricultural ecologies and develop a systems approach. Permaculture is a good example of a whole systems approach to sustainable agriculture (Code 2018), although relatively little formal research has been undertaken with regard to productivity and realisation if its claims as a self-sustaining productive food system (Ferguson and Lovell 2013).

Regenerative practices strive to do more good than harm by actively giving back, renewing, restoring and achieving net benefit rather than the net balance often seen in other sustainable practices (Zeunert 2018). In discussing regenerative farming systems, LaCanne and Lundgren (2015) note the following unifying principles that are consistent across these systems: (1) abandoning tillage (or actively rebuilding soil communities following a tillage event), (2) eliminating spatio-temporal events of bare soil, (3) fostering plant diversity on the farm, and (4) integrating livestock and cropping operations on the land. Referring back to natural ecosystems can provide a reference ecosystem to enable us to put in place ‘preventative’ rather than ‘curative’ practices (Vandermeer 2011), thus allowing for a re-introduction of more ecologically friendly interventions, such as biocontrol. The overall goal is to design in more ecological functions that result in increased system self-regulation and decreased costs and environmental impacts (Granatstein 2021). The work of Davis *et al*. (2012) supports the hypothesis that diversity is key in the development of ecosystem services that displace the need for external synthetic inputs to maintain crop productivity.

There is potential for a broad suite of ecosystem services from agricultural lands that both support crop production and reduce the impact of agriculture on the environment (Schipanski *et al*. 2014). Important ecosystem services that can be delivered from agricultural land include: improving soil quality, nutrient cycling, pest and disease regulation, crop productivity, weed suppression, habitat provision, seed dispersal, pollination, and soil formation and retention, as well as broader services such as water purification, breakdown of wastes and toxins, regulation of atmospheric gases (including carbon and nitrogen) and water flows, regulation of weather and climate and maintenance of genetic diversity (Department of the Environment, Water, Heritage and Arts 2009; Maynard *et al*. 2010; Cork *et al*. 2012a).

In moving away from conventional agriculture with its heavy reliance on pesticides and synthetic fertilisers, farmers often experience decreased yields, severe weed problems, increased pest pressure and reduced soil fertility until the system finds a new balance. However, by careful management and a slow change in practices, the long-term benefits are likely to be substantial. On the flip side, reduced yields during a transition period are often counterbalanced by a reduction in input costs (Reganold *et al*. 1991).One important misconception that needs to be addressed is that sustainable agriculture does not represent a return to old farming methods but combines traditional methods focussing on soil conservation with modern technology. There is a continuum between conventional farming, relying predominantly on manufactured chemicals, and systems with a total reliance on natural additives. There are advantages and disadvantages to any system, and the key will be to achieve a balance to enable the production of high-quality crops without degrading the environment.

The soil environment

Soil is defined as the top layer of the earth’s crust. It is an extremely complex medium formed by mineral particles, organic matter (OM), water, air and living organisms. The living component of soil, the food web, is complex and has different compositions in different ecosystems. While an obvious function of soil is its physical role in supporting plants, it plays a major role in underpinning all the processes that support human societies and economies (Cork *et al.* 2012). Because the disintegration of parent rock to form a functional soil (pedogenisis) can take hundreds to thousands of years, soil is regarded as a non-renewable resource, however it has been demonstrated that with the adoption of regenerative practices, healthy living soil can be built in a few years rather than millenia (Massy 2020).

To produce agricultural crops, soil serves as a reservoir of plant nutrients and normally supplies a substantial amount of the nutrient requirements for crops, as long as factors such as temperature, light and moisture are not limiting (Ludwick *et al.* 1995a). Soil also functions as a habitat and genetic reserve for numerous organisms (Liebig 2001), supporting a complex community of beneficial micro-organisms that decompose organic materials, recycle plant nutrients, and protect plants from pests (Parr *et al*. 1992). It has also been described as an environmental filter that cleans air and water, acting as a major sink for unwanted or waste gas and materials, a detoxifying agent for the decomposition of organic waste and a means for recycling of the nutrients needed at all levels of life (Parr *et al*. 1992; Wallace and Terry, 1998). In addition, soil buffers the influx of rain to control the flow of water to rivers and streams, also affecting the likelihood of flood events and drought (Hillel, 1991). In describing the ecosystem services provided by soil and their biota, Doran and Zeiss (2000) include storing and releasing water, decomposing plant and animal residues, transforming and recycling nutrients, sequestering and detoxifying organic toxicants, and promoting plant health by suppressing plant-pathogenic microbes and phytophagous fauna.

The overall condition of soils is influenced by the interaction of soil physics and chemistry with soil biodiversity. Soil properties vary depending on where and how the soil has been formed, and changes in soil properties can be brought about through agricultural activity (Cotching 2009). When discussing soil quality, there are two components that need to be considered: the inherent component, relating to the natural characteristics of the soil (such as texture) which are the result of soil-forming factors; and the dynamic soil quality component which is readily affected by management practices and includes characteristics such as compaction, biological functioning and root proliferation.

More recently the term resilience has been introduced into soil science to address sustainability of the soil resource and to combat soil degradation. According to Seybold *et al*. (1999), *soil resilience* is related to soil quality in terms of the recovery of soil functions, while *soil resistance* relates to the degree of change in soil functions following a disturbance. Thus, during a disturbance soil quality becomes a function of soil resistance, and after a disturbance soil quality becomes a function of soil resilience.

Cork *et al*. (2012b) described the multiple factors that influence soil resistance and resilience, including soil properties such as OM, aggregation, the quantity and quality of carbon inputs, clay content and soil pH. They also list terrain characteristics, landscape position, parent material, climate, water balance, vegetation and soil biodiversity as important. The 2011 State of the Environment Report (Australian State of the Environment Committee 2011) included the following features of good-quality and resilient land:

- leakage of nutrients is low
- biological production is high relative to the potential limits set by climate
- levels of biodiversity are relatively high
- rainfall is efficiently captured and held within the root zone
- rates of soil erosion and deposition are low, with only small quantities transferred out of the system
- contaminants are not introduced into the landscape, and existing contaminants are not concentrated to levels that cause harm
- systems for producing food and fibre for human consumption do not rely on large net inputs of energy.

Soil health

The terms quality and health are often used interchangeably in relation to soils. Soil quality is generally associated with the fitness of a soil for a specific use and includes an inherent component determined by the physical and chemical properties of the soil within the constraints set by climate and ecosystem (Doran and Zeiss 2000). Traditionally, soil quality focussed on soil productivity (Parr *et al*. 1992). With the awareness of the importance of soil microbiology and potential impacts on plant, human and animal health and on environmental quality (Parr *et al*. 1992), the use of the term soil health is more encompassing and it has been defined as the capacity of a soil to sustain biological productivity, promote or maintain environmental health, and promote plant, animal, and human health (Doran and Zeiss 2000), or put more simply, the capacity of the soil for self-renewal (Cotching 2009).

The concept of soil health is not new - according to Liebig (2001) Greek and Roman philosophers were aware of the importance of soil health to agricultural prosperity over 2,000 years ago. However, our awareness of the soil ecosystem has increased dramatically over the last few decades, and we now understand that the soil ecosystem is an interdependent life-support system. A healthy soil contains adequate levels of all nutrients, small and large pore spaces for air and water, good levels of OM and a thriving population of micro-organisms. Ultimately, the health of a soil can only be identified by how the soil performs all its functions (Cotching 2009). Management strategies that optimise multiple soil functions have a greater potential for improving soil health over strategies focussing on a single function (Liebig 2001). Cotching (2009) reminds us that poor soils can be in good health, just as good soils can be in a degraded state.

Measurement of soil health has traditionally been based on a range of soil physical and chemical characteristics as they are relatively easy to measure , however no single soil property can be used to define the health of a soil. Indicators that are useful to determine soil health include soil carbon and/or OM, water infiltration, macropores, texture, aggregate size and stability, aeration, compaction (synonymous with soil bulk density), runoff and erosion, and pH. Liebig (2001) emphasises that, as well as reflecting producer success and natural resource conservation, indicators should be easy to measure and simple to interpret. Examples of indicators meeting his criteria include crop yield, profit, risk of crop failure, soil OM content, soil depth, percent soil cover, leachable salts and energy use. Biodiversity should also be added to this list.

Soil physical properties

Soil physical properties include soil texture, structure and porosity, bulk density, and water holding capacity. Physical properties influence air-water relations in the soil (Fageria 2012) and can be improved by the addition of OM.

Soil texture

Soil texture refers to the inorganic solid material of the soil mass and defines the relative amounts of fine and coarse material present. There are three separate components that make soil texture: sand (0.02-2mm diameter), silt (0.002-0.02mm), and clay (≤0.002mm). Soil organic matter (SOM) content is related to its clay content, tending to increase as the clay content increases; in predominantly inorganic soils, a major part of the OM is found in the clay and silt fractions. Texture influences aggregation and is one of the relevant attributes in resistance to compaction (Fageria 2012).

Soil structure

The aggregation of soil particles is one of the most important physical properties of soils as it is essential in maintaining good soil structure for plant growth (Ibrahim and Shindo 1999). Good soil structure allows greater levels of air exchange and water infiltration, which encourages root growth. Increased water infiltration also results in less run-off during irrigation or rain, while larger particle sizes mean that soils are more resistant to wind erosion. Soil structure also determines the workability of the soil. A poorly aggregated soil is less functional at different levels of wetting, as it can be massive when dry and a slurry when wet. Poorly bound aggregates are more likely to disintegrate into smaller crumbs or individual particles when exposed to a mechanical force such as soil tilling, freeze/thawing and the force of falling raindrops.

Soil aggregation is part of an organised hierarchy with different factors responsible for binding the sub-units of soil aggregates at each level (Brady and Weil, 1999). Aggregates are naturally formed assemblages of sand, silt, clay, OM, root hairs, microorganisms and their mucilaginous secretions, extracellular polysaccharides, and fungal hyphae as well as the resulting pores (Fortuna 2012) and can be broadly classified into micro (<0.25mm) and macro-aggregates (>0.25mm). Tisdall and Oades (1982) put forward the theory that there is a strong correlation between overall stability and OM content, with OM increasing proportionally with a rise in aggregate stability and, conversely, SOM decreasing with a corresponding deterioration in soil structure and aggregate stability. The improvement in soil aggregate size and reduction in bulk density following addition of OM to the soil observed by Bound and Wilks (2003) supports this theory.

Brady and Weil (1999) described two factors or processes as contributing to the formation of soil aggregates: biological and physical-chemical (abiotic) processes. The physical-chemical processes of aggregation formation tended to be the most important at the smaller end of the scale, being mainly associated with clays and consequently finer texture soils. In this case divalent and polyvalent ions are important in binding small clay particles together with electrostatic forces. Where monovalent ions are in excess in soil there is a distinct lack of this type of soil binding. For example, soils with excessive amounts of monovalent sodium ions (Na^+), described as sodic soils, tend to be dispersive. In extreme cases sodic soils can be highly erosive in the presence of water; tunnel erosion is a severe symptom of sodic soils. Biological processes of aggregate formation tend to be most important at the larger scale, being mainly associated with sandy soils with little clay content (Brady and Weil, 1999).

Haynes and Swift (1990) describe the biological formation of stable soil aggregates as occurring in two phases, the first phase being the aggregation phase involving production of exocellular microbial polysaccharide mucigels by microorganisms. The second phase involves stabilising of the aggregates due to the build-up of soil humic material over time. It was further suggested that a pool of carbohydrate from OM is involved in the formation of stable aggregates. This expanded on comments by Oades (1984) that the degree of macro-aggregation was provided by hyphae through the physical enmeshment of soil particles.

In summary, soil aggregation is dependent on divalent ions, fungal hyphae, mucigels produced by soil biota and, most importantly, OM to physically bind a hierarchy of particles together.

Soil porosity

Soil porosity refers to the space between soil particles, which consists of various amounts of water and air. Porosity depends on both soil texture and structure. For example, a fine soil has smaller but more numerous pores than a coarse soil. A coarse soil has bigger particles than a fine soil, but it has less porosity, or overall pore space. Water can be held tighter in small pores than in large ones, so fine soils can hold more water than coarse soils.

Water-holding capacity

Water holding capacity of soil is the ability of a particular type of soil to hold water against the force of gravity. Available water is the difference between field capacity, which is the maximum amount of water the soil can hold, and wilting point where the plant can no longer extract water from the soil. Soil texture and structure greatly influence water infiltration, permeability, and water-holding capacity. Soils with smaller particles (silt and clay) have a larger surface area than those with larger sand particles, and a large surface area allows a soil to hold more water. In other words, a soil with a high percentage of silt and clay particles, which describes fine soil, has a higher water-holding capacity. Organic matter percentage also influences water-holding capacity.

Bulk density

Soil bulk density is defined as the mass of dry soil per unit bulk volume and is often used as a simple index for assessing compaction and productivity. It is significantly influenced by SOM, with higher OM levels resulting in lower bulk density, in other word, as SOM increases, the susceptibility to compaction decreases (Zhang *et al.* 1997). According to Fageria (2012), soil bulk density significantly influences nutrient uptake through its effect on physical, chemical and biological properties of soil-plant systems.

Soil organic matter

Soil organic matter is a major source of nutrients such as phosphorus, sulphur and nitrogen, and the main food that supplies carbon and energy to soil organisms. It has been described by Brady and Weil (1999) as consisting of a wide range of organic substances (carbon containing molecules). Organic substances have been categorised as polysaccharides (cellulose, hemicellulose, sugars, starches, and pectin substances), lignins and proteins (Ludwick *et al.* 1995b). The breakdown of plant, animal and microorganism residues provide material for the synthesis of new compounds by different microorganisms.

Cotching (2018) describes SOM as a dynamic, changing resource that reflects the balance between the living components that add new organic matter and the loss of organic matter from the dead component. Organic matter is a vital component of a healthy soil, and the amount of OM in a soil is determined by the balance between accumulation and loss. Without adequate plant materials being returned to the soil or without replacement with soil amendments, SOM continuously degrades in the soil (Sainju and Singh 1997). Organic matter has a major influence on physical, chemical, and biological properties of soil (Table 1) and is also essential for a healthy, diverse soil fauna, playing a pivotal role in many soil processes crucial to productive and sustainable agriculture (Masciandaro *et al* 1997; Aslam *et al* 1999; Cotching 2009).

Contributions to the soil-plant system from the addition of composted OM include improved soil structure (through aggregation of clay particles), increased microbial activity (enhanced nutrient cycling and weathering of soil materials), improved soil stability and water infiltration and provision to plants of a larger pool of nutrients from which to draw (Stratton and Rechcigl 1998). According to Bot and Benites (2005), the rate of decomposition and accumulation of SOM is determined by soil properties such as texture, pH, temperature, moisture, aeration, clay mineralogy and soil biological activities, in turn SOM can modify many of these same soil properties. In soils with low clay content, as is the case with many orchard topsoils, OM plays the major role in stabilisation of structure and nutrient and water retention.

***Table 1**. Functions of soil organic matter (adapted from Cotching 2009)*

Physical functions	Chemical functions	Biological functions
- bind soil particles together in stable aggregates - influence water holding and aeration - greater porosity - reduced bulk density - improved water infiltration	- major source of cation exchange capacity (CEC) - source of pH buffering - binding site for heavy metals and pesticides	- food source for microbes, meso- and macrofauna - major reservoir of plant nutrients

Soil organic matter is not homogeneous in its composition but exists as a mixture of plant and animal litter in various stages of decomposition, microbial biomass and its detritus, and charcoal (Skjemstad *et al.* 1998). In his description of SOM, Cotching (2009) divides non-living OM into four distinct pools:

(i) OM dissolved in soil water,
(ii) particulate OM that is partially decomposed but has identifiable cell structure,
(iii) humus comprising organic molecules of identifiable structure such as proteins and cellulose, and molecules with no identifiable structure but with reactive regions that allow the molecule to bond with other mineral and organic soil components (humic and fulvic acids and humin, and
(iv) inert OM or charcoal derived from the burning of plants.

Humus is normally the largest pool and can comprise over 50% of the total SOM, while particulate OM can constitute up to 25%. Inert OM can be up to 10% of the total SOM. Turnover of non-living SOM is influenced by:

- environmental factors such as rainfall, temperature, and biomass input,
- edaphic factors such as associations with the mineral fraction, soil pH and redox potential, and
- management practices through the impacts of tillage, weed and trash management, rotation, and fertilisers.

Function of humus

Humus is a black or brown decay resistant complex organic compound derived from decaying OM that accumulates in soil. It is formed by humic substances, including humic acids, fulvic acids, hymatomelanic acids and humins (Bot and Benites 2005). Along with colloidal clay particles, humus plays a significant role in the nutrient holding capacity of the soil. Humic substances can interact with metal ions, oxides, hydroxides, mineral and organic compounds, including toxic pollutants, to form water-soluble and water-insoluble complexes. The surface of humus has negatively charged sites which are able to loosely bind and temporarily store cations (positively charged ions) (Brady and Weil 1999). This ability to bind exchangeable cations is known as the Cation Exchange Capacity (CEC). CEC is important in plant nutrition and soil fertility as it is considered an indicator of the nutrient holding capacity of the soil (Ludwick *et al.* 1995b).

Humus is an important buffer, reducing fluctuations in soil acidity and nutrient availability. Compared with simple organic molecules, humic substances are very complex and large, with high molecular weights. Because of the complex structure of humic substances, humus cannot be used by many micro-organisms as an energy source and thus remains in the soil for a relatively long time. Fulvic acids are produced in the earlier stages of humus formation and have smaller molecules than humic acids. The relative amounts of humic and fulvic acids in soils varies with soil type and management practices. The humus of forest soils is characterized by a high content of fulvic acids, while the humus of agricultural and grassland areas contains more humic acids (Bot and Benites 2005).

The process of decomposition

Decomposition of OM is a natural biological process. It involves the physical breakdown and biochemical transformation of complex organic molecules into simpler organic and inorganic molecules. The speed of decomposition is determined by three major factors: soil organisms, the physical environment, and the quality of the OM (Brussaard 1994, cited in Bot and Benites 2005). In the decomposition process, different products are released: carbon dioxide (CO_2), energy, water, plant nutrients and resynthesized organic carbon compounds. The simpler organic molecules such as sugars, amino acids, and cellulose are readily consumed by many organisms, hence do not remain in the soil for long, chemicals such as resins and waxes are more difficult for soil organisms to break down.

Carbon cycling

Organic matter has also been considered to play a critical role in the global carbon (C) balance. Tate (1987) has suggested that under favourable conditions, the atmospheric carbon dioxide that has been sequestered by plants into abundant tissues would eventually be incorporated back into the soil OM and subsequently released back into the atmosphere through microbial respiration (Brady and Weil 1999). Carbon cycling (Figure 1) is the continuous transformation of organic and inorganic carbon compounds by plants and soil biota between the soil, plants and the atmosphere (Bot and Benites 2005). The continual addition of decaying plant residues to the soil surface, the breakdown of SOM, and root growth and decay contribute to the biological activity and the carbon cycling process.

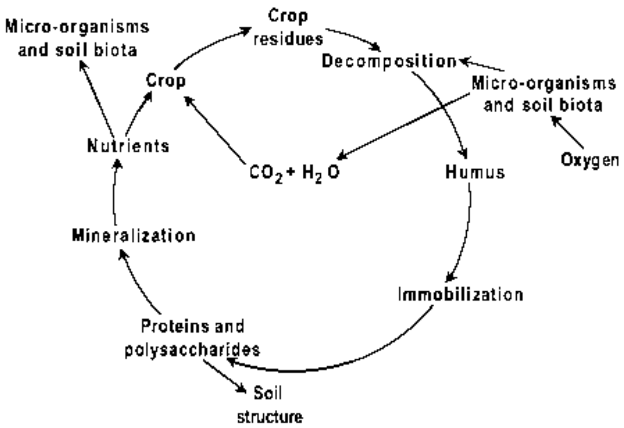

***Figure 1**: The carbon cycling process in soils (Source: Bot and Benites 2005).*

Non-humic substances

Non-humic organic molecules, such as proteins, amino acids, sugars, and starches, are released directly from cells of fresh residues (Bot and Benites 2005). This is the active (easily decomposed) fraction of SOM and is the main food supply for various organisms in the soil. It is influenced strongly by weather conditions, moisture status of the soil, growth stage of the vegetation, addition of organic residues, and cultural practices (such as tillage).

Carbohydrates occur in the soil in three main forms: free sugars in the soil solution, cellulose and hemicellulose, complex polysaccharides, and polymeric molecules of various sizes and shapes that are attached strongly to clay colloids and humic substances (Stevenson 1994, cited in Bot and Benites 2005). The simple sugars, cellulose and hemicellulose are easily broken down by micro-organisms, and may constitute 5-25 % of the OM in most soils. Polysaccharides (long-chain sugar molecules) promote better soil structure through their ability to bind inorganic soil particles into stable aggregates. Other soil properties affected by polysaccharides include CEC, anion retention and biological activity (Bot and Benites 2005).

Nitrogen mineralisation

The biological oxidation of relatively immobile ammonium (NH_4^+) or ammonia (NH_3) to the highly mobile nitrate (NO_3^-) is known as nitrification. This is a two-step process in soils in which ammonium or ammonia is first converted to nitrite (NO_2^-) and then to nitrate. Two groups of obligate autotrophic bacteria are involved in this process – *nitrosomonas* are responsible for the first conversion to nitrite, and *nitrobacter* convert nitrite to nitrate (Sahrawat

2008). Denitrification is the reduction of nitrogen (N) oxides (nitrate and nitrite) and is one of the major mechanisms for N loss from the soil (Fageria 2012). Soil organic matter, soil pH, temperature, nitrate concentration, aeration and water status control denitrification rates in soils. Both nitrification and denitrification produce nitrous oxide (N_2O).

By-products of the metabolic oxidation or reduction of C and N compounds include greenhouse gases (GHG) such as CO_2, methane (CH_4) and N_2O (Fortuna 2012).

Phosphorous mineralisation and solubilisation

The efficiency of phosphorous (P) use by plants from both soil and fertiliser sources is often poor, even in soils with relatively high amounts of total P. Phosphorous is a relatively immobile element compared to other macronutrients; plants acquire phosphorous from soil solution as phosphate anion (HPO_4^{2-} and $H_2PO_4^-$). Soil P dynamics are characterised by physicochemical (sorption-desorption) and biological (immobilisation-mineralisation) processes (Khan *et al.* 2009). Large amounts of P applied as fertiliser enters the immobile pools through a precipitation reaction with highly reactive aluminium (Al^{3+}) and iron (Fe^{3+}) ions in acidic soils, and calcium (Ca^{2+}) ions in calcareous or normal soils (Gyaneshwar *et al.* 2002). Soil microorganisms play a key role in soil P dynamics and subsequent availability of phosphate to plants (Richardson 2001).

Soil biota

There is a diverse array of organisms inhabiting the soil, ranging in size from microscopic to larger organisms such as earthworms and, according to Cotching (2018), soil biology is potentially the most dynamic component of SOM. Soil biota can be divided into flora (plants) and fauna (animals). Plant roots and macro-algae comprise the macroflora, while soil microflora consist of bacteria, actinomycetes, fungi and algae. Bacteria take part in some of the most important transformations in soils including weathering of rocks and minerals, breakdown of OM, and many aspects of nutrient cycling. Fungi are important in the decomposition of OM and play an important part in stabilising soil aggregates. Mycorrhizal fungi play a major part in securing nutrients for plant production and many plants are dependent on such relationships.

Soil fauna is classified according to size. Although there is some variation between authors as to the upper and lower limits of each size category, macrofauna is generally defined as being larger than 2mm in size; mesofauna are 0.1 to 2mm in size, and microfauna less than 100µm (0.1 mm) in size.

Soil biota play a key role in cycling of organic nutrients for plant growth and some beneficial soil microbes can compete with disease causing agents, thus reducing the incidence of disease in plants. Table 2 lists soil dwelling organisms that can be beneficial to plant production.

Table 2*. Soil biota (adapted from Peterson and Luxton 1982)*

Taxonomic group	Common name	Food source
Microflora (< 5µm in size)	Bacteria Fungi Actinomycetes Algae	
Microfauna (0.1 – 2.0mm in size***)***		
Protozoa		Bacteria, fungi, algae, detritus, microfauna
Nematoda	Nematodes	Plant juices, fungal mycelia, bacteria, algae, micro- & mesofauna
Mesofauna (0.1 – 2.0mm in size***)***		
Oligochaeta - Enchytraidae	Potworms	Dead plant material, fungal mycelia
Collembola	Springtails	Dead plant material, bacteria, fungi
Acari	Mites	Dead plant material, microflora, micro- & mesofauna
Protura	Coneheads	Detritus, microflora, mycorrhiza
Diplura	Two-tailed bristletails	Detritus, microflora, mesofauna
Pauropoda	Multipedes	Detritus, microflora
Symphyla	Garden centipedes	Detritus, microflora, plant roots
Macrofauna (> 2mm in size)		
Oligochaeta - Lumbricidae - Megascolecidae - Acanthodrilidae	Earthworms	Dead plant material, microflora
Crustacea - Isopoda	Slaters	Dead plant material, microflora

- Amphipoda	Landhoppers	
Diplopoda)	Millipedes	Dead plant material, microflora
Diptera (larvae	Flies	Dead plant material, microflora, plant roots, meso- & macrofauna
Isoptera	Termites	Living plant tissue, dead leaves, dead wood, fungi
Trichoptera (larvae)	Caddis fly	Dead plant material, plant roots
Lepidoptera (larvae)	Moths / butterflies	Dead plant material, plant roots
Coleoptera	Beetles / weevils	Dead organic material, microflora, roots, macro- & mesofauna
Chilopoda	Centipedes	Macro- & mesofauna
Arachnomorpha - Pseudoscorpiones	False scorpions	
- Opiliones	Harvestmen	Macro- & mesofauna
- Aranae	Spiders	
Formicoidea	Ants	Living plants, fungi, macro- & mesofauna
Gastropoda	Snails / slugs	Living plants, dead plant material, fungi

Soil fauna

Earthworms are an important component of the soil biota, transporting and mixing organic, mineral and microbial soil components to deeper soil horizons. Their activities have been noted to greatly enhance soil fertility and productivity by altering both the physical and chemical conditions in the soil and increasing the availability of mineral nutrients to plants (Brady and Weil 1999). Hartley and Rahman (1994) suggest that a good earthworm population is between 100-400 earthworms per m^2 for cultivated land and between 400-1000 for permanent pasture. Pettersson and Wistinghausen (1979) reported that the prevalence of earthworms within compost-amended soils appeared to be representative of an improvement in the living conditions for soil organisms, which acted to open up the soil. Based upon this assertion, it has been further stated that organic fertilisers, via earthworms, indirectly increased the area penetrable by roots, subsequently improving the conditions for increase in humus in the subsoils. In contrast, inorganic soil amendments appeared to restrict activity due to subsoils being more compacted (Pettersson and Wistinghausen 1979).

Brady and Weil (1999) have suggested that earthworm activity enhances soil fertility and productivity by altering the physical and chemical conditions in the soil and increasing the availability of mineral nutrients to plants. Bound and Wilks (2003) found that the addition of any organic material in vegetable cropping soils increased the population of earthworms; Pérès *et al.* (1998) also found that OM quantitatively increased the abundance and biomass of the earthworm community in French vineyards.

Mesofauna play a role in nutrient cycling by shredding materials into smaller pieces with higher surface area, thus providing greater access for microorganisms that recycle most of the carbon (Fortuna 2012). Soil invertebrate biomass and diversity, particularly of mites, is often positively correlated with soil health (Coleman *et al*. 2004; Axelsen and Kristensen 2000) and crop performance (Baker and Crisp 2009) and hence can be used as indicators of soil health.

Soil microbial biomass

Soil microbial biomass is the living component of soil OM, excluding soil animals and plant roots (Dalal 1998). It comprises less than 5% of OM in soil but, according to Dalal, performs at least three critical functions: acting as a labile source; an immediate sink of carbon, nitrogen, phosphorous and sulphur; and an agent of nutrient transformation and pesticide degradation. Dalal also states that microorganisms form symbiotic associations with roots, act as biological agents against plant pathogens, contribute towards soil aggregation, and participate in soil formation. Soil microorganisms rely on inputs of fresh, labile substrate such as plant and animal residues and root exudates for growth and reproduction. As these substrates are not always abundant, the soil microbial life-cycle is characterised by intermittent periods of growth and dormancy depending on the availability of readily degradable fresh substrates (Mondini *et al.* 2006). Following a study aimed at clarifying the mechanisms involved in the transition from dormancy to activity, Mondini *et al.* (2006) reported that trace amounts (micro-grams) of different simple and complex substrates (glutamic acid, amino acids mix, glucose, protein hydrolysates, carbohydrates, compost extracts) caused an immediate and significant increase in soil microbial activity, indicating that soil microorganisms have evolved specific metabolic and physiological strategies to equip them for survival and growth in the soil.

Microbial biomass is central to OM cycling, and hence, carbon sequestration by soil. The higher the level of microbial activity the higher the rate of mineralisation of OM (Pettersson and Wistinghausen 1979). Soil microbial biomass has been described as the "eye of the needle" through which all decomposing OM must pass before being transformed into plant available nutrients and soil humus (Sparrow, pers. communication). Thus it can be considered a measure of the OM processing capacity or turnover rate of a soil, the flux of which has been reported as being affected by the higher levels of organic C in the larger pools of microbial biomass (Cooper and Warman 1997). Furthermore, microbial activities within the residues have been suggested to mimic slow-release type fertiliser with minimal leaching of the plant available nutrients into the groundwater (Muchovej and Pacovsky 1997).

The importance of soil microbes in a healthy system is outlined by Kausadikar (2010) who summarises the following roles of soil microbes:

- Conversion of complex organic nutrients into simpler inorganic forms (mineralisation) that are readily absorbed by the plant for growth.
- Production of a variety of substances like indole acetic acid (IAA), gibberellins, antibiotics etc. that directly or indirectly promote plant growth.
- Synthesis of polysaccharides, lignins and gums that have an important role in cementing/binding of soil particles to produce stable aggregates.
- Degradation of OM - including cellulose, lignins and proteins (in plant cell walls), glycogen (animal tissues), proteins and fats (plants, animals). Cellulose is degraded by bacteria and fungi. Lignins and proteins are partially digested by fungi, protozoa and nematodes. Proteins are degraded to individual amino acids mainly by fungi.
- Humus formation.
- Biological nitrogen fixation - conversion of atmospheric nitrogen into ammonia and nitrate.

Comparative ‘benchmark’ references of microbial biomass as critical or threshold and optimum levels do not currently exist. All currently used soil microbial biomass methods have some limitations, and it is difficult to compare soil microbial biomass values which have often been obtained by different methods in different laboratories. In a study by Cooper and Warman (1997), conducted to assess microbial activity within both composted and fertilised plots, dehydrogenase enzyme activity (DHA) was implicated as being one of the better indicators of microbial activity, due to its occurrence only within living cells.

Soil biology and mineralisation

Mineralisation is the conversion by soil micro-organisms of organically bound elements such as N, P, and sulphur (S) into inorganic mineral forms (in the case of N into NH_4^+ and NO_3^-). Studies have shown that only 1.5 - 3% of organic N mineralises annually (Roy *et al.* 2006). Immobilisation is the opposite of mineralisation (mobilisation) where, using N as an example, inorganic N is utilised by the micro-organisms in decomposing organic residues in the soil. As the microbes die the organic N may be released as either NH_4^+ or NO_3^- or be incorporated in the humus complex. Both reactions occur simultaneously, with the net balance of available mineral N depending on the C/N ratio of the decomposing organic residues (Brady and Weil 1999). Hence by breaking down C structures and rebuilding new ones or storing the C into their own biomass, soil biota plays a major role in the ability of a soil to provide the crop with sufficient nutrients through nutrient cycling processes (Bot and Benites 2005).

Nutrient mobilisation increases with temperature. According to Roy *et al.* (2006), a temperature increase of 10ºC doubles the rate of chemical reactions involved in nutrient mineralisation. Hence the rate of mineralisation in tropical climates is 4-6 times higher than in temperate climates.

Working with living mulches, Masciandaro *et al.* (1997) reported that living mulches stimulated soil metabolism through the bioactivity of micro-organisms, worms, and plant roots; living mulch treatments accelerated C and N metabolism through enzymatic processes. Pettersson and Wistinghausen (1979) have also stated that, although OM levels can be equal to or higher in inorganic amended soils than in organic (compost) amended soils, the turnover rate or mineralisation is often much lower in inorganic soil. Subsequently, the higher rate of mineralisation of OM in compost-amended soils has been attributed to the level of microbial activity in organic amended soils.

N-fixing bacteria

The major conversion of atmospheric nitrogen (N_2) into ammonia, and subsequently into proteins, is achieved by prokaryotes (bacteria) in the process of nitrogen fixation (or dinitrogen fixation). Two groups of nitrogen fixers are recognised:

1. free-living bacteria, including the cyanobacteria (blue-green algae), *Azotobacter*, *Nitrosomas*, and *Nitrobacter*; and
2. mutualistic (symbiotic) bacteria such as *Rhizobium*, associated with legumes, and *Spirillum lipoferum*, associated with cereal grasses (Leu 2012; Wagner 2012).

The symbiotic N-fixing bacteria attach and colonise host roots at epidermal cell junctions, root hairs, cap cells and sites of emerging lateral roots (McNear 2013), where they multiply and stimulate formation of root nodules - enlargements of plant cells and bacteria in intimate association. Within the nodules the bacteria convert free nitrogen to nitrates, which the host plant utilizes for its development.

P-solubilising microorganisms

Up to 40% of the culturable population of soil bacteria and fungi is able to solubilize various forms of precipitated P, including *Bacillus*, *Pseudomonas*, *Penicullium* and *Aspergillus* spp. (Richardson 2001). The mechanisms involved in microbial solubilisation of inorganic phosphate (PO_4^{3-}) include acidification and chelation by organic acids produced by the microorganisms, releasing P (He *et al.* 2002).

Richardson and Simpson (2011) summarise the mechanisms by which microorganisms enhance the capacity of plants to acquire P from soil as follows:

1. increased root growth through an extension of existing root systems (ie. mycorrhizal associations) or by hormonal stimulation of root growth, branching or root hair development (phytostimulation through production of hormones and enzymes),
2. alteration of sorption equilibria that increases the net transfer of phosphate ions into soil solution or facilitate the mobility of organic P through microbial turnover,
3. through induction of metabolic processes that directly solubilise and mineralise P.

Mycorrhizal fungi

Mycorrhizal fungi form a symbiotic relationship that aids the plant through an increase in effective root area, thus providing access to an increased supply of nutrients in the soil. There are two distinct types of mycorrhizal fungi (Figure 2):

1. ectomycorrhiza (EM) where the fungus forms a dense covering of hyphae over the root tip from which hyphae grow into the intercellular spaces forming a net (Hartig net) of hyphae around the root cortex cells, but do not penetrate the cell walls; and
2. endomycorrhiza in which the fungal hyphae grow into the root cortex, entering the cells to form a fan-like highly branched structure known as an arbuscule. This gives rise to the name arbuscular mycorrhiza (AM); endomycorrhiza are obligate symbionts, hence cannot be grown independent of their plant hosts.

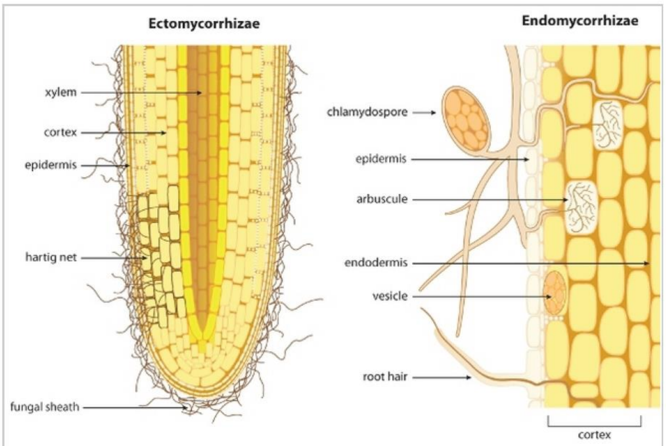

Figure 2:
Schematic showing the difference between ectomycorrhizae and endomycorrhizae colonization of plant roots.
(Source: McNear 2013)

Both endo- and ectomycorriza (Figure 2) can demand up to 20-40% of the photosynthetically fixed carbon produced by the plant (McNear 2013). The AM fungi are the most abundant of all mycorrhizal associations, forming associations with about 90% of terrestrial plant species (Smith and Smith 2012). AM fungi play a significant role in plant P uptake, regardless of whether the plant responds positively to colonisation in terms of growth or P content; they also provide other benefits including avoidance of toxins, and increased plant tolerance to drought and to some diseases (Smith and Smith 2012).

Mycorrhizal networks are common between plants, both of the same and different species, and these networks can influence plant establishment, growth, physiology and defence chemistry, with communication occurring via nutrients, defence signals, and allelochemicals (Granatstein 2021). As most fruit trees are mycorrhizal there is considerable potential to manipulate this network to provide benefits to the orchard as a whole.

Soil fertility

According to Voorhees (1916) soil fertility involves many conditions, all of which exert varying degrees of influence. His primary condition was that a soil should contain those elements found in the plant; however even with these elements being present in the soil, without adequate water and suitable soil/air temperatures and physical soil characteristics, crops cannot be grown successfully. Voorhees suggests that the benefits of addition of OM in the form of farmyard manures and green-manures are the result of indirect action resulting in an increase in soil water-holding capacity, and improved tilth or physical character. His implication that nutrients are not readily available for plant uptake in manures compared with artificial fertilisers, and an absence of discussion on the role of soil microbiology indicates a lack of understanding of the role of soil microbes in nutrient cycling.

The assertion by Francis (2005) that fertile soils normally hold all the nutrition required for healthy crop growth but rely on the right combination and volume of microbial populations to digest and transform these minerals to compounds readily available for plant uptake agrees with the statement by Krasil'nikov in 1958 (cited in Anderson 1992) that the degree of soil fertility is determined by the intensity of the life processes of the microbial population. Considering the discussion in previous sections of this review, this definition is a logical one, and goes a long way towards explaining why soils depleted of OM and microorganisms require increasing inputs of chemical fertilisers to enable continued crop production.

Plant nutrients and uptake

Chemical elements (nutrients) required for healthy plant growth are divided into non-mineral and mineral. The non-mineral nutrients are C, hydrogen (H) and oxygen (O) and these are obtained from the atmosphere and water. The mineral nutrients are obtained from the soil and are divided into macro- and micro-nutrients; micro-nutrients are just as important for plant growth as macro-nutrients but are required in smaller quantities. Optimising plant growth and fruit quality involves balancing all the macro- and micro-nutrients (Grobe 1997). When one element is deficient, its absence affects uptake and utilisation of other elements. Liebig's Law of the Minimum - *that growth is controlled not by the total amount of resources available, but by the scarcest resource (limiting factor)* - was postulated in terms of nutrient availability; however it applies equally to all resources required for plant growth. Albrecht (cited in Leu 2012) strongly supported the concept of the soil as a living body and was the first soil scientist to show the importance of having all the soil minerals in a balanced ratio along with adequate levels of OM.

The ultimate source of all soil minerals, with the exception of N, is the parent rock from which the soil is derived. Soils derived from mineral-poor rocks will have lower nutrient (mineral) reserves as will soils where considerable leaching has occurred, such as older soils or soils in higher rainfall climates. Whatever the nutrient content of a soil, the bulk of it is not immediately accessible to plants as large quantities of nutrients are locked up by complex chemical and physical interactions with minute soil particles (colloids). Nutrients are present in the soil in three states: unavailable, exchangeable and water soluble. Plant nutrient uptake is from the soil solution, but only a small portion of the available nutrients move freely in the soil solution; most are loosely bound by negatively charged clay colloids, layer silicates and OM in exchangeable form. Metal hydroxides present in soil and some humic substances are positively charged and bind anions such as phosphate (Roy *et al.* 2006). This mechanism acts as a storehouse for nutrient cations (positive charge) and anions (negative charge). Cations such as Ca^{2+}, magnesium (Mg^{2+}) and potassium (K^{+}) are adsorbed to the negatively charged surfaces and hence are protected against leaching. Nitrogen can be taken up as either NO_3^- or NH_4^+, but NO_3^- moves freely through the soil whereas NH_4^+ is held by cation exchange sites and hence is less mobile. Unbound ions can be easily leached and hence lost from the rooting zone.

The availability of nutrients in the soil is also strongly affected by soil pH (acidity/alkalinity) (Figure 3). Soil pH is the negative logarithm of the hydrogen ion activity of a soil. Low pH (excessive acidity) reduces the availability of certain beneficial nutrients such as Ca, Mg and P. At the same time undesirable and potentially toxic elements such as Al become plant available. Similarly soils with a high pH have reduced availability for many nutrients.

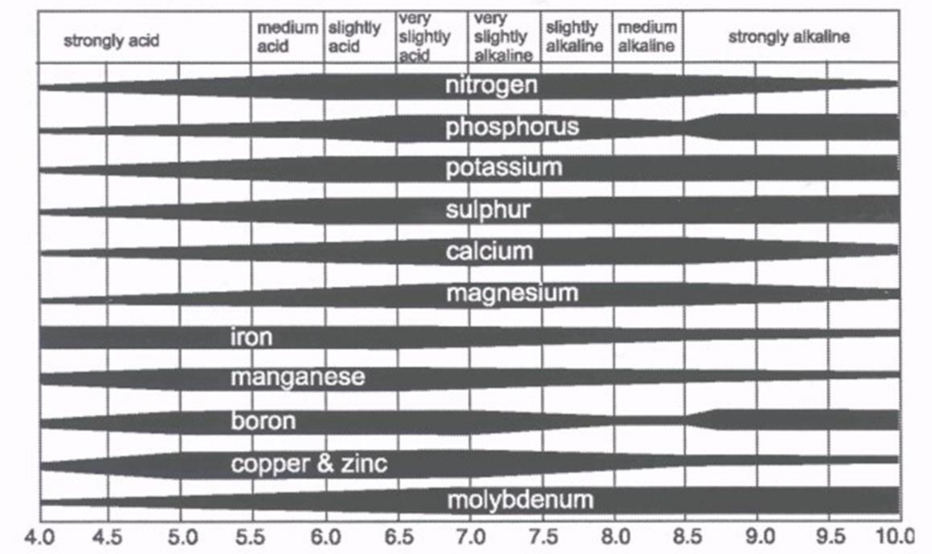

Figure 3: *Effect of soil pH on nutrient availability. (Source: SSD 2015)*

As discussed previously, the amount of OM and clay colloids and the type of clay determine cation exchange capacity of a soil. The higher the amount of colloidal material in the soil the greater the ability of the soil to absorb and exchange nutrients. Soils low in OM, and thus humus content, also have a weak anion exchange capacity, hence the reason why anions such as NO_3^-, S and boron (B) are readily leached (Leu 2012). By determining the available nutrient status of a soil, measures can be taken to ensure optimal plant nutrition and minimise depletion of soil fertility.

Essential nutrients

Based on criteria formulated by Arnon and Stout (1939), there are 16 elements considered essential for plant growth and development. These criteria are:

1. An element is essential if, being deficient, the plant is unable to complete the vegetative or reproductive stage of its life cycle,
2. The deficiency can be prevented or corrected only by supplying the specific element causing the deficiency, and
3. That element is directly involved in the nutrition of the plant.

A fourth criterion has been added over time: that the essentiality of any element is proved in all plants tested. The essentiality of most micronutrients was established between 1922 and 1954, with nickel (Ni) being added as a 17th element in 1987 (Roy *et al*. 2006). There are other elements that perform beneficial functions in plants and Subbarao *et al*. (2003) suggested the term ‘functional nutrient’, which they defined as *a nutrient being required for maximal biomass yield and/or is functional in a metabolic role to the extent that the critical level of an essential nutrient is reduced*. Nutrients that fit this definition include Na, silicon (Si), cobolt (Co), and vanadium (V). It is probable that more nutrients may be added in future.

The nutrients considered essential and functional are listed in Table 3.

***Table 3**: Essential and functional nutrients for plant growth (Source: Glendinning 1999; Jones and Jacobsen 2001).*

Element	Role in plant	Form used by plant	Source
Carbon (C)	Constituent of carbohydrates; Necessary for photosynthesis	CO_2	air
Hydrogen (H)	Maintains osmotic balance; Important in numerous biochemical reactions; Constituent of carbohydrates	H_2O (liquid) H^+	water
Oxygen (O)	Constituent of carbohydrates; Necessary for respiration	H_2O (liquid) O_2 (gas)	air/water
Nitrogen (N)	Necessary for chlorophyll synthesis; Constituent of proteins, nucleic acids	NO_3^- (nitrate) NH_4^+ (ammonium)	air/soil
Phosphorous (P)	Role in photosynthesis, respiration, energy storage and transfer, cell division, cell enlargement; Constituent of many proteins, coenzymes, nucleic acids, and metabolic substrates	$H_2PO_4^-$ HPO_2^{2-} (phosphate)	soil
Potassium (K)	Involved with photosynthesis, carbohydrate translocation, protein synthesis	K^+	soil
Calcium (Ca)	Component of cell walls; Activates several plant enzyme systems; plays a role in structure and permeability of membranes	Ca^{2+}	soil
Magnesium (Mg)	Component of chlorophyll Enzyme activator	Mg^{2+}	soil
Sulphur (S)	Necessary for chlorophyll formation; Constituent of enzymes and volatile organic compounds	SO_4^{2-} (sulphate)	soil
Boron (B)	Important in sugar translocation and carbohydrate metabolism	H_3BO_3 (boric acid) $H_2BO_3^-$ (borate)	soil
Chlorine (Cl)	Involved in energy reactions; activates enzyme systems; involved in transport of K, Ca, Mg within the plant	Cl^- (chloride)	soil
Copper (Cu)	Catalyst for respiration; component of various enzymes	Cu^{2+}	soil
Iron (Fe)	Involved with chlorophyll synthesis and in enzymes for electron transfer; acts as an oxygen carrier	Fe^{2+} (ferrous) Fe^{3+} (ferric)	soil
Manganese (Mn)	Controls several oxidation-reduction systems and photosynthesis	Mn^{2+}	soil
Molybdenum (Mo)	Involved with nitrogen fixation and transforming nitrate to ammonium	MoO_4^{2-} (molybdate)	soil
Nickel (Ni)	Necessary for proper functioning of the enzyme urease, and found to be necessary in seed germination	Ni^{2+}	soil
Zinc (Zn)	Involved with enzyme systems that regulate various metabolic activities; necessary for production of chlorophyll and carbohydrates	Zn^{2+}	soil
Silicon (Si)	Improves cell wall rigidity; Stimulates nutrient uptake and photosynthesis	$Si(OH)_2$	soil
Cobolt (Co)	Component of several enzymes and co-enzymes Used by nodulating bacteria for fixing atmospheric N in legumes	Co^{2+}	soil
Sodium (Na)	Key in maintaining turgor within the plant stem Partly able to replace K	Na^+	soil
Vanadium (V)	Enhances chlorophyll formation and iron metabolism		soil

Plant nutrient uptake

Nutrient uptake is dependent on both the availability of the nutrient in the soil and the plant's ability to absorb that nutrient (Jones and Jacobsen 2001). Nutrients are taken up in an ionic, or charged, form, hence to become available to plants, nutrients must be solubilised or released from mineral sources and mineralised from organic sources (Roy *et al.* 2006). Nutrients vary in their mobility, both in the plant and in the soil, and this mobility can be influenced by pH, temperature, moisture, and proportion of OM, layer silicates and metal hydroxides.

Organic nitrogen

According to Bot and Benites (2005), more than 90% of soil N occurs in organic forms as amino acids, nucleic acids and amino sugars. Small amounts exist in the form of amines, vitamins, pesticides and their degradation products. The rest is present as ammonium and is held by the clay minerals. Plants synthesise the amino acids they require by combining nitrates with carbohydrates produced through photosynthesis. It has been assumed that amino acid molecules were too large to be absorbed by roots, and hence the belief has been that N present in the soil as amino acids was not available to plants unless it was transformed into nitrate. But according to Leu (2012), scientists are now challenging the traditional view on organic N. Leu reports that researchers are finding an increasing number of crops that readily take up large amounts of amino acids from SOM.

Role of Boron and Silicon

There is anecdotal evidence to suggest that B, Si and Ca are important in the hierarchy of plant chemistry, and without these nutrients in readily available form, the plant is unable to optimise use of N, Mg, P, C, K and trace elements in the metabolic pathways involved in growth, flower initiation and fruit development. Yamaguchi *et al.* (1986) discuss the cooperative role of B and Ca in the building of the plant cell wall. Dick (2009) states that B is required to activate Si.

Lewin and Reimann (1969) suggest that Si can be considered to be an essential element. Silicon has also been implicated in the water economy of plants, with a higher transpiration rate seen in Si deficient plants. According to Marschner (2002), Si not only contributes to cell wall rigidity and strengthening but might also increase cell wall elasticity during extension growth. In his review, Epstein (1994) reports ample evidence that when readily available to plants, Si plays a large role in growth, mineral nutrition, mechanical strength, and resistance to fungal diseases, herbivory, and adverse chemical conditions of the growing medium. Husby (1998) reported that Si has been shown to ameliorate abiotic stresses and concluded that it has the potential to significantly decrease the susceptibility of plants to disease. Julien (2000) states Si affects the absorption and translocation of several macro- and micro-nutrients. Fruit firmness in both strawberry and plum has been shown to increase following foliar application of Si (Grajkowski *et al.* 2006; Ochmian *et al.* 2006).

Lovel (2009) proposed a hierarchy for how elements work in living organisms and named this the biochemical sequence. He theorises that there are eight elements (B, Si, Ca, N, Mg, P, Ca and K) required in the soil for natural, robust plant health. The sequence of the elements is significant. The presence of B in soil allows adequate Si to be released from clay and primed for plant uptake (Dick 2009). Silicon plays an important role in improving sap circulation, thus facilitating the distribution of relatively immobile nutritive elements throughout the plant (Toresano-Sanchez *et al.* 2010). The postulated biochemical sequence not only applies to plant health, but also impacts on the diversity of the soil's microbial activity. Deficiency or toxicity in any one of the elements disrupts the balance and 'thins out' the interdependent web of microbial species that provide plants with nutrients in their naturally occurring states.

According to Lovel (2009), growers who simply use NPK fertilisers are short-circuiting the biological process where strong sap pressure (B) leads to good nutrient transport (Si), followed by optimal cell division and photosynthesis (Ca, N, Mg and P). High plant energy (C and K) then enables plants to shed enough of their sap as root exudates to feed abundant microbial mineral release, N fixation and protozoal digestion around crop roots – when soils are truly fertile plant health is maximised and reflected in fruit quality and shelf life. While there is logic in the way that the sequence has been put together, there is no scientific proof to support its validity.

The rhizosphere

The rhizosphere is the soil zone immediately surrounding the roots, ie the plant-root interface. It is the most dynamic environment in the soil and is directly influenced by root secretions, exudates and associated soil microorganisms. Root secretions are composed of sloughed-off cells from the growing root tip and mucilage secreted by root cap and epidermal cells, as well as a range of chemical substances released by intact cortical cells and root hairs (Forbes and Watson 1992). Mucilage is a viscous, high molecular weight insoluble polysaccharide-rich material that provides protection from desiccation and binds soil particles to form aggregates (McNear 2013). McNear describes root exudates as including the secretions that are actively released from the root (such as mucilage) and diffusates passively released due to osmotic differences between the cell and soil solution, or lysates from autolysis of epidermal and cortical cells. The organic compounds released through these processes include amino acids, proteins, organic acids, carbohydrates, sugars, vitamins, mucilage, phenolics and other secondary metabolites. Exudates vary according to the stages of plant growth (Lines-Kelly 2005) and act as messengers that stimulate biological and physical interactions between roots and soil organisms, thus modifying the biochemical and physical properties of the rhizosphere. Through the exudation of a wide variety of compounds, roots are able to regulate the soil microbial community, cope with herbivores, encourage beneficial symbioses, acquire nutrients, change the chemical and physical properties of the soil, and inhibit the growth of competing plant species (allelopathy) (Walker *et al.* 2003; McNear 2013). Rhizosphere microbial communities may also play a role in protecting plants from chemical injury; Anderson *et al.* (1995) present evidence of toxic chemical effects being abated or reversed by the presence of microorganisms in the soil.

Root exudates provide the food source for microorganisms, particularly those that form symbiotic relationships such as AMF and N-fixing bacteria. Curl (1986, cited in Anderson *et al.* 1995) states that micro-organisms can also stimulate exudation. Protozoa and nematodes that graze on bacteria are also more abundant in the rhizosphere. Much of the nutrient cycling and disease suppression needed by plants occurs within the rhizosphere. Rhizosphere microbes also produce polysaccharides that bind soil particles, increasing the stability of soil aggregates.

Impacts of conventional farming practices in orchards

Environmental impact of artificial inputs in orchards

Chemical use in perennial fruit orchards has been extensive since World War II. In the Huon Valley catchment in Tasmania, the intensive usage of pesticides due to orcharding has been historically documented; Wotherspoon *et al.* (1994) has estimated annual pesticide usage (insecticides, miticides, fungicides and herbicides) in the region at 50 kilograms of solid and 40 litres of liquid per hectare. This has led to environmental contamination, the effects of which are only recently becoming understood.

The Huon valley catchment in southern Tasmania provides several examples of the long life of many chemicals. Even 10 years after ceasing use of DDT (dichlorodiphenyltrichloro-ethane), residues were found to be significantly higher in three fish species in Mountain River in the agricultural Huon region of Tasmania (up to 10.1 ppm DDT and 11 ppm DDE (dichlorodiphenyldichloro-ethylene, a degradation product of DDT)) than in fish in the less agricultural Russell River catchment (*Huon catchment Healthy Rivers Project - Water quality assessment report*. January 1996). The highest concentrations of unresolved DDT/DEE residues (up to 24.5 ppm) were detected in crabs in the Huon Estuary. While little analysis of systemic pesticides has been undertaken there is sufficient evidence to indicate both the role of the estuary as a sink for contaminants applied upstream and bio-accumulation by aquatic biota. There have also been reports of the persistent pesticide carbaryl, a widely used insecticide and chemical thinning agent in apple orchards, being found downstream of orchards in other catchment areas (S Wilson, pers comm.). Miller (1999) has also reported contamination of waterways by agricultural chemicals in Gippsland.

Although it is well recognised that soil fertility can be improved by regular additions of OM (Handreck 1988; Hillel 1991), conventional agriculture depends on large applications of synthetic chemical fertilisers to sustain high yields. While chemical fertilisers played a significant role in the Green Revolution, excessive use has led to reduction in soil fertility and to environmental degradation (Gyaneshwar *et al*. 2002). Wotherspoon *et al.* (1994) found that each year local Huon Valley orchards used fertiliser at a rate of 500-1,000 kg/ha compared with 250 kg/ha applied to pasture or

235 kg/ha in forestry. According to Bünemann *et al.* (2006) Australian farmers used around 5.25 million t of fertiliser products in 1999, with a value of approximately AU$2 billion. Grobe (1997) reports that growers relying on NPK fertiliser to meet market demand for economically priced fruits and vegetables were finding that their soils were becoming depleted. Excessive fertilisation and poor soil and crop management practices have increased nitrate pollution in groundwater (Linville and Smith 1971; Follet, cited in Sainju and Singh 1997). According to the *Huon catchment Healthy Rivers Project - Water quality assessment report* (1996) several tributaries are showing what the report regarded as high phosphate (up to 0.24 mg/L) and nitrate (up to 0.33 mg/L) levels.

The maintenance of a bare earth strip along the tree row using herbicides is the standard method of weed control in orchards. Herbicides are the pesticide group most utilised in any crop production system in the US (Ozores-Hampton 1998). The use of herbicide to remove vegetation from the tree line leads to a slow reduction in OM in the soil, and has become associated with a number of problems, including decreased populations of beneficial invertebrates, poor water infiltration and retention resulting in runoff of applied water, wastage of applied fertilisers, poor root growth resulting in sub-optimum tree growth and performance, loss in orchard productivity and an increase in herbicide resistance. Prior to the development of herbicides, composted and non-composted organic mulches were an important method of weed control (Altieri and Liebmans – cited in Ozores-Hampton 1998).

Soil degradation

Many issues are associated with soil degradation, however soil fertility and soil erosion are paramount. Soil erosion by both wind and water is affected by SOM which is essential in maintaining soil structure and water infiltration rates. Other large-scale issues that can arise from soil degradation include soil acidification, sodicity, salinity, nutrient leaching and contamination of waterways, and vegetation degradation.

As noted earlier, soil structure is the result of physical, chemical and biological influences operating in the soil (Masciandaro *et al*. 1997). Many orchards are exhibiting signs of soil degradation, usually first seen as reduced water infiltration and declining tree health and productivity. Boucher (1998) describes the problems of soil compaction in orchards in Tasmania caused by a loss of SOM. Compaction decreases water and nutrient infiltration, reduces root growth, decreases water and nutrient uptake, and can also decrease soil oxygen levels (Unger and Kaspar 1994).

Organic matter has a major influence on physical, chemical, and biological properties of soil and creates a favourable medium for biological reactions in soil environments (Aslam *et al*. 1999). Soil OM levels in agricultural soils have decreased with years of cultivation, compared with native soil conditions (Wallace and Terry 1998; Hoogmoed *et al*. 2000). Sainju and Singh (1997) also describe the continuous degradation of SOM following cultivation without adequate plant material being returned to the soil or without replacement using soil amendments.

It has become evident that increasing OM levels in soil can improve soil fertility, nutrient retention and soil structure. Hence the logical step for improving degraded soils would be to improve the OM content of the soil. There are also other benefits to society of using composts and mulches produced from organic wastes, including reduction in landfill. The conversion of these materials for use as a soil improver, an aid to halt further degradation, or to improve agricultural soils (Handreck 1988) is one of the primary benefits.

Nutrient Depletion and Soil Fertility

The chemical and mineralogical properties of soils are important in determining soil fertility. These soil properties include OM, clay, iron and aluminium oxides, salts (N, P, K, S), pH and the percentage of base saturation (Brady and Weil 1999).

Chemical fertilisers often have low use efficiency, meaning that only a portion of the applied nutrients are taken up by plants (Gyanesgwar *et al.* 2002). Ahmed (1995, cited in Gyanesgwar *et al.* 2002) suggests that the use of chemical fertilisers is reaching the theoretical maximum beyond which there will be no further increase in yields. Hence the logical step for improving degraded soils would be to improve the OM content of the soil. Muchovej and Pacovsky (1997) described the OM richness of most compost products as being normally more beneficial at improving the characteristics of a soil than inorganic fertilisers which provided the same chemical nutrients, but in a strictly mineral form. They also stated that C content was usually a great deal higher in organic fertilisers and the N, P, S, present in organic residues was often covalently bound to C. To maintain SOM, Wallace and Terry (1998) suggested levels of OM addition should be around 10 tonne/ha/year for tilled soil.

It is important to note that to obtain a full indication of soil nutrient status, the topsoil and subsoil should be sampled separately as surface soil samples reflect the accumulation of nutrients from recent fertiliser application while subsoil samples are more likely to indicate inherent soil fertility or long-term effects of fertiliser programs (Stiles and Reid 1991). When reporting on their study on the effects of ground cover treatments in a young apple orchard, Choi and Rom (2011) also noted that soil samples collected at a relatively shallow depth may not reflect soil nutrient values at deeper rooting depths.Soil acidity/alkalinity determines the numbers and kinds of organisms that change plant residues into SOM. The pH of the soil directly affects the availability of nutrients to plants (Figure 3). The major nutrients are available to plants in the greatest quantities (and toxic elements are limited) when soil pH is between 6.5-7.0. In a review by Stratton and Rechcigl (1998), it was suggested that the application of composts might improve pH to more neutral levels; however, the acidity of the organic materials in the compost must be identified to ensure that pH was not altered to the detriment of plant growth. For example, if the compost was low in base-forming cations, pH can be reduced and alternatively if farm manures or alkaline composts were used, pH can be increased (Brady and Weil 1999).

The application of chemical fertilisers has been linked to a reduction of pH values in soil. Brady and Weil (1999) reported that chemical fertilisers have had a dramatic effect on pH values over the last fifty years at some sites. The basis of their statement was that microbes in the soil have oxidised the widely used ammonium-based fertilisers to produce inorganic acids, providing H^+ ions that have resulted in lower pH values. Soil CEC and OM are linked with pH. This linkage or general relationship between pH and CEC can be demonstrated by the fact that CEC increases with pH, as less hydrogen ions (H^+) are adsorbed to the negatively charged sites at the particle surface.

Soil fertility can be reduced in several ways: changes in pH, erosion, oxidation and depletion of OM and losses to the atmosphere. To improve soil CEC, OM can be added to a soil more easily than increasing the clay content or changing soil pH. Stratton and Rechcigl (1998) suggested that the addition of compost could increase the number of cations adsorbed by the soil (increased CEC) with improved cation retention in the root zone.

According to Californian soil scientist Ralph Jurgen (quoted in Grobe 1997), over fertilisation with nitrogen is a common problem. He states that this *results in higher magnesium availability, but lowers uptake of potassium, calcium and other nutrients. The end result is rapid cell wall expansion, which results in weak cell walls. This disrupts the transport mechanism of the plant, and results in crops that are more susceptible to insect and disease attack*.

Soil Erosion

With regard to plant production, the top layer or A horizon is the most important layer of the soil. It is typically rich in nutrients, OM and biological activity (Hillel 1991; Pimental *et al.* 1995). In a typical ecosystem, loss of soil material occurs due to the action of wind and water, but when the rate of soil loss is greater than soil forming processes (pedogenesis) the thickness of the fertile A horizon is reduced. The mechanisms of soil erosion and particle deposition by both wind and water can be described in terms of the two equations, Universal Soil Loss Equation (Wischmeier and Smith 1978) and wind erosion equation (Chepil and Woodruff 1963). Soil erosion is initiated when wind speed or surface run off flow rate exceeds the saltation threshold velocity for a given field condition. More simply, wind and water erosion is reduced when soil particle sizes are made larger or the rate of flow of air or water at the soil surface is slowed

Soil erosion rates range from 0.004-0.05 tonne/ha/year in undisturbed forests; in the US and Europe rates of 17 tonne/ha/year have been measured, while in Asia, Africa and South America erosion rates can be as high as 30-40 tonne/ha/year (Pimental *et al.* 1995). Pedogenisis takes place at an average sustainable rate of 1 tonne/ha/year in a temperate climate, depending on soil parent material, land use and climate. Hence it is clear that the rates of soil erosion on farmed land greatly exceed the rate of soil formation. Considering that erosion processes remove topsoil, the most fertile portion of the soil, this eroded soil is 1.3 to 5 times richer in OM than soil left behind. An average tonne of fertile topsoil contains 1-6 kg N, 1-3 kg P and 2-30 kg K. Moderately eroded soils absorb 7-44% less rainfall than the original soil (Pimental *et al.* 1995).

Leaching

Leaching is relevant to both on-farm soil degradation issues as well as off-site problems. Once the nutrients have been leached from the soil they travel through the water table to streams and waterways.

A study into the effect of time of application and continuity of rainfall on leaching of surface applied nutrients found that solute remaining on the soil surface was more readily leached than solute that had diffused into intra-aggregate pore spaces (McLay *et al.* 1991); as the principal source of nutrient leaching losses was considered to be fertilisers, the slow-release action of compost soil amendments could reduce leaching potential. Withers *et al.* (2001) also found that surface runoff of P significantly increased after the application of inorganic and organic fertilisers, suggesting that this was due to dissolved P and not to particulate P. A comparison between surface applied and incorporated amendments found that more P was released in the surface applied amendments regardless of whether the amendment was inorganic or organic. A study by Eghball and Power (1999) into the application of feedlot manure to soil surfaces by both tillage and non-tillage systems found that it was the form of the nutrient within the amendment that was the key to leaching or non-leaching of plant available nutrients. They found that surface application of feedlot manure did not result in significant N losses as it contained mainly organic forms of N and only small concentrations of ammonia, due to the maturity of the amendment, and suggested that more studies were needed to determine the amount of manure and compost N that becomes plant available under different environmental and soil conditions over time without adverse effects such as leaching.

Returning to sustainable production

Interest in alternative production systems has increased with concern growing over the environment and the long-term productivity of the soil (Hanninen 1998). Rovira (cited in Masciandaro *et al*. 1997) states the principal aims of sustainable soil and land uses are to maintain productivity, replenish nutrients removed by crops, enhance desirable soil physical condition and biological activity, minimise use of non-renewable resources, and develop environmental quality.

In orchard systems, there is scope for an integrated approach involving the use of alternative orchard floor management practices to reduce pesticide, herbicide and synthetic fertiliser use, and at the same time improve soil structure and productivity. By building the soil and letting the soil feed the plant, rather than feeding the plant and bypassing the soil system with the use of NPK fertilisers, growers in California found they no longer had to rely on synthetic fertilisers and pesticides to produce marketable crops (Grobe 1997). Massy (2020) provided multiple examples of successful farming without the use of synthetic fertilisers or pesticides. According to Seybold *et al.* (1999), most soil recovery mechanisms are biologically mediated, including formation and stabilisation of soil structure, cycling of nutrients, detoxification of pollutants and suppression of pathogenic organisms. These authors stress that the inability of microorganisms such as mycorrhizal fungi to recover can lead to long term soil degradation.

Incorporation/addition of OM is a proven method of building the soil, and this can be done in numerous ways: application of humates, composts and/or compost teas, use of organic or living mulches, growing cover crops. The use of soil microorganisms to increase the availability and uptake of mineral nutrients for plants is becoming increasingly popular. Inoculation of soils with microbial mixes such as mycorrhizal fungi, N-fixing bacteria or ‘effective’ microbes is termed bio-fertilisation or bio-inoculation.

Esitken *et al*. (2003) lists several plant growth promoting rhizobacteria (PGPR) to include strains in the genera *Pseudomonas*, *Azospirillim*, *Burkholdria*, *Bacillus*, *Enterobacter*, *Rhizobium*, *Erwinia*, *Serrotia*, *Alcaligenes*, *Athrobacter*, *Acinetobacter* and *Flavobacterium*, many of which have N-fixing properties. Khaliq *et al*. (2006) state that inoculation of soil with effective micro-organisms (EM), a mixed culture of active anaerobic and aerobic microbes, along with organic or inorganic materials is an effective technique for stimulating supply and release of nutrients. The potential of EM to increase plant productivity has been reported by Abobaker *et al*. (2016). Cavalcante *et al*. (2012) discusses the emergence of bio-fertilisers as an important component in integrated nutrient supply.

The use of bio-stimulants is also increasing. Bio-stimulants are natural substances applied to soil and plants to improve and regulate physiological processes. When applied in small quantities, bio-stimulants enhance plant growth and development such that the response cannot be attributed to application of traditional plant nutrients. Acid based bio-stimulants include humic acid, fulvic acid and amino acids; extract based bio-stimulants contain seaweeds and fish products.

There is considerable evidence that a transition from traditional to biological agricultural practices can lead to a significant decrease in crop yields in the short term (Oberson *et al*., 1993; Reganold *et al*., 2001). However, several studies have demonstrated that organic systems are able to achieve high fertility and high yields in the longer term (Granstedt and Kjellenberg, 1997; Glover *et al*., 2000; Reganold *et al*., 2001). It should be noted that profitability is not necessarily related to yield; for example, LaCanne and Lundgren (2018) found that profits in corn farms under a regenerative system with high particulate organic matter and low bulk density were nearly twice as high as farms under conventional management, even though yields were lower. As traditional and organic systems both have benefits, the challenge is to integrate these systems in such a way as to maximise the beneficial aspects of each system, while limiting their respective detrimental effects.

Increasing soil organic matter content

As noted previously, compared with native soil conditions, SOM levels in agricultural soils have decreased considerably with years of cultivation, reliance on synthetic fertilisers and extensive use of pesticides, resulting in chemical and physical degradation of the soil. Adequate amounts of SOM maintain soil quality, preserve sustainability of cropping systems and reduce environmental pollution (Fageria 2012).

Crop residues are a readily available source of OM and can have favourable effects on soil restorative processes, including enhancement of soil structure, conservation of soil moisture and addition of plant nutrients as well as increasing SOM (Lal 1995). Other sources of OM used in agricultural applications include animal manure, fresh green-waste, processing waste, sewage sludge and compost. Some of these sources are not appropriate in the production processes of all crops so it is important to consider this when choosing an appropriate material. For example, many buying groups insist that fresh uncomposted manures are not appropriate to use in the production of salad vegetables, due to the health concerns posed. There are, however, fewer restrictions in perennial tree cropping systems when materials are applied to the orchard floor.

Compost

Prior to the introduction of synthetic fertilisers, compost was applied to the soil as a conditioner or amendment, and various Asian countries have been preparing and using compost as a soil amendment for at least 4,000 years without depleting the fertility of their soil (Howard 1950; Reganold *et al.* 1990). More recently, the application of compost has had renewed interest as part of both organic and conventional food production systems. Compost has been defined as a humus like product of an engineering process derived from OM, imparting to the soil all the benefits received from traditional OM additions in such forms as leaf litter and crop residues (Stratton and Rechcigl, 1998). According to Grobe (1997), compost should be used as a stimulant for microbial activity and an activator for soil fertility, rather than as a source of N.

In Australia all commercially produced composts and mulches must adhere to Australian Standard for Composts, soil conditioners and mulches, AS4454-2012. High quality compost typically has the following characteristics before and during composting:

- Total C:N ratio of 25-30:1, by weight. Microorganisms require a C:N ratio of approximately 30 to make essential proteins. If the ratio varies so that less N is available, microbial growth (and nutrient conversion) is limited. If N is low when organic material is being acted upon by microorganisms, it can be to the detriment of the plant (Handreck 1988). As microorganisms are much better at scavenging N in comparison to plants, the N immediately available to the plant may be limited (until microbial biomass reduces and releases the N tied up in the cycle) (Dr M. Line, pers. communication). If N is supplied in greater volumes than the microbial population can process it may mean that the excess N will be lost as ammonium gas (Handreck 1988).
- C:P ratio of 75-150:1.
- Moisture content of 50-55% is optimal in the finished product (Handreck 1988).
- The microbial population in composts and soils are essential to maintain the nutrient cycle, to decompose organic materials and convert nutrients so they are available to plants.

In a review on the effects of compost amendments on soil physical properties, Stratton and Rechcigl (1998) outlined properties such as bulk density, water holding capacity, porosity and aggregate stability that may have been influenced by compost application; this was with reference to marginal soils with poor soil structure and low levels of OM and plant nutrients. Many authors cited in the review attributed the potential benefits of compost applications to OM content and level of microbial activity. Such benefits included improvement of soil structure due to the increased integrity of aggregates stabilised by the interaction of micro-organisms and the mineral fraction of the soil, stabilisation of the aggregates with a subsequent decrease in bulk density, increase in porosity and increase in water filtration rate, and soil erosion prevention. Enzymatic activity was also implicated as contributing to the beneficial effects of micro-organisms, together with fungal hyphae acting as a short term binding agent and aggregate stabiliser.

In a comparative study where organic and inorganic amendments were applied to sandy soils (97% sand), Tester (1990) concluded that the decrease in bulk density and increase in porosity due to compost amendments were significant indicators of root system performance, and that these two factors represented the strength of the soil and the resistance encountered by plant roots. The study was divided in two, with one being a single application of amendment and the other as an annual application over a five-year period. The single application of amendments used compost at rates of 60-240 t/ha and fertiliser at N, P, K total rates of 600 kg/ha, while the annual application used compost at the same rates but fertiliser at a reduced rate of ~ 300 kg/ha. Lime was also added in both studies, as the soil pH was around 4.0. Although the results of the study found that compost amendments improved soil structure more so than fertiliser amendments, it should have been questioned whether the high rates of compost used may have posed environmental concerns (ie. nutrient leaching through to groundwater), been toxic to plants, or been practical and economical for general agricultural production systems.

Annual applications of compost can increase SOM (Maynard and Hill 1994). This leads to a change in physical characteristics, including a decrease in bulk density of the soil, enabling plant roots to penetrate the soil more readily and scavenge a greater volume for nutrients, promotion of fine soil particle aggregation, reduced crusting after rains, and increased water holding capacity. Compost has also been shown to assist in the suppression of plant diseases and pests, through the activity of antagonistic micro-organisms (Sotomayor *et al*., 1999), as well as inducing growth promotion by a direct enzymatic or hormonal effect on plant roots (Raviv, 1998).

Verma *et al.* (2013) demonstrated that surface application of compost increased P mobilisation from rock P, but also reported that plant growth and P uptake were not increased by compost plus P rock compared to compost alone and concluded that both composts and composts with rock P can act as slow-release fertiliser. These conclusions are supported by the findings of Malik *et al.* (2013) who reported increased microbial activity and concentrations of available P pools following soil amendment with three different organic sources. However, these authors found that while all organic amendments used were suitable P sources for plants, farmyard manure was better than poultry litter, leading them to suggest that while organic amendments could be used as alternatives to inorganic P fertilisers, a clear understanding of the relationship among type of P amendment, microbial activity and changes in soil P fractions is required to optimise their use.

Although composts, in lieu of synthetic fertilisers, have a potential use in plant production systems, unrestricted use of compost to realise this potential may not be favourable for the environment or the soil resource in the longer term. In Australia, the Australian Standards for compost only cover production and not regulation of its use. The closest guidelines available are European but remain largely untested for Australian conditions (Wilkinson *et al.* 1998). These guidelines recommended that the benefits from compost should be long term, that composts should not damage soil or plants, and that leaching of nutrients from compost into groundwater should be minimised. In relation to the last point, it has been stated that many countries in Northern Europe have enacted legislation to protect groundwater and soil resources from over-application of nitrogenous fertilisers, manures, and organic wastes (Wilkinson *et al.* 1998). Regulatory requirements governing the processing, distribution, use and disposal of organic materials, together with all other agricultural wastes and biproducts, have also been determined by the U.S. Environmental Protection Agency (Walker *et al.* 1997).

A study by Cooper and Warman (1997) found that compost application increased DHA and organic C levels in soil. The microbial action increased the rate of the incorporation of OM into the soil. In a five-year glasshouse experiment in Italy, fertiliser and compost treatments were applied to a sandy soil (85% sand) to examine possible benefits of long-term compost treatment of soil. Microbial activity was similar across all treatments although yields were higher for the compost treatments than the fertiliser treatments. It was suggested that the microflora developed in the composted mixes consisted of qualitatively different populations offering more beneficial conditions for plant growth (hence, higher yields) and at the same time excluding the development of harmful organisms (Marchesini *et al.* 1988).

Hartley *et al.* (1996) suggest that, if CO_2 emission figures are taken as a measure of total bioactivity in the soil, then adding organic compounds in the form of compost has a substantial and lasting effect on life in the soil. They found that the type of material added was important, with grass and sawdust resulting in greater bacterial and fungal biomass in the soil than herbicide treated plots, and wooldust reducing the bacterial and fungal biomass below that seen in the herbicide plots.

According to Grobe (1997), if soil is completely compacted or too wet or dry, results with compost will be disappointing no matter how high the quality of the compost.

Surface Mulching

Mulching is the process of covering bare soil with some type of material. A layer of litter is typical in natural systems, particularly forests, so mulching can be considered as an agroecological approach to orchard floor management. Mulches can be sourced from a range of materials, including organic (eg. straw, sawdust, grass, greenwaste, compost), non-organic (gravel) and synthetically produced products such as plastic, foil, or shredded rubber.

Covering soil with mulch has been shown to strongly influence crop growth and development as well as the environment (Larsson 1997). Mulches reduce water evaporation and increase infiltration, resulting in greater soil moisture (Knavel and Herron 1986; Schonbeck *et al.* 1993; Lal 1995). Mulches impact on soil temperature, particularly as air temperature increases during summer, with inorganic mulches tending to raise soil temperature while soil temperature is usually reduced under organic mulches such as corn stalk, alfalfa and grasses (Han *et al*. 2015). As root growth is affected by both soil temperature and moisture, application of mulches may be either beneficial or detrimental to tree growth. According to Han *et al*. (2015) the optimal soil temperature for pear root growth ranges from 21.6-22.2°C, and roots stop growing when the soil temperature surpasses 27-29.8°C. Larsson (1997) found that mulches which reduced water loss increased shoot and root growth, and reported pronounced root proliferation in the soil surface but no deleterious effects on root growth in deeper soil layers. In a study of several organic mulches applied at different depths in a newly planted pecan orchard, Foshee *et al*. (1996) concluded that applying at least 20cm of mulch soon after planting would substantially improve tree growth.

The use of mulch also has the potential to increase crop production and to effectively suppress weeds. As they decompose, organic mulches may improve soil physical and biological properties, reducing soil erosion, improving soil structure, minimising soil compaction, increasing water holding capacity and microbial activity, slowing the release of nutrients and controlling soil temperatures (Putnam 1990; Foshee *et al.* 1996; Buckerfield and Campbell 1998; Buckerfield and Webster 1998; Masiunas 1998). Application of organic materials as mulches can also increase SOM (Han *et al*. 2015). However Larsson (1997) suggests that, at least in the short term, it is difficult to achieve improved soil fertility with mulching.

In work undertaken at Tasmania's Grove Research Station, Boucher (1998) demonstrated that mulching of compacted soils with composted sawdust or wood fines could improve water infiltration. Spent mushroom substrate has been shown to improve the environment for plant root growth by decreasing soil bulk density, increasing aggregate stability, reducing clod and surface crust formation, improving water infiltration rates, increasing the water content of the soil, and reducing diurnal temperature changes (Stewart *et al*. 1998). Some of these changes, however, were not evident until repeated applications of 80 t/ha spent mushroom substrate had been made. Taylor (1998) found that applying grape marc as a surface mulch helped retain soil moisture and suppress weeds; there was no change in soil pH during the monitoring period, which was dry. Villareal (cited in Ozores-Hampton 1998) saw increased yields in tomatoes mulched with rice straw which also prevented erosion, slowed weed growth and minimised soil compaction. The benefits of woody mulches in particular are outlined by Granatstein (2021), and include water conservation; weed control; increased tree growth, fruit yield, and fruit size; increased soil carbon and biology; and plant health stimulation. Granatstein (2021) also notes that not all organic mulches are created equal and suggests that research is needed into the effects of mulch based on source species. The physical characteristics of different mulch materials can also impact on the speed at which changes are observed in soil characteristics –

Boucher (1998) noted the rapid changes in soil structure following the application of composted sawdust compared with wood fines, concluding that because the composted sawdust was biologically predegraded it was more readily incorporated into the soil.

Boynton and Anderson (1956) report that the effects on ‘McIntosh’ apple tree behaviour of mulching with hay were similar to and additive to the effects of N fertilisation. They found mulching increased K and N intake by the trees, however there was no effect on Mg, Ca, P or B. Hartley and Rahman (1994) found that mulches (straw, compost, sawdust, wooldust) had negligible effect on leaf and fruit nutrient analysis. Further work by Hartley and Rahman (1998) confirmed that even though mulches affected the chemical characteristics of the soil there was little effect on the nutrient status of apple leaves or fruit. However, in a study of cover crops and mulching in an organic apple orchard in Denmark, Kűhn *et al*. (2009) found that cut grass mulch applied to the tree row increased leaf N, shoot growth and yield but decreased fruit colour, while clover mulch had no effect other than an increase in soil water content; hence they concluded that the effect of mulch clippings was dependent on the cover crop material. In a study with red Delicious apple, alfalfa (*Medicago sativa* L.) hay mulch increased tree growth, yield and leaf N, but fruit colour was reduced (Granatstein and Mullinix 2008). After finding that green compost and woodchip mulches supplied larger amounts of N compared to shredded paper and mow & blow mulches, Choi and Rom (2011) concluded that tree growth was affected more by N input from mulch rather than soil after finding that green compost and woodchip mulches improved shoot growth and TCSA as a result of greater amounts of available N.

A six-year Canadian study comparing a range of living and organic mulches with a herbicide control found that spray-on paper mulch improved tree growth and annual yield and reduced weed growth (Hogue *et al*. 2010). Shredded paper mulch has also been shown to give good weed control and increase tree growth in red Delicious apple, but had to be replaced annually as it decomposed rapidly (Granatstein and Mullinix 2008).

For weed control, mulches are more expensive to establish and maintain than herbicides because, as the material breaks down, more must be added to maintain the necessary thickness for optimum weed control. Hence the benefits of compost/mulch utilisation must compensate for the additional expense. Ozores-Hampton (1998) reports that some economic studies indicate the increase in crop value justifies the greater cost. Merwin *et al.* (1995) also reports that higher establishment and maintenance costs of certain organic and synthetic mulches in apple orchards were offset by their prolonged efficacy over successive years. Singh *et al.* (cited in Ozores-Hampton 1998) reported that organic mulches applied at 5 t/ha in herb production were able to control weeds as effectively and at lower costs than the herbicides simazine, diuron and oxyfluorfen.

The choice of mulching materials can have an influence on soil fauna. Hartley and Rahman (1994) found that earthworm populations were increased by straw and compost, but reduced by sawdust, wooldust and herbicide. Trials in Australia’s Barossa Valley by Buckerfield and Webster (1998) showed significant increases in earthworm activity using straw under vines, with substantial savings in soil water and increases in grape yields. Biggs (1997) also reported similar effects following the application of straw under vines. Whalen *et al.* (1998) report that earthworm numbers and biomass were significantly greater in manure amended plots compared to inorganic fertiliser treated plots for the six years of the study period and the following two years. According to Peres *et al.* (1998), organic matter quantitatively increased the abundance and biomass of the earthworm community in French vineyards. These earthworm community changes were associated with an increase in granular bioturbated areas and in macroporosity in the top soil layer. Sparrow *et al.* (1999) found lower earthworm numbers in cropping paddocks compared with pasture paddocks, but also reported a loss of organic C which may have contributed to this observation. Both soil type and mulch composition impact on soil fauna. Bound (2003) observed that earthworm numbers were at least three times higher under greenwaste, compost, living grass and hemp mulches compared with herbicide strip, but numbers were also higher in clay soils than in sandy soil. Hemp mulch also increased earthworm numbers to over 1200 per m^2 compared with other mulch types which averaged 350 worms per m^2.

Use of straw mulch under vines has demonstrated significant increases in soil moisture (Biggs 1997); the additional OM and increased earthworm activity also improved soil conditions, leading to increased yields. Buckerfield and Webster (1998) also report that a surface mulch significantly enhanced the development of young vines and suggest that composted matter can be considered an alternative to straw mulches. They found that a 5 cm layer of composted ‘green-organics’ was as effective as 20 cm of straw in conserving soil moisture undervine. However, they concluded that it is essential that only compost which complies with the Standard AS-4544 is used to reduce risks from weed seed and plant pathogens.

Heavy fertilisation before mulching with woodchips has been shown to increase shallow root growth of black currants Larsson (1997). Combining organic manure with chemical fertiliser can increase microbial activity, however Ding *et al.* (2013) suggested that there is a threshold effect of organic manure addition on soil microbial residue build-up after finding that the highest organic inputs did not produce the highest amounts of microbial residues.

Manna *et al.* (2001) found that mulch application increased microbial activity and biomass in soil under a soybean-wheat rotation and Mundy and Agnew (2002) reported higher numbers of soil fungi under mulch treated plots compared with non-mulched. According to O'Callaghan *et al* (2001), microbial control of soil-dwelling pests and pathogens depends on the successful establishment of microbial inocula in soil. This can be achieved through adequate soil moisture and lower soil temperatures.

Cover crops / Living mulches

An alternative to organic mulches is the use of cover crops or living mulches. Cover crops have been defined by Hartwig and Ammon (2002) as any living ground cover that is planted into or after a main crop and then commonly killed before the next crop is planted, while living mulches are defined as cover crops maintained as a living ground cover throughout the season. Use of perennial species for the living mulch enables the sward to be maintained without the need for reseeding each year; where reseeding is required, as in the case of annuals, this is normally done by reseeding directly into the suppressed cover crop (Hartwig and Ammon 2002). Cover crops are becoming increasingly common in vegetable production, but in perennial cropping systems such as orchards, a living mulch dominated by perennials is more logical and many growers have adopted a version of living mulches with a permanent sward in the inter-row, even though a bare strip under the tree row is still maintained.

Grasses, legumes and *Brassica* species have all been used as living mulches. Living mulches have been shown to reduce soil compaction problems in vegetable production systems (Nicholson and Wien 1983; Stirzaker and White 1995). Other benefits of living ground covers include increased SOM, improved soil structure, reduced mechanical tillage, and decreased erosion. An important advantage is the ability of ground covers to suppress weed growth, reducing or removing the necessity of herbicides (Hanninen 1998) and potentially preventing the development of herbicide-resistant weeds (Hartwig and Ammon 2002). Cover crop mulch systems modify the micro-environment of the crop, impacting on pest populations and crop yields (Masiunas 1998), and also reduce soil erosion through diminished raindrop impact and surface runoff (Sainju and Singh 1997). According to Ingels *et al.* (1994), cover crops are recognised as an important component of 'sustainable' production systems in most areas of California.

Up to 40% of the N fertiliser applied to orchards each season can be lost by leaching. This loss of soil nutrients can be minimised by the use of deep-rooted cover crops to retrieve and recycle the lost nutrient (Stork and Jerie 1996). Several authors have suggested that autumn established cover crops prevent nutrients from leaching during winter months by capturing excess nitrate and by recycling nutrients (Eckert 1991; Paine and Harrison 1993; Shepherd and Lord 1996). When balanced nutrient resources are available, apples and living groundcovers compete for N and tree growth is inhibited (Shribbs and Skroch 1986), however, different species exhibit different degrees of competition and nutrient uptake. Shribbs and Skroch (1986) reported that cocksfoot (*Dactylis glomerata* L.) and red sorrel (*Rumex acetosella* L.) inhibited growth of 'Golden Delicious' apple trees more than Kentucky bluegrass (*Poa pratensis* L.); the more competitive ground covers had greater mass, which probably increased N capture. Use of legumes as ground covers can increase the availability of N, but there is the potential for excess N, particularly when additional inorganic N is added; Granatstein and Mullinix (2008) reported that red Delicious apple trees with white clover (*Trifolium repens* L.) understorey showed increased growth and yields and high leaf N, but fruit quality was negatively impacted, with reduced colour and firmness.

The most often reported disadvantage of vegetative ground covers is that of competition for water and nutrients between the crop and cover vegetation, resulting in reduced crop growth. If a cover crop is actively growing during the early spring, soil moisture may be depleted (Drost and Price 1991), and this is likely to be to the detriment of the crop. Working with a range of cover crops, Glenn *et al.* (1996) and Welker and Glenn (1988) reported reduced growth in peach, Shribbs and Skroch (1986) and Merwin and Stiles (1994) found growth depression in apple trees, and Forshee *et al.* (1995) in young pecan trees. Hogue *et al*. (2010) reported that several cover crops including clover sweet clover, winter rape, hairy vetch and annual grasses were all sufficiently competitive to diminish tree growth and yield in 'Gala' apple. In a four-year study by Ingels *et al.* (1994), 20-25% more water was used by resident vegetation and strawberry clover compared with a bare floor in an almond orchard. While summer-active cover crops in orchards compete directly with the cash crop for water, winter cover crops have relatively little impact on soil moisture (Ingels *et al.* 1994). One way of avoiding this problem of competition is perhaps to use summer dormant species. Ingels *et al.* (1994) suggest that summer dormant perennial grasses have potential value in orchards and vineyards and conclude that, in spite of these problems, the soil improvements resulting from cover crops may lead to more efficient use of water, especially on sandy soils (Ingels *et al.* 1994).

The effects of living mulches on coffee have been found to be both species- and site-specific (Bradshaw and Lanini 1995). Parker and Meyer (1996) found great differences between cover species and stressed the need for identification and selection of non-competitive vegetative covers. Grasses and legumes are reported to have both beneficial and detrimental characteristics. Determining an appropriate cover crop for a given system will depend on finding a species that effectively inhibits the wide diversity of weed species found in orchards without competing with the trees (Bradshaw and Lanini 1995). Plant material and establishment method can also impact on the success of cover crops as living mulches; Harrington *et al*. (1999) found that *Dichondra micrantha* formed dense swards more rapidly when started from seeds compared to stolon fragments, while Bradshaw and Lanini (1995) reported that *Commelina diffusa* transplants established more rapidly than stolons of *Arachis pintoi* or seed of *Desmodium ovalifolium* due to the greater plant biomass. Bradshaw and Lanini (1995) also concluded that the management intensity provided during the first three months after planting will affect how soon a cover crop forms a complete soil cover and becomes effective in suppressing weeds; however they also acknowledged that an intensive weeding program during establishment was unlikely to be viable for growers.

A summary of some of the effects of different mulches on crop growth and yield, and soil characteristics and fauna can be found in Tables 4 and 5.

Exudates from actively growing plants provide a food source for microbes (Jones 2020), so ensuring full ground cover with a range of species is likely to increase the abundance and diversity of the soil microbial community. The effects of cover crop species on microbial community functional diversity at different soil depths in apple orchard inter-rows was examined by Jiao *et al*. (2013), comparing clean tillage with native wild grasses, red clover and ryegrass. They found that root distribution was the dominant factor on microbial biomass and activity at different depths, with the deeper rooting red clover showing high diversity at all measured depths. Fierer *et al*. (2003) attributed the vertical soil distribution of microbial communities to the relative decline in carbon availability with increasing soil depth.

Increasing biodiversity (beneficial insects**)**

Pest problems in agriculture are often the product of low biodiversity and simple community structure on numerous spatial scales (Tscharntke *et al*. 2012). According to Jones (2020), diverse communities exhibit far greater resilience to stress (eg. drought) and resistance to pests/diseases.

Mulches, either organic or cover crops / living mulches, often improve pest control by attracting and supporting populations of beneficial parasites and predators. These natural enemies include predators of aphids and mites, such as lady birds, lacewings, syrphid flies, predatory bugs, and parasitic wasps and flies (Alway 1998). Ingels *et al.* (1994) also suggests that cover crops may provide food or shelter to beneficial insects, mites and spiders, and may compete with and suppress weeds. Any proliferation of beneficial invertebrates is likely to result in reduced pest pressure, assisting in the reduction in pesticide use

LaCanne and Lundgren (2018) reported that pests were 10-fold more abundant in insecticide-treated corn fields than on insecticide-free regenerative farms. Lower pest abundance has been reported in cornfields with greater insect diversity, enhanced biological network strength and greater community evenness (Lundgren and Fausti 2015). Studying plant and arthropod biodiversity within prairies, pastures and cornfields, Schmid *et al*. (2015) found that species richness was highest in the undisturbed native prairies (148 species), with a 31% reduction in pastures, and a 77% reduction in cornfields. They also demonstrated a correlation between habitat biodiversity and gut bacterial diversity of insects living in that habitat and noted the potential importance of gut bacterial species richness in expanding the dietary breadth and services that insects can perform in a habitat. Christine Jones (2020) described how a citrus grower in Florida reversed the devastating problem of Citrus Greening (a bacterium *Candidatus liberibacter asiaticus* (HLB)) which is transferred from tree to tree via the sap sucking Asian citrus psyllid *Diaphorina citri*) in monoculture citrus orchards by planting multispecies cover crops to increase plant diversity. She noted that increasing diversity changes microbes in plants, so by rebalancing the system, the HLB bacteria were no longer dominant. According to Lundgren and Fausti (2015) increased habitat biodiversity can lead to a suite of ecosystem benefits, which include increased methane consumption, increased predation of pest eggs, and decreased pest pressure.

In discussing agroecological approaches to tree fruit production, Granatstein (2021) describes numerous examples of insect biocontrol. Reducing the mowing frequency in pear orchards resulted in an increased cover of grasses, broadleaf plants and broadleaf plants in flower, and led to a substantial increase in predators and parasitoids, with sweep net samples of natural enemies in the ground cover and tree canopy dominated numerically by spiders (Araneae), parasitic Hymenoptera, and predatory Heteroptera, with lesser numbers of Syrphidae, Neuroptera and Coccinellidae (Horton *et al*. 2002). De Pedro *et al*. (2020) confirmed that the ground cover in pear orchards has a significant impact on the diversity and abundance of arthropods, with a rich cover of vegetation increasing the biodiversity of ground-dwelling arthropods. Reviewing 66 studies on the management of floral biodiversity in apple orchards, Herz etal (2019) reported that resident natural enemies and their impact in pest control reacted positively to the introduction of a more diversified vegetation, concluding that careful selection and management of plants with particular traits exploitable by most natural enemies is a key-point for success.

Impact of soil organic matter on crop growth and yield

Impact on tree growth

There are limited studies on the impact of increasing OM in the tree-line on growth of perennial tree crops. In relation to application of mulches in perennial cropping situations, reports on crop growth are conflicting. In studies on a range of different mulch materials, Bound (2003) reported an increase in tree trunk cross-sectional areas (TCSA) with green-waste or hemp straw mulches, but observed different results with composted bark and bark/fishwaste mulches in two different orchards on different soil types. Using a range of organic mulches in a pecan orchard Foshee *et al.* (1996) found that TCSA of mulched trees were larger than those in un-mulched plots, and increased linearly as mulch depth increased (10, 20 or 30 cm). They concluded that common yard-waste mulches (leaves, grass clippings, clipped limbs, pine nuggets) can be used effectively to increase growth of young pecan trees.

Compost mulches have been shown to promote the growth of both young and established vines, even in irrigated soils with adequate organic content (Biggs 1997), and in olives (Bound 2003). In comparing cultivation, bare soil and straw treatments, Cockcroft and Tisdall (1974) found that straw treatments produced the most vigorous trees, whereas Hartley and Rahman (1994) found that a range of mulches including straw, compost, sawdust, and wooldust had negligible effect on tree growth. Biggs (1997) reported a 50% increase in growth of young almonds under 15 cm of mulch; similarly, Goulart *et al.* (1996) reported an increase in canopy volume in blueberries following mulching with a 10 cm layer of rotted sawdust.

These reported differences may be due to a multitude of factors including soil type and initial condition, along with origin, maturity and application thickness of the mulch material

Crop yield and quality

There have been numerous reports discussing the effects of organic composts and mulches on crop yields, with varying results. Larsson *et al*. (1997) reported that wood chip mulch negatively affected the growth of black currant (*Ribes nigrum*) as a result of N deficiency, postulating that this was the result of a lower potential NH_4^+ oxidation rate and a higher metabolic quotient. Hartley and Rahman (1994) found that mulches (straw, compost, sawdust, wooldust) had negligible effect on tree growth or fruit yield, however, Goulart *et al.* (1996) found an increase in blueberry yield and berry size with rotted sawdust mulch. Boynton and Anderson (1956) saw an increase in fruit size of 'McIntosh' apple in plots mulched with hay, and Baxter (1970) found straw mulch around apple trees doubled the fruit yield in the 5th and 6th years when compared to a cultivation treatment for weed control. In addition to seeing an increase in fruit size at harvest in apple and peach trees following mulching, Hartley *et al* (1996) found that mulched apple trees carried relatively higher return bloom in the season following a heavy crop.

By incorporating composts into soil, Bound and Wilks (2003) observed increased yields in potato and lettuce crops, however when lime was added to the compost instead of fertiliser, yields were reduced. They also reported an increase in growth of grapevines following the addition of composted eucalypt bark mulch along the rows, however the level of maturity of the compost affected the amount of growth, with fully composted mulch producing the most growth, and a gradation in growth with semi-composted and then raw mulch. However, all mulch types produced more growth than un-mulched plots.

The impact of mulching on leaf nutrient levels reported by Bound (2003) agrees with the findings of Hartley and Rahman (1994) who found that mulches had negligible effect on leaf and fruit nutrient analysis. While there were variations between mulches in the levels of soil nutrients in year one, by year two these differences were no longer evident. This suggests that once mulches begin to degrade, nutrients are released into the system and become available for uptake by plants.

In mulched vineyards, Biggs (1997) reported a 50% increase in grape yields without a change in juice quality. Mundy and Agnew (2002) reported a lower incidence of bunch rot on grapes from mulched plots compared with un-mulched plots. Hemp mulch has been shown to reduce the incidence of powdery scab in potatoes (Bound and Wilks 2003). The disease suppressing effect of organic material supplements has been reported by several authors.

In comparing three low growing ground cover species with bark mulch and herbicide, Hartley *et al* (2000) found that ground covers reduced tree growth and fruit yield in the first year. Bound (2003) reported a reduction in crop load and yield in two apple orchards in the first year of study on living mulches (*Dactylis glomerata* and *Festuca ovina*), but there was no effect in the second year once the grasses had become established. Fescue (*Festuca longifolia*) has been found to reduce apple yield after three years, but this treatment also reduced the proportion of small reject apples (Hartley and Rahman 1998). However, *Dichondra* ground covers have been shown to cause no decrease in fruit yields when grown under well established apple trees (Harrington *et al.* 1999). These authors also saw no differences in soil C, N or pH.

Neilsen *et al.* (1999) found that greater vegetation competition in apple orchards decreased yield but had few effects on leaf and fruit nitrogen levels. They also reported that potassium levels in leaves and fruit increased with increasing vegetative competition, as did titratable acidity of stored fruit, red colour and fruit firmness, however total soluble solids (TSS) was reduced at harvest. Atkinson and Crisp (1983) also showed the yield of both young and mature apple trees was reduced by grass between the tree rows.

Working with black currants (*Ribes nigrum*), Larsson (1997) and Larsson *et al*. (1997) found that competition for water from cover crops growing at either side of the rows resulted in reduced fruit yield. Tworkoski *et al.* (1997) reported that competition with grass will reduced fruit yield and yield efficiency in young peach trees, largely by interfering with N availability and uptake. They suggested that internal sink competition and competition among plants can interact to affect the partitioning of dry mass and N within the current-year growth of peach trees. Putting this into practical terms, they suggest that peach trees with more competition from grass may require less fruit thinning than trees with less competition. However Bound (2003) found no negative effects of living grass mulches in an apple orchard over three years.

Using bio-fertilisers to improve sustainability in orchard crops

In addition to improving microbiological activity in the rhizosphere, N-fixing bacteria and AMF have been found to significantly enhance the growth and production of several fruit plants (Aseri *et al.* 2008). In an examination of N-fixing bacteria and AMF used either alone or in combination, Aseri *et al.* (2008) found that a combined application of *Azotobacter chroococcum* and *Glomus mosseae* was most effective, not only in enhancing the rhizosphere microbial activity and concentration of metabolites and nutrients, but also in assisting the establishment of pomegranate plants under field conditions. They also reported improved plant growth and fruit yield as long as 5 years after inoculation at planting.

Root inoculations of *Bacillus* M3 and OSU142 and *Microbacterium* FS01 have been reported to promote tree growth and yield in apple trees (Karlidag *et al.* 2007). However these authors found growth responses varied with different combinations of these bacteria. Many PGPR strains are able to produce the plant growth regulators IAA, cytokinin and other plant hormones in the rhizosphere, hence they suggest that the observed increases in growth and yield may be due to the production of plant growth regulators and an increase in available nutrients in the rhizosphere.

Cavalcante *et al.* (2012) reported improvements in fruit size and quality of passion fruit following treatment with simple biofertiliser brewed through anaerobic fermentation from fresh bovine manure, and enriched biofertiliser brewed from fresh bovine manure plus protein and nutrient sources. They found that the simple biofertiliser promoted optimum supplies of K, Ca and S whereas N, P, K and Ca were optimised in the enriched biofertiliser, hence they concluded that bovine biofertiliser could be an important key to reducing chemical fertiliser use while still maintaining fruit quality and profitable returns.

The use of biofertilisers need not be restricted to soil applications. Esitken *et al.* (2003) reported a 30% yield increase in apricot following a full bloom application of *Bacillus* OSU142; application in the following year resulted in 90% yield increase. Additionally, these authors reported increased shoot length and higher N, P, K, Ca and Mg content of leaves. They concluded that the better nutrition in the treated trees may have promoted flower bud formation and/or decreased the abortive flower ratio. Karakurt and Aslantas (2010) concluded that the growth increase effects observed in their studies of four strains of PGPR on several apple cultivars could be explained by the production of plant growth regulators by the bacteria. Sudhakar *et al.* (2000) reported an increase in mulberry leaf yield and higher leaf protein content following foliar application with N-fixing bacteria. Of the three bacteria studied they found *Azotobacter* was more beneficial than *Azospirillum* or *Beijerinckia*. After finding no ill effect on silkworm rearing, they concluded that foliar application of biofertilisers, especially *Azotobacter*, could safely be used with half the normal dose of chemical N fertiliser to improve mulberry leaf production.

In summarising the work of other researchers, Sudhakar *et al.* (2000) concluded that the advantages of foliar applications of biofertiliser over soil applications were substantial and included:

- fixation of N at the site of its utilisation
- N fixers encounter less competition from other microorganisms and environmental factors on the phylloplane (leaf surface) compared to the rhizosphere
- reduction of foliar diseases as a result of N fixers antagonising the pathogens.

Bacillus subtilis strain EBW4 has been used as a biological treatment of apple replant disease (ARD). Utkhede and Smith (1993) reported consistent performance over three years of this *B. subtilis* strain on growth of newly planted apple trees, suggesting that the mechanism may be through production of antibiotics that are inhibitory to pathogens isolated from ARD soils. They also report that this strain has the ability to control crown and root rot of apple trees caused by *Phytophthera cactorum*.

Observing a positive response in apple seedling growth, nutrient uptake and soil fertility following soil inoculation of locally isolated strains of *Azotobacter*, *Azospirillum* and AMF, Singh *et al*. (2013) concluded that multi-inoculation of synergistically interacting species caused rhizosphere modification through changes in root colonisation and microbial counts.

In a comparison of bio-organic fertiliser which was a combination of manure composts and antagonistic microorganisms, and organic fertiliser, Qiu *et al.* (2012) reported an 83% suppression of *Fusarium* wilt in cucumbers which led to a three-fold reduction in yield loss. They concluded that biofertiliser application was an effective approach to suppress *Fusarium* wilt through inhibition of the soil-borne pathogens and recovery of microbial populations damaged by *Fusarium*.

According to O'Callaghan *et al* (2001), microbial control of soil-dwelling pests and pathogens depends on the successful establishment of microbial inocula in soil. This can be achieved through adequate soil moisture and lower soil temperatures. Bound and Wilks (2003) reported higher soil moisture content in lettuce plots showing the higher levels of microbial biomass.

Conclusions

It is possible to move away from conventional agriculture with its heavy reliance on pesticides and synthetic fertilisers to a natural system that increases biodiversity, provides natural control of pests, and builds soil health. The common misconception that sustainable agriculture means a return to old farming methods needs to be addressed; use of the term biological or regenerative, rather than sustainable, brings the emphasis back to where farmers need to be looking in the future. Regenerative farming works with natural systems and processes to build optimum soil and plant health, while also incorporating the best of conventional farming methods to maintain production levels and quality. Not all regenerative practices are suitable for perennial tree production, particularly in established orchards, but lessons can be learnt from practices such as permaculture food forests and by referring back to natural ecosystems. It is clear that biodiversity, both above and below ground, is the key in the development of ecosystem services that enable a move away from reliance on synthetic fertilisers and pesticides.

Most orchardists in Australia have planted permanent grass swards in the inter-rows, but these can be improved by increasing species diversity. Use of biocontrol methods for pest control is becoming increasingly common along with the incorporation of compost into soil prior to planting new blocks. These practices are a good start to reinstating a healthy ecosystem. To become truly regenerative, a paradigm shift is needed to enable a return to complex systems with strong food webs and beneficial trophic interactions. The starting point is to increase biodiversity within the orchard, and simple methods for achieving this include:

- increasing soil organic matter
- diversifying orchard floor vegetation
- use of cover crops
- mulching in the tree row
- mow and blow inter-row vegetation
- reducing frequency of mowing
- planting hedgerows around the orchard and/or between blocks
- planting of multiple tree species
- use of biocontrol strategies rather than pesticides

There is the opportunity to design new plantings to include more ecological functions that result in increased system self-regulation and decreased costs and environmental impacts; Granatstein (2021) observed that although redesign is a difficult change to make it yields the most sustainability improvement per unit of change. There is already extensive research undertaken, so as noted by Granatstein (2021), we need to “connect the dots” to maximise the benefits of existing knowledge and to determine what future research needs to be undertaken for specific situations..

***Table 4**: Effect of tree-line mulches on crop growth and yield. Note that impact is in relation to an herbicide or untreated control.*

Mulch type	Impact	Crop	Authors
Alfalfa (*Medicago sativa* L.) hay mulch	• Increased tree growth and yield but reduced fruit colour • High leaf N • Delayed autumn senescence	Red Delicious apple	Granatstein & Mullinix 2008
• Compost • Straw • Sawdust	No effect on yield, tree growth or leaf/fruit nutrient levels	Apple	Hartley & Rahman 1994
Compost	Reduced yields	Apple	Hartley & Rahman 1998
Composted eucalypt bark	Increase in growth	Grapevines	Bound & Wilks 2003
Composted green organics	Increased vine vigour and yields	Grapevines	Buckerfield & Webster 1998
Composted green waste + vermicompost	• 20% yield increase • Increased fruit size	Cherry	Buckerfield & Campbell 1998
Green waste	• 50% yield increase • No change in juice quality	Grapevines	Biggs 1997
Green compost, woodchips	Increased growth and earlier bearing	Enterprise apple	Choi & Rom 2011
• Hardwood leaves • Pine nuggets • Pine straw • Grass clippings • Chipped limbs	60-70% increase in growth of young trees	Pecan	Foshee *et al*. 1996
• Plastic – black (0.2 mm thick) • Woodchips	No effect on yield	Blackcurrant	Larsson 1997
Rotted sawdust	increase in canopy volume	Blueberry	Goulart *et al*. 1996
• Shredded paper • Woodchips • Mow • Black fabric cloth	No impact on foliar nutrient status, tree growth or yield.	Braeburn, Gala, Jonagold apple	Choi *et al*. 2011
Straw	Increased yield	Grapevine	Buckerfield & Webster 1996
Straw	Increased tree growth	Apple	Walsh *et al*. 1996
• Silage • Woodchips	Increased root growth	Black currants	Larsson 1997
Vineyard & winery waste	Lower incidence of bunch rot	Grapevines	Mundy & Agnew 2002
• Yard waste wood chip mulch • Shredded paper mulch	Increased tree growth, no effect on yield or fruit colour	Red Delicious apple	Granatstein & Mullinix 2008
Yard-waste mulches	Increased growth	Pecan	Foshee *et al*. 1996
• White clover (*Trifolium repens* L) • Sweet clover (*Melilotus* L.) • Winter rape (*Brassica napus* L) • Hairy vetch (*Vicia villosa* L.) + oats (*Avena sativa* L.) + annual rye (*Secale cereale* L.)	Diminished tree growth and yield	Gala apple	Hogue *et al*. 2010
• Cocksfoot (*Dactylis glomerata* L.) • Red sorrel (*Rumex acetosella* L.)	Inhibited tree growth	Golden Delicious apple	Shribbs and Skroch 1986
• Cocksfoot (*Dactylis glomerata*) • Fescue (*Festuca ovina*)	Reduced crop load and yield in first year of study but no effect once established	Royal Gala & Jazz apple	Bound 2003
• Dichondra (*Dichondra micrantha*)	Reduced growth and yield in the first year	Apple	Hartley *et al*. 2000

• Hydrocotyle (*Hydrocotyle heteromeria*) • Creeping red fescue (*Festuca rubra*) + white clover (*Trifolium repens*)			
Dichondra (*Dichondra micrantha*)	No effect on yield	Apple	Harrington *et al*. 1999
Hard fescue (Fescue longifolia)	Yields depressed but less reject fruit	Apple	Hartley & Rahman 1998
• Fescue (Festuca rubra) • Rough meadow grass (Poa trivalis)	• Variable effects on yield across years and cultivars • No effect on tree growth	Peach	Glenn & Welker 1996
Kentucky bluegrass (*Poa pratensis*) + orchard grass (*Dactylis glomerata*)	• Increased leaf P, K • Low leaf N	Bisbee Delicious apple	Neilsen *et al*. 1986
• Lupin (*Lupinus albus*) + wild carrot (*Daucus carota*) mix • Permanent grass (*Festuca rubra*)	Reduced yield and growth rate	Apple	Walsh *et al*. 1996
White clover (*Trifolium repens* L.) - mown and flamed	• Increased tree growth, no effect on yield or fruit colour • High leaf N	Red Delicious apple	Granatstein & Mullinix 2008
Winter rye (*Secale cereale* L)	No effect on tree growth or yield	Red Delicious apple	Granatstein & Mullinix 2008
Fresh cut alfalfa (*Medicago saliva*) + cocksfoot (*Dactylus glomerata*)	Reduced yield	Blackcurrant	Larsson 1997 Larsson *et al*. 1997
Fresh cut red clover (*Trifolium pratense*) + timothy (*Phleum pratense*)	Reduced yield 2 out of 3 years	Blackcurrant	Larsson 1997 Larsson *et al*. 1997

***Table 5**: Effect of mulches on soil characteristics and soil fauna. Note that impact is in relation to an herbicide or untreated control.*

Mulch material	Impact	Crop	Authors
Compost	Increased earthworm numbers	Apple	Hartley & Rahman 1994
Composted green organics	Increased soil moisture	Grapevines	Buckerfield & Webster 1998
• Composted green waste • Composted green waste + vermicompost	Increased soil moisture	Cherry	Buckerfield & Campbell 1998
• Corn stalk • Purple alfalfa • Tall fescue • Bluegrass	• Reduced summer soil temperatures • Increased available P, K • SOM increased by corn stalk	Asian pear	Han *et al*. 2015
• Fresh cut alfalfa (*Medicago sativa*) + cocksfoot (*Dactylus glomerata*) • Fresh cut red clover (*Trifolium pratense*) + timothy (*Phleum pratense*)	Total C, N unaffected	Blackcurrant	Larsson *et al*. 1997
Geotextile mulch	• Higher soil water content • High spring/summer soil temperatures	Apple	Walsh *et al*. 1996
Grape marc	• Increased winter and reduced summer soil temperatures • Retained soil moisture • Suppressed weeds	Grapevines	Taylor 1998
• Greenwaste • Compost • Hemp straw	earthworm numbers increased by > 300% - 350 m^{-2} in compost and greenwaste and 1200 m^{-2} in hemp straw	Royal Gala & Jazz apple	Bound 2003
Plastic film	Increase in summer soil temperature	Asian pear	Han *et al*. 2015
Plastic – black (0.2 mm thick)	Increase in summer soil temperature (3.2°C)	Blackcurrant	Larsson *et al*. 1997
Plastic mulch (black) - woven	Amplified daily and annual soil temperature fluctuations	Bisbee Delicious apple	Neilsen *et al*. 1986
Shredded paper	• Good weed control but required annual renewal • Increased water infiltration	Red Delicious apple	Granatstein & Mullinix 2008

	• Lower spring soil temperature		
Spent mushroom substrate	• Reduced soil bulk density • Reduced clod & surface crust formation • Increased aggregate stability • Increased infiltration rate and soil water content • Reduced diurnal temperature changes	Vegetable crops	Stewart *et al*. 1998
Straw	Increased soil moisture	Grapevines	Biggs 1997
Straw	• Higher soil water content • Buffered soil from temperature variation	Apple	Walsh *et al*. 1996
• Straw • Compost	• Increased earthworm numbers • Reduced weed cover	Apple	Hartley & Rahman 1994
Straw	• Increased earthworm numbers • Reduced water use	Grapevine	Buckerfield & Webster 1996
• Sawdust – composted • Wood fines	• Improved infiltration • Composted sawdust showed rapid improvement in soil structure	Apple	Boucher 1998
• Sawdust • Wooldust	Decreased earthworm numbers	Apple	Hartley & Rahman 1994
• Silage • Woodchips	Higher soil moisture in spring	Black currants	Larsson 1997
Woodchips	Increase in soil OM, nitrate, Mg, B	Braeburn, Gala, Jonagold apple	Choi *et al*. 2011
Woodchips	N deficiency in plants	Black currant	Larsson *et al*. 1997
Yard waste woodchip mulch	• Good weed control for 3 years • Lower spring soil temperature • Increased water infiltration	Red Delicious apple	Granatstein & Mullinix 2008
• Alfalfa (*Medicago sativa* L.) hay mulch • White clover (*Trifolium repens* L.) - mown and flamed	• Lower spring soil temperature • Increased water infiltration	Red Delicious apple	Granatstein & Mullinix 2008
• Cocksfoot (*Dactylis glomerata*) • Fescue (*Festuca ovina*)	Earthworm numbers tripled	Royal Gala & Jazz apple	Bound 2003
Cress (*Lepidium sativum*) + vermicast	• Increased microorganism, worm & plant root activity in clay and sandy soils • C & N metabolism accelerated	Pot trials	Masciandaro *et al*. 1997
Dichondra (*Dichondra micrantha*)	Good weed suppression	Apple	Hartley *et al*. 2000
• Strawberry clover • Resident vegetation	Water use increased	Almond	Ingels *et al*. 1994

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AP19006 - Improved Australian apple & pear orchards soil health and plant nutrition

MS190: Final report

Prepared by Sally Bound

Literature review

A desktop literature review was undertaken to explore the impact of soil and orchard floor management practices on soil biology, nutrient availability, organic carbon capture, and potential reduction to the environmental footprint in apple and pear production. A total of 206 scientific journal publications and reports were reviewed, and the knowledge gained used to inform species selection for treatments in research and demonstration sites established as part of this project.

Conclusions from the review:

It is possible to move away from conventional agriculture with its heavy reliance on pesticides and synthetic fertilisers to a natural system that increases biodiversity, provides natural control of pests, and builds soil health. The common misconception that sustainable agriculture means a return to old farming methods needs to be addressed; use of the term biological or regenerative, rather than sustainable, brings the emphasis back to where farmers need to be looking in the future. Regenerative farming works with natural systems and processes to build optimum soil and plant health, while also incorporating the best of conventional farming methods to maintain production levels and quality. Not all regenerative practices are suitable for perennial tree production, particularly in established orchards, but lessons can be learnt from practices such as permaculture food forests and by referring back to natural ecosystems. Biodiversity, both above and below ground, is the key in the development of ecosystem services that enable a move away from reliance on synthetic fertilisers and pesticides.

Many orchardists in Australia have planted permanent grass swards in the inter-rows, but these can be improved by increasing species diversity. Use of biocontrol methods for pest control is becoming increasingly common along with the incorporation of compost into soil prior to planting new blocks. These practices are a good start to reinstating a healthy ecosystem, but to become truly regenerative a paradigm shift is needed to enable a return to complex systems with strong food webs and beneficial trophic interactions. The starting point is to increase biodiversity within the orchard, and simple methods for achieving this include:

- increasing soil organic matter
- diversifying orchard floor vegetation
- use of cover crops
- mulching in the tree row
- mow and blow inter-row vegetation into the tree row
- reducing frequency of mowing
- planting hedgerows around the orchard and/or between blocks
- planting of multiple tree species
- use of biocontrol strategies rather than pesticides

There is the opportunity to design new plantings to include more ecological functions that result in increased system self-regulation and decreased costs and environmental impacts. Granatstein (2021) observed that although redesign is a difficult change to make it yields the most sustainability improvement per unit of change; we need to “connect the dots” to maximise the benefits of existing knowledge and to determine what future research needs to be undertaken for specific situations.

Research and demonstration sites

To investigate how different orchard floor management practices influence soil health, tree health and nutrition, fruit yield and quality, field sites were established in five apple growing regions. Two intensive research trials were established in Tasmania, demonstration sites with limited data collection were established in New South Wales, South Australia and Western Australia, the Victorian site was part of the PIPS3 project *AP19002 – Strengthening cultural and biological management of pests and diseases on apple and pear*.

The treatments established in each region included a range of tree-line cover crops, composts, mulches, and herbicide bare-earth strip; inter-row plantings included native herbaceous and/or grass mix, flowering meadow mix, and grass/legume mixes. Treatments and species used reflected regional priorities and soil, climatic and management system differences to assist with:

- identification of the biological, structural, and chemical indicators for soil health, including relationship to regional and soil type differences, and assessment methods;
- improving understanding of the interaction between management practices, soil health, nutrient availability, water availability, pest and disease control and fruit productivity/quality;
- measuring the impact of sustainable orchard floor management on the presence and function of mycorrhizal fungi and the organic carbon content of the soil;
- providing a better understanding of the relationships between soil health, tree health, growth and fruit yield, productivity, and quality; and
- addressing grower perceived impediments to adoption including water requirements, herbicide and fungicide use, tractor movements and fire risk.

Intensive trial sites in Tasmania

Two research trial sites were established in Spring 2020 on a commercial orchard at Ranelagh in the Huon Valley (R&R Smith Rookwood orchard (43° 1' 3.9612" S; 146° 59' 11.6628 E)).

Trial 1 was established in a 12-year-old 'Jazz' block and Trial 2 in a newly planted block of 'Morgana' ('Kazari')/M26 (Figure 1). Both blocks were on sandy loam soils, with a north-south row orientation. Inter-row spacing in both blocks was 3.5 m with 1.0 m tree spacing within the row.

Figure 1*: Intensive research trial blocks at R&R Smith Rookwood orchard in Tasmania's Huon Valley.*

Each trial block consisted of three inter-row treatments and three tree-line treatments with five replicates per treatment. Trial design was a randomised complete block. Treatments are shown in Table 1.

Table 1: Inter-row and tree-line treatments in the intensive trial blocks

Trial 1 -Mature 'Jazz' block	Trial 2 – Newly planted 'Morgana' block
Inter-row treatments	
1. Grower sward	1. Grower sward
2. Flowering meadow mix	2. Flowering meadow mix
3. Native flowering mix	3. Legume/grass mix
Tree-line treatments	
1. Herbicide strip	1. Mow & throw
2. Compost	2. Compost
3. Legume/grass mix	3. Hemp straw

A bare earth / herbicide strip in the tree line was adopted as the control in the established 'Jazz' block as it is normal practice in most orchards. In the newly planted 'Morgana' block the legume/grass tree line treatment was replaced with hemp straw to avoid root competition.

The flowering meadow and native flowering mixes were aimed at providing habitat and a food source for bees and beneficial insects (Table 2).

Table 2: Species in each mix and planting rates

	Common name	Rate
Grower sward		
Victorian ryegrass		8 kg/ha
Kingston ryegrass		12 kg/ha
USA red clover		5 kg/ha
USA white clover		2 kg/ha
'Apex' white clover		1 kg/ha
Legume/grass mix		
Festuca rubra	creeping red fescue	5 kg/ha
Festuca ovina	sheeps fescue	5 kg/ha
Festuca rubra ssp Commutata	chewings fescue	5 kg/ha
Dactylis glomerata cv. Summadorm	cocksfoot	5 kg/ha
Trifolium fragiferum cv. Palestine	strawberry clover	3 kg/ha
Trifolium repens cv. Apex	white clover	3 kg/ha
Flowering meadow mix		
Phacelia tanacetifolia	lacy phacelia / blue tansy	4 kg/ka
Fagopyrum esculentum	buckwheat	5 kg/ka
Coriandrum sativum cv. Santo	coriander	3 kg/ka
Plantago lanceolata cv. Tonic	plantain	4 kg/ka
Trifolium michelianum	Balansa clover	2 kg/ka
**Brassica sp.*	BQ mix	2 kg/ka
**Raphinus sativus acanthiformis*	daikon radish	3 kg/ka
**Cichorium intybus* cv. Commander	chicory	2 kg/ka
Native flowering mix		
Microleana stipoide	Weeping grass	2 kg/ha
Viola hederacea	Native violet	0.5 /m
Einardia nutans	Climbing saltbush	0.3 /m
Geranium solanderia	Native geranium	0.3 /m
Goodenia elongata	Lanky goodenia	0.3 /m
Arthropodium milleflorum	Vanilla lily	0.3 /m
Calocephalus lacteus	Milky beauty-head	0.3 /m

* not included in Trial 2

Figure 2*: 'Jazz' (Trial 1) and 'Morgana' (Trial 2) blocks prior to trial establishment.*

Treatment establishment

Planting of trial treatments were delayed due to wet conditions in August/September and challenges in obtaining seed, as most suppliers were either out of stock or had limited supplies.

As the ground in Trial 2 was already worked up from planting the trees in this block in July 2020, Trial 2 was sown first. The inter-rows in the trial section were harrowed on 27th October 2020 and seed was broadcast by hand 29th October 2020 followed by a light harrow (Figure 3).

Figure 3*: Harrowing (left) and hand sowing (right) Trial 2 in the newly planted 'Morgana' block.*

The inter-rows and tree-lines in the established 'Jazz' trial block were sprayed with knockdown herbicide on 2nd November 2020 and inter-rows cultivated on 10th November. Seed was sown by hand broadcasting and the inter-rows harrowed on 10th November. Due to dry conditions during late spring and summer, seed germination and establishment was very patchy, so inter-row treatments were reseeded in August 2021.

Except for the *Microleana stipoides* native grass, the native species in the native flowering mix treatment were planted out as plugs in June 2021 after starting from seed in the greenhouse. Seed of *Microleana stipoides* was on backorder and not received until August 2021, so was broadcast by hand once it was received.

The tree-line legume/grass mix plots were prepared by raking, seed was broadcast by hand and lightly incorporated into the soil by raking to encourage germination. The tree-line legume/grass treatment established well, however was accidently sprayed off with herbicide in January 2021 during routine orchard weed control by orchard staff, so was resown in autumn 2021. The remaining tree-line treatments were set up in early 2021. Compost was provided by Nic Hansen from Cherries Tasmania. Hemp straw was donated by Andi Lucas at X-Hemp Pty Ltd. As the 'Jazz' block went into conversion from conventional to organic six months after trial establishment, the organic approved herbicide Slasher (525 g/L nonanoic acid, Organic Crop Protectants Pty Ltd) was applied in the herbicide tree line treatment plots. Organic matter for the Mow and throw treatments was gathered whenever the orchard was mown and distributed across the relevant plots.

Figure 4*: Inter-row treatments in Trial 2 - flowering meadow mix (left and centre), legume/clover mix (right).*

Figure 5*: Compost being delivered to the site (left) and after application to tree rows (right).*

Figure 6*: Hemp straw being collected from X-Hemp (left, centre) and after application to tree rows (right).*

Sampling and monitoring

Sampling was undertaken at periods throughout the project to enable determination of soil physical parameters, soil chemistry, soil microbiology, arthropod populations, pest damage, tree growth and fruit quality (Table 3).

***Table 3**: assessments undertaken during the project.*

Soil	Biology	Crop
- compaction - moisture content - water infiltration - aggregate stability - organic carbon - nutrient status	Soil: - arthropods - microbial biomass - microbial diversity -mycorrhizal fungi Crop & groundcover: - pest arthropods - beneficial arthropods	- growth - yield - fruit quality - tree physiology - pest/disease damage

Soil sampling

Soil samples were collected from both trial blocks in May 2021 and 2023. A total of six cores were collected from each plot, vegetation removed and cores thoroughly mixed for each plot before oven drying. Inter-row and tree-line treatments were sampled separately. In 2021 all samples were pooled for each treatment, while in 2023 samples were kept separate for each plot.

Samples were forwarded to CSPB Soil and Plant Analysis Laboratory for the following tests:

- Phosphorus (Colwell), Potassium (Colwell), Sulphur (KCl 40), Organic Carbon
- (Walkley-Black), Nitrate Nitrogen, Ammonium Nitrogen, Electrical Conductivity, pH (water), pH (CaCl2),
- Boron, Trace Elements (DTPA) - Copper, Zinc, Manganese, Iron, Exchangeable Cations without pre-wash
- Calcium, Magnesium, Sodium, Potassium, Aluminium, Texture (In-house method)
- Total C
- Total N
- ECEC calculation
- Exchangeable Sodium Percentage (ESP calculation)

Additional samples were taken for analysis of physical properties, earthworm populations and microbial studies.

Soil chemical analysis

In the 'Jazz' block tree-line (Table 4), there was an increase in soil pH over time in all treatments, and in 2023 the compost and grass/legume plots were significantly higher in pH than the herbicide plots. Conductivity increased significantly in the compost and grass/legume plots compared to the herbicide plots. Exchangeable sodium percent was more than double the 2021 measurement in the compost plot, but there was no change in the other two treatments. Ammonium N increased 1.5-fold in the herbicide and compost plots and 3-fold in the grass/legume plots. Nitrate N increased in all treatments over the two years and was significantly higher in the compost plots compared with herbicide and grass/legume plots in 2023, being more than double the level measured in other treatments. Total N doubled in all treatments over time, but there was no significant difference between treatments.

Colwell P levels tripled in the herbicide and grass/legume plots over time while there was a 7-fold increase in the compost plots, which had significantly higher levels than the other treatment plots. There was no change over time in Colwell K in the herbicide plots, but levels tripled in the compost and grass/legume plots, with compost having a significantly higher level than the grass/legume plots.

There were no significant differences between treatments in exchangeable Al, Ca, or Mg, but exchangeable Ca and Mg levels doubled over time. Exchangeable K showed no change over time in the herbicide plots, but 2023 levels were significantly higher in the compost and grass/legume plots, with compost showing significantly higher levels than the other two treatments, and levels in grass/legume plots were higher than herbicide plots. Exchangeable Na increased over time in all treatments. Compost plots showed significantly higher levels than herbicide or grass/legume plots.

There were no significant differences between treatments in levels of S, B, Cu, Fe, Mn, or Zn, but Cu, Fe, an Zn showed higher levels in 2023 than in 2021.

Table 4*: The effect of different tree-line treatments on soil characteristics in an established 'Jazz' apple orchard (Trial 1) at treatment establishment (2021) and two years after establishment (2023).*

		Herbicide	Compost	Grass/Legume	*Fprob*	*Lsd (p≤0.05)*
pH (CaCl2)	**2021**	5.6	5.6	5.6	-	-
	2023	6.08 [b]	6.20 [ab]	6.27 [a]	*0.02*	*0.122*
pH (H2O)	**2021**	6.63	6.63	6.63	-	-
	2023	6.90 [b]	7.08 [a]	7.08 [a]	*0.047*	*0.162*
Conductivity (dS mm^{-1})	**2021**	0.088	0.088	0.088	-	-
	2023	0.090 [b]	0.203 [a]	0.150 [a]	*0.004*	*0.0549*
ESP Exchangeable (%)	**2021**	0.6	0.6	0.6	-	-
	2023	0.633 [b]	1.417 [a]	0.533 [b]	*<0.001*	*0.2297*
Organic carbon (%)	**2021**	2.592	2.592	2.592	-	-
	2023	4.19	3.985	4.19	*0.624*	*ns*
Total C (%)	**2021**	3.463	3.463	3.463	-	-
	2023	5.98	5.84	6.29	*0.361*	*ns*
Ammonium N (mg/kg)	**2021**	3	3	3	-	-
	2023	4.5 [b]	5.1 [b]	10 [a]	*0.003*	*2.911*
Nitrate N (mg/kg)	**2021**	1.8	1.8	1.8	-	-
	2023	11.5 [b]	33.5 [a]	14.7 [b]	*0.023*	*15.81*
Total N (%)	**2021**	0.187	0.187	0.187	-	-
	2023	0.378	0.398	0.398	*0.697*	*ns*
Colwell P (mg/kg)	**2021**	31.5	31.5	31.5	-	-
	2023	98 [b]	215 [a]	100 [b]	*0.012*	*78.8*
Colwell K (mg/kg)	**2021**	187	187	187	-	-
	2023	164 [c]	590 [a]	438 [b]	*<0.001*	*117.6*
Exch. Al (meq/100g)	**2021**	0.01	0.01	0.01	*0.01*	
	2023	0.007	0.013	0.013	*0.199*	*ns*
Exch. Ca (meq/100g)	**2021**	9.38	9.38	9.38	-	-
	2023	18.25	17.82	18.46	*0.804*	*ns*
Exch. Mg (meq/100g)	**2021**	1.51	1.51	1.51	-	-
	2023	3.2	3.19	3	*0.796*	*ns*
Exch. K (meq/100g)	**2021**	0.445	0.445	0.445	-	-
	2023	0.327 [c]	1.252 [a]	0.917 [b]	*<0.001*	*0.2251*
Exch. Na (meq/100g)	**2021**	0.06	0.06	0.06	-	-
	2023	0.142 [b]	0.325 [a]	0.120 [b]	*<0.001*	*0.0582*
S (mg/kg)	**2021**	11.35	11.35	11.35	-	-
	2023	7.32	13.03	10.1	*0.064*	*ns*
B (mg/kg)	**2021**	1.29	1.29	1.29	-	-
	2023	2.05	2.43	2.27	*0.724*	*ns*
Cu (mg/kg)	**2021**	8.16	8.16	8.16	-	-
	2023	15.46	12.84	15.58	*0.245*	*ns*
Fe (mg/kg)	**2021**	48.13	48.13	48.13	-	-
	2023	84.3	84.1	64.1	*0.119*	*ns*
Mn (mg/kg)	**2021**	5.74	5.74	5.74	-	-
	2023	5.55	4.61	6.97	*0.071*	*ns*
Zn (mg/kg)	**2021**	20.6	20.6	20.6	-	-
	2023	44.3	47.4	44.5	*0.662*	*ns*

Within each row, means followed by different letters are significantly different according to the LSD means comparison test at p = 0.05.

In the ‘Morgana’ block treeline, (Table 5), no differences in pH were observed between treatments. Conductivity and exchangeable sodium percent were both significantly higher in the compost treatment plots in 2023 compared to the mow & throw and hemp straw plots.

There was no significant difference between treatments in organic C, Total C, or ammonium N but levels increased over time (Table 5). Nitrate N increased markedly over time in all tree-line treatments, with nitrate N in the compost plots (84 mg/kg) in 2023 being significantly higher than the mow & throw (40 mg/kg) or hemp straw plots (37 mg/kg).

Colwell P and K levels more than doubled over time in the tree-line treatments in the ‘Morgana’ block, but there was no significant difference between treatments (Table 5).

Exchangeable Al, Ca, Mg, and K showed no significant differences between treatments in 2023, while exchangeable Na levels in the compost plots was significantly higher than in the mow & throw and hemp straw plots (0.37 meq/100g compared with 0.07 and 0.08 meq/100g respectively).

There were no significant differences between treatments for S, B, Cu, Fe, or Zn, but Mn was significantly higher in the compost plots compared to the mow & throw and hemp straw plots.

As there was no replication of samples in the ‘Jazz’ block inter-rows (Table 6) no statistical analysis was undertaken, but some trends were observed. There was little change in the measured variable between years or between the treatments applied to the inter-row plots, but three variables did show marked differences between treatments in 2023. The Meadow mix plots had higher Fe and Colwell P and lower Colwell K than the other inter-row treatments.

In the ‘Morgana’ block inter-rows (Table 7), there were no significant differences between the difference treatments in 2021. In 2023 treatment differences were observed only in pH ($CaCl_2$) and Fe, with the Grower mix plots having the lowest pH and highest Fe levels.

In 2023, samples were collected at two depths in both trial blocks and these results are displayed in Tables 8 and 9.

In the ‘Jazz’ trial block (Table 8), pH in the tree-line was significantly lower at 10-20 cm depth than in the -10cm profile. Significant decreases were also observed with increasing depth for Total C, Total n, Exchangeable Mg, Exchangeable K, Cu and Zn.

In the ‘Morgana’ trial block tree-line (Table 9), significant reductions in nutrient levels were observed for Colwell P, Colwell K and Exchangeable K.

Significant reductions were observed with increasing depth in the ‘Morgana’ inter-rows (Table 9) for ammonium N, Colwell K, Exchangeable Ca, Exchangeable K, B, Cu, Fe and Zn. While levels of most other variable reduced at the lower soil depth, these differences were not significant due to the variability between samples. There were similar reductions in nutrient levels with increasing depth in the inter-row of the ‘Jazz’ trial block (Table 8)

More changes in nutrient levels were observed in the tree-line treatments in both trial blocks than in the inter-row treatment. Increases in the tree-line in soil pH, organic carbon and levels of many nutrients were observed over the two-year assessment period, but the changes were not always consistent between the two trial blocks.

Levels of most nutrients were higher in the both the grass/legume and compost treatments than in the herbicide treatment. In particular, ammonium N was highest in the grass/legume plots while nitrate N was increased most by addition of compost.

***Table 5**: The effect of different tree-line treatments on soil characteristics in a young 'Morgana' apple orchard (Trial 1) at treatment establishment (2021) and two years after establishment (2023).*

		Mow & throw	Compost	Hemp straw	*Fprob*	*Lsd (p≤0.05)*
pH (CaCl2)	**2021**	5.53	5.53	5.53	-	-
	2023	6.26	6.01	6.12	*0.329*	*ns*
pH (H2O)	**2021**	6.57	6.57	6.57	-	-
	2023	6.92	6.69	6.84	*0.222*	*ns*
Conductivity (dS mm^{-1})	**2021**	0.097	0.097	0.097	-	-
	2023	0.235 ^{b}	0.404 ^{a}	0.247 ^{b}	*0.024*	*0.1331*
ESP Exchangeable (%)	**2021**	0.983	0.983	0.983	-	-
	2023	0.367 ^{b}	1.733 ^{a}	0.417 ^{b}	*<0.001*	*0.465*
Organic carbon (%)	**2021**	2.802	2.802	2.802	-	-
	2023	3.426	3.957	3.802	*0.100*	*ns*
Total C (%)	**2021**	3.48	3.48	3.48	-	-
	2023	4.94	6.03	5.69	*0.075*	*ns*
Ammonium N (mg/kg)	**2021**	2.17	2.17	2.17	-	-
	2023	3.50	2.75	4.08	*0.054*	*ns*
Nitrate N (mg/kg)	**2021**	5.2	5.2	5.2	-	-
	2023	40.0 ^{b}	83.8 ^{a}	36.7 ^{b}	*0.023*	*36.79*
Total N (%)	**2021**	0.166	0.166	0.166	-	-
	2023	0.263	0.309	0.299	*0.354*	*ns*
Colwell P (mg/kg)	**2021**	33.1	33.1	33.1	-	-
	2023	61.3	90.6	77.4	*0.489*	*ns*
Colwell K (mg/kg)	**2021**	149	149	149	-	-
	2023	404	393	478	*0.446*	*ns*
Exch. Al (meq/100g)	**2021**	0.02	0.02	0.02	-	-
	2023	0.018	0.008	0.013	*0.490*	*ns*
Exch. Ca (meq/100g)	**2021**	7.03	7.03	7.03	-	-
	2023	11.38	13.48	13.90	*0.162*	*ns*
Exch. Mg (meq/100g)	**2021**	3.34	3.34	3.34	-	-
	2023	5.31	6.56	5.70	*0.069*	*ns*
Exch. K (meq/100g)	**2021**	0.333	0.333	0.333	-	-
	2023	0.856	1.075	0.834	*0.246*	*ns*
Exch. Na (meq/100g)	**2021**	0.08	0.08	0.08	-	-
	2023	0.066 ^{b}	0.367 ^{a}	0.084 ^{b}	*<0.001*	*0.092*
S (mg/kg)	**2021**	13.1	13.1	13.1	-	-
	2023	42.1	65.3	61.9	*0.449*	*ns*
B (mg/kg)	**2021**	0.68	0.68	0.68	-	-
	2023	1.08	1.38	1.25	*0.517*	*ns*
Cu (mg/kg)	**2021**	2.43	2.43	2.43	-	-
	2023	4.21	3.07	7.85	*0.064*	*ns*
Fe (mg/kg)	**2021**	29.1	29.1	29.1	-	-
	2023	30.2	39.7	39.8	*0.411*	*ns*
Mn (mg/kg)	**2021**	4.12	4.12	4.12	-	-
	2023	4.08 ^{b}	6.98 ^{a}	5.50 ^{ab}	*0.004*	*1.599*
Zn (mg/kg)	**2021**	4.4	4.4	4.4	-	-
	2023	7.2	11.7	21.6	*0.136*	*ns*

Within each row, means followed by different letters are significantly different according to the LSD means comparison test at p = 0.05.

Table 6*: The effect of different inter-row treatments on soil characteristics in an established 'Jazz' apple orchard (Trial 1) at treatment establishment (2021) and two years after establishment (2023).*

		Grower mix	Meadow mix	Native mix	*Fprob*	*Lsd (p≤0.05)*
pH (CaCl2)	**2021**	5.50	5.50	5.50	-	-
	2023	5.70	6.25	5.45	-	-
pH (H2O)	**2021**	6.30	6.55	7.00	-	-
	2023	6.45	7.00	6.45	-	-
Conductivity (dS mm^{-1})	**2021**	0.16	0.13	0.10	-	-
	2023	0.11	0.09	0.05	-	-
ESP Exchangeable (%)	**2021**	0.45	0.35	0.35	-	-
	2023	0.25	0.30	0.65	-	-
Organic carbon (%)	**2021**	4.54	5.15	2.65	-	-
	2023	4.10	4.35	3.64	-	-
Total C (%)	**2021**	5.46	7.19	3.38	-	-
	2023	5.88	6.75	4.66	-	-
Ammonium N (mg/kg)	**2021**	5.00	4.50	3.50	-	-
	2023	8.00	7.50	3.50	-	-
Nitrate N (mg/kg)	**2021**	7.5	11.0	7.5	-	-
	2023	23.5	16.5	7.0	-	-
Total N (%)	**2021**	0.31	0.38	0.21	-	-
	2023	0.34	0.42	0.28	-	-
Colwell P (mg/kg)	**2021**	64.0	32.5	15.0	-	-
	2023	63.0	121.0	27.5	--	
Colwell K (mg/kg)	**2021**	266	342	253	-	-
	2023	178	68	107	-	-
Exch. Al (meq/100g)	**2021**	0.015	0.010	0.010	-	-
	2023	0.010	0.010	0.015	-	-
Exch. Ca (meq/100g)	**2021**	15.99	17.70	8.92	-	-
	2023	17.14	20.52	10.95	-	-
Exch. Mg (meq/100g)	**2021**	2.33	2.89	1.49	-	-
	2023	2.86	2.37	1.61	-	-
Exch. K (meq/100g)	**2021**	0.60	0.84	0.61	-	-
	2023	0.38	0.12	0.18	-	-
Exch. Na (meq/100g)	**2021**	0.09	0.08	0.05	-	-
	2023	0.05	0.07	0.08	-	-
S (mg/kg)	**2021**	-	-	-	-	-
	2023	5.50	6.65	4.85	-	-
B (mg/kg)	**2021**	1.60	2.33	1.34	-	-
	2023	1.29	2.00	0.93	-	-
Cu (mg/kg)	**2021**	15.45	21.55	3.09	-	-
	2023	15.39	19.94	8.66	-	-
Fe (mg/kg)	**2021**	81.4	78.8	23.9	-	-
	2023	80.2	151.3	173.9	-	-
Mn (mg/kg)	**2021**	10.03	9.21	5.72	-	-
	2023	4.12	3.47	4.48	-	-
Zn (mg/kg)	**2021**	27.8	36.1	15.0	-	-
	2023	22.7	43.5	16.5	-	-

Within each row, means followed by different letters are significantly different according to the LSD means comparison test at p = 0.05.

***Table 7**: The effect of different inter-row treatments on soil characteristics in a young 'Morgana' apple orchard (Trial 2) at treatment establishment (2021) and two years after establishment (2023).*

		Grower mix	Meadow mix	Fescue/clover	*Fprob*	*Lsd (p≤0.05)*
pH (CaCl2)	**2021**	5.33	5.85	5.65	*0.220*	*ns*
	2023	5.12 b	5.92 a	6.07 a	*0.395*	*0.395*
pH (H2O)	**2021**	6.42	6.85	6.72	*0.147*	*ns*
	2023	6.33	6.88	7.00	*0.531*	*ns*
Conductivity (dS mm^{-1})	**2021**	0.083	0.106	0.115	*0.735*	*ns*
	2023	0.049	0.036	0.067	*0.121*	*ns*
ESP Exchangeable (%)	**2021**	0.525	0.550	0.725	*0.143*	*ns*
	2023	0.625	0.500	0.400	*0.532*	*ns*
Organic carbon (%)	**2021**	3.88	3.73	3.59	*0.951*	*ns*
	2023	2.76	1.44	1.83	*0.357*	*ns*
Total C (%)	**2021**	4.71	4.86	4.31	*0.902*	*ns*
	2023	4.10	1.88	2.61	*0.307*	*ns*
Ammonium N (mg/kg)	**2021**	3.75	3.25	3.50	*0.851*	*ns*
	2023	4.00	1.25	2.00	*0.233*	*ns*
Nitrate N (mg/kg)	**2021**	7.2	5.5	4.5	*0.733*	*ns*
	2023	1.75	2.00	6.25	*0.114*	*ns*
Total N (%)	**2021**	0.220	0.242	0.217	*0.919*	*ns*
	2023	0.175	0.090	0.123	*0.261*	*ns*
Colwell P (mg/kg)	**2021**	23.0	53.0	66.0	*0.602*	*ns*
	2023	14.8	8.0	18.5	*0.344*	*ns*
Colwell K (mg/kg)	**2021**	165	198	256	*0.697*	*ns*
	2023	212	90	165	*0.209*	*ns*
Exch. Al (meq/100g)	**2021**	0.0125	0.0100	0.0175	*0.285*	*ns*
	2023	0.0403	0.0033	0.0068	*0.255*	*ns*
Exch. Ca (meq/100g)	**2021**	9.5	10.0	9.5	*0.984*	*ns*
	2023	5.9	3.8	5.5	*0.488*	*ns*
Exch. Mg (meq/100g)	**2021**	4.18	4.21	3.87	*0.949*	*ns*
	2023	2.77	2.13	2.77	*0.710*	*ns*
Exch. K (meq/100g)	**2021**	0.348	0.453	0.588	*0.616*	*ns*
	2023	0.453	0.175	0.340	*0.177*	*ns*
Exch. Na (meq/100g)	**2021**	0.070	0.083	0.092	*0.715*	*ns*
	2023	0.050	0.027	0.032	*0.470*	*ns*
S (mg/kg)	**2021**	5.9	15.2	13.0	*0.634*	*ns*
	2023	3.6	3.6	4.9	*0.546*	*ns*
B (mg/kg)	**2021**	0.60	1.27	1.05	*0.426*	*ns*
	2023	0.47	0.29	0.40	*0.346*	*ns*
Cu (mg/kg)	**2021**	2.82	3.98	3.08	*0.801*	*ns*
	2023	1.43	0.69	1.04	*0.278*	*ns*
Fe (mg/kg)	**2021**	43.8	34.0	49.9	*0.409*	*ns*
	2023	30.3 ^{a}	8.8 ^{b}	17.9 ^{ab}	*0.024*	*13.39*
Mn (mg/kg)	**2021**	6.48	5.80	4.61	*0.366*	*ns*
	2023	4.44	1.86	2.03	*0.301*	*ns*
Zn (mg/kg)	**2021**	6.2	8.5	8.5	*0.823*	*ns*
	2023	3.2	1.9	2.7	*0.567*	*ns*

Within each row, means followed by different letters are significantly different according to the LSD means comparison test at p = 0.05.

***Table 8**: Changes in soil characteristics with increasing soil depth in the tree-line and inter-row of an established 'Jazz' apple orchard (Trial 1) two years after treatment establishment. Note: samples from the inter-row were not replicated.*

	Tree-line				Inter-row	
	0-10 cm	10-20 cm	Fprob	Lsd ($p \leq 0.05$)	0-10 cm	10-20 cm
pH (CaCl2)	6.36 [a]	6.01 [b]	<0.001	0.0996	5.83	5.77
pH (H2O)	7.11 [a]	6.93 [b]	0.014	0.1324	6.67	6.60
Conductivity (dS mm^{-1})	0.16	0.13	0.095	ns	0.10	0.07
ESP Exchangeable (%)	0.88	0.84	0.7	ns	0.37	0.43
Organic carbon (%)	4.26	3.98	0.173	ns	4.54	3.51
Total C (%)	6.32 [a]	5.75 [b]	0.145	0.554	6.56	4.97
Ammonium N (mg/kg)	6.89	6.22	0.546	ns	10.00	2.67
Nitrate N (mg/kg)	25.6	14.2	0.079	ns	20.7	10.7
Total N (%)	0.42 [a]	0.35 [b]	0.011	0.048	0.42	0.27
Colwell P (mg/kg)	148	127	0.475	ns	77	64
Colwell K (mg/kg)	480	315	0.003	96	155	81
Exch. Al (meq/100g)	0.012	0.011	0.791	ns	0.02	0.10
Exch. Ca (meq/100g)	18.39	17.96	0.604	ns	17.78	14.62
Exch. Mg (meq/100g)	3.45 [a]	2.80 [b]	0.035	0.594	2.67	1.89
Exch. K (meq/100g)	1.00 [a]	0.66 [b]	0.002	0.1838	0.31	0.14
Exch. Na (meq/100g)	0.20	0.19	0.37	ns	0.07	0.06
S (mg/kg)	11.06	9.24	0.318	ns	6.03	5.30
B (mg/kg)	2.4	2.11	0.466	ns	1.55	1.26
Cu (mg/kg)	16.25 [a]	13.01 [b]	0.043	3.121	17.73	11.60
Fe (mg/kg)	80	75	0.562	ns	107	163
Mn (mg/kg)	6.40	5.03	0.091	ns	5.16	2.89
Zn (mg/kg)	50.1 [a]	40.7 [b]	0.012	6.79	34.5	20.7

Within each row and location, means followed by different letters are significantly different according to the LSD means comparison test at p = 0.05.

***Table 9**: The effect of soil depth on soil characteristics in the tree-line and inter-row of a young 'Morgana; apple orchard (Trial 2) two years after treatment establishment*

	Tree-line				Inter-row			
	0-10 cm	10-20 cm	Fprob	Lsd ($p \leq 0.05$)	0-10 cm	10-20 cm	Fprob	Lsd ($p \leq 0.05$)
pH (CaCl2)	6.14	6.12	0.870	ns	5.83	5.58	0.672	ns
pH (H2O)	6.80	6.83	0.753	ns	6.88	6.58	0.566	ns
Conductivity (dS mm^{-1})	0.312	0.279	0.542	ns	0.067	0.040	0.075	ns
ESP Exchangeable (%)	0.839	0.839	1.000	ns	0.367	0.650	0.125	ns
Organic carbon (%)	3.797	3.659	0.496	ns	2.67	1.35	0.115	ns
Total C (%)	5.69	5.42	0.478	ns	3.82	1.91	0.133	ns
Ammonium N (mg/kg)	3.72	3.17	0.206	ns	4.17 [a]	0.67 [b]	0.030	2.99
Nitrate N (mg/kg)	60.9	46.1	0.323	ns	4.67	2.00	0.150	ns
Total N (%)	0.311	0.270	0.149	ns	0.183 [a]	0.075 [b]	0.033	0.095
Colwell P (mg/kg)	97.1 [a]	55.8 [b]	0.045	40.42	19.0	8.7	0.116	ns
Colwell K (mg/kg)	515 [a]	335 [b]	0.005	120.8	221 [a]	90 [b]	0.043	124.0
Exch. Al (meq/100g)	0.013	0.014	0.881	ns	0.012	0.021	0.610	ns
Exch. Ca (meq/100g)	13.36	12.49	0.445	ns	7.40 [a]	2.77 [b]	0.023	3.663
Exch. Mg (meq/100g)	5.56	6.15	0.180	ns	3.55 [a]	1.56 [b]	0.035	1.793
Exch. K (meq/100g)	1.124 [a]	0.719 [b]	0.003	0.259	0.475 [a]	0.170 [b]	0.030	0.2622
Exch. Na (meq/100g)	0.176	0.168	0.835	ns	0.042	0.032	0.522	ns
S (mg/kg)	54.3	58.6	0.793	ns	3.9	4.1	0.881	ns
B (mg/kg)	1.35	1.13	0.309	ns	0.52 [a]	0.26 [b]	0.037	0.230
Cu (mg/kg)	5.10	4.98	0.941	ns	1.58 [a]	0.53 [b]	0.025	0.850
Fe (mg/kg)	40.6	32.5	0.237	ns	26.0 [a]	12.0 [b]	0.022	10.9
Mn (mg/kg)	5.71	5.32	0.544	ns	4.01	1.53	0.125	ns
Zn (mg/kg)	15.5	11.5	0.504	ns	4.0 [a]	1.2 [b]	0.025	2.33

Within each row and location, means followed by different letters are significantly different according to the LSD means comparison test at p = 0.05.

Soil physical properties

(data and interpretation provided by David Page)

Soil samples were collected from each of the tree-line and inter-row plots in early September 2022 and in May 2023 and returned to the soil physics laboratory for analysis of bulk density, moisture content, aggregate stability, infiltration rate, hydraulic conductivity, mean pore size and contribution of pore size to maximum flow. Soil water retention was also determined for the 2023 samples.

Statistical analysis

Two-Way Repeated Measures ANOVA (Mixed-Factor ANOVA) were conducted in SPSS (IBM Corp, New York). 2022 and 2023 samplings were defined as repeated measures within subjects, Interrow and Tree-line Treatments were defined as between subject factors. In some measurements tractor wheel rut was not included in statistical analyses as they were sampled as exploratory data and time constraints dictated they could not be sampled in a balanced design.

Large error ranges / high variation between replicates were regularly observed. This is not unexpected with soil measurements, particularly in measurements of hydraulic conductivity, because for example a pore size change as small as 1 um can affect the infiltration rate exponentially. Unfortunately, the issue with high variability of soils is that even if the sample size was increased the same error rate could just as easily occur. Non-statistically significant results were still assessed for trends.

- Assessments of main effects were carried out on adjusted confidence intervals using the Bonferroni correction.
- Box's test was used to confirm that the observed covariance matrices of the dependant variables are equal across groups.
- The Levene's Test of equality of error variances was employed to test the null hypothesis that the error variance of the dependent variable was equal across groups. Analyses which weakly violated the homogeneity of variances assumption still proceeded to interpretation.
- In analyses that failed Mauchley's test of sphericity (heteroscedasticity), Greenhouse-Geisser's or the Huynh-Feldt tests of within subject effects were interpreted.
- Where applicable post-hoc multiple range comparisons were conducted with Duncan's new multiple range test (MRT), and where appropriate compact letter display was used to differentiate treatment statistically different factor groups
- Results of null hypothesis assumptions tests were deemed significant at $p = 0.05$

Main effects, interaction effects, and differences between and within subject groups were designated as strongly significant when $p \leq 0.01$***, significant at $p \leq 0.05$** and weakly significant at $p = 0.05\text{-}0.1$*

Bulk density

Two intact soil cores (sample volume of each = 201.06 cm^3) were taken from the soil lying under each tree-line mulching/cover crop treatment of replicates 1-5, one from the centre of each interrow cover crop treatments replicates 1-5, and one from the tractor wheel rut of each interrow treatment from replicate 1-5. The soil was oven dried at 105 °C for 48 hours, and bulk density (BD) (g/mm^3) calculated by dividing dry soil weight by sample volume.

The soils in the A Horizon of the intensive trial sites classify most closely to a sandy loam.

Table 10*: Effect of bulk density on soil condition for horticulture: amelioration treatments that move soil Bulk Density values towards the range 1.2-1.4 are desirable.* Source: Hazelton and Murphy (2007)

Bulk density (g/cm^3)	Sandy soils	Loams
<1.0	-	Satisfactory
1.0-1.2	-	Satisfactory
1.2-1.4	Very open	Satisfactory
1.4-1.6	Satisfactory	Some too compact

1.6-1.8	Mostly too compact	Very compact
>1.8	Very compact	Extremely compact

Treatments means for bulk density in the inter-row treatments in the young 'Morgana' block and the mean difference between the different treatments are provided in Tables 11a and 11b. There was no significant main effect of *Interrow* treatment [F(2, 18) = 2.083, p = 0.154, η2 = 0.188], or of *Interrow Tractor Rut* [F(1, 18) = 1.111 p = 0.351, η2 = 0.110] on bulk density.

Interrow and *Interrow Tractor Rut* bulk densities were highly significantly different [F(2, 18) = 20.115, p < 0.001, η2 = 0.528].

There was no significant interaction effect of *Year* between *Interrow* treatments on BD [F(2, 18) = 0.729, p = 0.496, η2 = 0.075]. There was a weakly significant interaction effect of *Year* between *Interrow Tractor Ruts* on BD [F(1, 18) = 3.729, p = 0.069, η2 = 0.172].

There was no significant interaction effect of *Year* between *Interrow* treatments and *Interrow Tractor Ruts* on soil BD [F(2, 18) = 1.583, p = 0.233, η2 = 0.150].

Table 11a: *Effect of inter-row treatments on soil bulk density in a young 'Morgana' orchard*

Inter-row treatment	Location	Year	Mean bulk density (g/cm^3)	Std. Error	Mean Difference	*p value* (between years)
Fescue/clover	Inter-row	2022	1.17	0.054	-0.015	0.867
		2023	1.15	0.082		
	Tractor rut	2022	1.32	0.054	-0.730	0.422
		2023	1.25	0.082		
Grower mix	Inter-row	2022	1.22	0.054	-0.330	0.717
		2023	1.19	0.082		
	Tractor rut	2022	1.47	0.054	-0.730	0.422
		2023	1.40	0.082		
Meadow mix	Interrow	2022	1.10	0.054	-0.020	0.823
		2023	1.12	0.082		
	Tractor rut	2022	1.50	0.054	-0.300	0.003**
		2023	1.20	0.082		

Table 11b: *Effect of inter-row treatments on soil bulk density in a young 'Morgana' orchard*

Inter-row treatment	IR treatment comparison	Year	Difference in Mean Bulk Density	Std. Error	*p value* (within year)
Fescue/clover	Grower mix	2022	-0.055	0.039	0.575
	Meadow mix		0.065	0.039	0.388
Grower mix	Fescue mix		0.055	0.039	0.575
	Meadow mix		0.12	0.039	0.039**
Meadow mix	Fescue/clover		-0.065	0.039	0.388
	Grower mix		-0.12	0.039	0.039**
Fescue/clover	Grower mix	2023	-0.038	0.088	1
	Meadow mix		0.03	0.088	1
Grower mix	Fescue/clover		0.038	0.088	1
	Meadow mix		0.067	0.088	1
Meadow mix	Fescue/clover		-0.03	0.088	1
	Grower mix		-0.067	0.088	1

The Inter-row treatments in the 'Jazz' orchard (Tables 12a and 12b) showed no significant main effect of *Inter-row* treatment on BD [F(2, 18) = 0.877, p = 0.433, η2 = 0.089].

There was a highly significant main effect of *Interrow Tractor Rut* on BD [F(1, 18) = 58.998 p <0.001, η2 = 0.766]. *Interrow* and *Interrow Tractor Rut* BDs were highly significantly different [F(2, 18) = 20.115, p < 0.001, η2 = 0.528].

There was a weakly significant interaction effect of *Year* between *Interrow* treatments on BD [F(2, 18) = 12.525, p = 0.06, η2 = 0.075].

There was no significant interaction effect of *Year* between *Interrow Tractor Ruts* on BD [F(1, 18) = 2.633, p = 0.122, η2 = 0.128].

There was a weakly significant interaction effect of *Year* between *Interrow* treatments and *Interrow Tractor Ruts* on soil BD [F(2, 18) = 2.865, p = 0.083, η2 = 0.241].

Table 12a*: Effect of inter-row treatments on soil bulk density in a mature 'Jazz' orchard*

Inter-row treatment	Location	Year	Mean bulk density (g/cm^3)	Std. Error	Mean Difference	*p value* (between years)
Grower mix	Interrow	2022	1.15	0.059	-0.077	0.256
		2023	1.07	0.048		
	Tractor rut	2022	1.45	0.059	-0.070	0.303
		2023	1.38	0.048		
Meadow mix	Interrow	2022	1.22	0.059	-0.137	0.052*
		2023	1.09	0.048		
	Tractor rut	2022	1.54	0.059	-0.137	0.052
		2023	1.40	0.048		
Native mix	Interrow	2022	1.18	0.059	0.060	0.376
		2023	1.24	0.048		
	Tractor rut	2022	1.51	0.059	-0.210	0.005**
		2023	1.30	0.048		

Table 12b*: Effect of inter-row treatments on soil bulk density in a mature 'Jazz' orchard*

Inter-row treatment	IR treatment comparison	Year	Difference in Mean Bulk Density	Std. Error	*p value* (within year)
Grower mix	Meadow mix	2022	-0.082	0.059	0.544
	Native mix		-0.047	0.059	1
Meadow mix	Grower mix		0.082	0.059	0.544
	Native mi		0.035	0.059	1
Native mix	Grower mix		0.047	0.059	1
	Meadow mix		-0.035	0.059	1
Grower mix	Meadow mix	2023	-0.019	0.048	1
	Native mix		-0.046	0.048	1
Meadow mix	Grower mix		0.019	0.048	1
	Native mix		-0.027	0.048	1
Native mix	Grower mix		0.046	0.048	1
	Meadow mix		0.027	0.048	1

Tree-line treatment means for bulk density in the young 'Morgana' block and the mean difference between the different treatments are provided in Tables 13a and 13b.

There was no significant main effect of *Year* on *Tree-line* treatment on BD [F(1, 33) = 2.536 , p = 0.121, η2 = 0.071]. There was no significant main effect of T*ree-line* treatment on BD[F(2, 33) = 0.508, p = 0.606, η2 = 0.030]. There was no significant interaction effect of *Year* between *Tree-line* treatments on BD [F(2, 33) = 0.454, p = 0.639, η2 = 0.027[.

Table 13a*: Effect of tree-line treatments on soil bulk density in a young 'Morgana' orchard*

Tree-line treatment	Year	Mean bulk density (g/cm^3)	Std. Error	Mean Difference	*p value* (between years)
Compost	2022	0.972	0.0260	0.02	0.599
	2023	0.988	0.0300		
Hemp straw	2022	0.944	0.0260	0.02	0.599
	2023	0.961	0.0300		
Mow&throw	2022	0.924	0.0260	0.05	0.099*
	2023	0.977	0.0300		

Table 13b: *Effect of tree-line treatments on soil bulk density in a young 'Morgana' orchard*

Tree-line treatment	Treatment comparison	Year	Difference in Mean Bulk Density	Std. Error	*p* value (within year)
Compost	Hemp straw	2022	0.03	0.0370	1
	Mow&throw		0.05	0.0370	0.612
Hemp straw	Compost		-0.03	0.0370	1
	Mow&throw		0.02	0.0370	1
Mow&throw	Compost		-0.05	0.0370	0.612
	Hemp straw		-0.02	0.0370	1
Compost	Hemp straw	2023	0.03	0.0420	1
	Mow&throw		0.01	0.0420	1
Hemp straw	Compost		-0.03	0.0420	1
	Mow&throw		-0.02	0.0420	1
Mow&throw	Compost		-0.01	0.0420	1
	Hemp straw		0.02	0.0420	1

In the 'Jazz' orchard tree-line treatments, there was no significant main effect of either *Year* [$F(1, 33) = 1.924$, $p = 0.175$, $\eta 2 = 0.055$], or *Tree-line* treatment on bulk denisty [$F(2, 33) = 0.156$, $p = 0.856$, $\eta 2 = 0.009$] (Tables 14a and 14b).

There was no significant interaction effect of *Year* between *Tree-line* treatments on bulk density [$F(2, 33) = 0.452$, $p = 0.640$, $\eta 2 = 0.027$].

Table 14a: *Effect of tree-line treatments on soil bulk density in a mature 'Jazz' orchard*

Tree-line treatment	Year	Mean bulk density (g/cm^3)	Std. Error	Mean difference	*p value* (between years)
Herbicide	2022	0.993	0.0230	0.038	0.368
	2023	1.032	0.0320		
Compost	2022	0.997	0.0230	0.059	0.168
	2023	1.056	0.0320		
Grass/legume	2022	1.021	0.0230	0.003	0.937
	2023	1.024	0.0320		

Table 14b: *Effect of tree-line treatments on soil bulk density in a mature 'Jazz' orchard*

Tree-line treatment	Treatment comparison	Year	Difference in Mean Bulk Density	Std. Error	*p value* (within years)
Herbicide	Compost	2022	0.00	0.0330	1
	Grass/legume		-0.03	0.0330	1
Compost	Herbicide		0.00	0.0330	1
	Grass/legume		-0.02	0.0330	1
Grass/legume	Herbicide		0.03	0.0330	1
	Compost		0.02	0.0330	1

Herbicide	Compost	2023	-0.02	0.0450	1
	Grass/legume		0.01	0.0450	1
Compost	Herbicide		0.02	0.0450	1
	Grass/legume		0.03	0.0450	1
Grass/legume	Herbicide		-0.01	0.0450	1
	Compost		-0.03	0.0450	1

Bulk densities of less than 1.4 g/cm^3 are satisfactory for this soil type. There was a reduction in bulk density in all inter-row treatments between the initial measurement in 2022 and the 2023 measurement in both the 'Morgana' and 'Jazz' trial orchards, with all measurements, including the tractor ruts, falling in the satisfactory range. Bulk density for all tree-line treatments were well within the satisfactory range for this soil type.

Infiltration and saturated hydraulic conductivity

K_{sat}, K_{10} and K_{60} were determined at the soil surface using the Mini Disk Infiltrometer (Meter Group, Inc. USA) operated for 40-60 minutes. The mini disk infiltrometer was used to take one measurement of hydraulic conductivity from the soil lying under each tree-line mulching treatment of replicates 1-5, one from the centre of each interrow cover crop treatments replicates 1-5, and one from the tractor wheel rut of each interrow treatment from replicate 2. Two negative pressure heads were applied in order to determine water flow through a range of pore sizes. At a suction of 10 mm (K_{10}) for water flowing only through pores ≥3 mm, and at 60 mm (K_{60}) for water only flowing through pores ≤0.5 mm. Measurement timing interval was dependent on both the suction rate and the level of compaction/infiltration rate of soil being measured. A time interval was chosen that allowed for at least 5 mL of water to be infiltrated per measurement. Calculation of saturated hydraulic conductivity was solved according to Zang (1997).

K at K_{60} represents water that flows through soil pores ≤500 µm. In many cases K_{60} may be considered an estimate of the hydraulic conductivity when a soil is structurally degraded, or as a rate at which water may be added to the soil and still maintain a good level of aeration (Murphy et al. 1993). A decrease in K_{60} value is desirable for a soil amelioration treatment in orchards, as it indicates greater structure to the soil and improved aeration.

K at K_{10} represents water that flows through all pores ≤3000 µm. An amelioration to a K_{10} range value of 20-80 mm/hr is desirable for orchard horticulture.

In most cases, $K_{10} = K_{sat.}$ (Hazelton, 2007). Saturated hydraulic conductivity can influence a wide range of important land management.

***Table 15**: Interpretations of the values of hydraulic conductivity.*

Saturated hydraulic conductivity (mm/hr)	Rating	Interpretation
<0.5	Extremely low	Suitable for water storage (1).
0.5–10	Very low	Likely to cause regular runoff under rainfall; irrigation likely to be inefficient (2).
10–20	Low	Runoff less regular (3) and soil is becoming suitable for irrigation (4).
20–60	Moderate	Runoff only occasional and soil is suitable for irrigation.
60–120	High	Runoff rarely occurs and soil is becoming too permeable for irrigation (5).
>120	Very high	If soil is used for effluent or waste disposal there may be potential problems with contamination of water tables (6).

(1) A water store of 5 m depth should hold water for at least one year. Soils are unsuitable for disposal of wastewater or effluent.
(2) The majority of rain falls at intensities of less than 10 mm/h.
(3) When soil is saturated, runoff will occur even with low intensity rainfall.
(4) Irrigation is difficult for soil with Ksat <10 mm/h. because: high runoff rates necessitate low application rates (<10 mm/h.); the length of time sprays need to be kept operating becomes costly; and it is difficult to replenish soil water when evaporation rates are high.
(5) Flood and sprinkler irrigation become very costly and difficult if soil permeabilities are too high.
(6) Soils with very high hydraulic conductivity are not suitable for effluent or wastewater disposal as the wastewater passes through the soil so rapidly that it remains untreated, or unaltered.
Note: Prediction of runoff is based on the soil being unsaturated so that water is still able to infiltrate into the soil. When the soil is saturated, runoff will occur even at low rainfall intensities.

In the 'Morgana' orchard block, no significant main effect of *Interrow treatment* [$F(2, 24) = 0.187$, $p = 0.837$, $\eta2 = 0.015$], or *Year* [$F(2, 24) = 2.304$, $p = 0.122$, $\eta2 = 0.161$[was observed on K60 (Tables 16a,b)

There was a significant main effect of *Interrow Tractor Rut* on K60 [$F(1, 24) = 1.072$ $p = 0.264$, $\eta2 = 0.024$], but *Interrow Treatment* and *Interrow Tractor Rut* K60 were not significantly different [$F(2, 24) = 0.081$, $p = 0.922$, $\eta2 = 0.007$].

There was a weakly significant interaction effect of *Year* between *Interrow Tractor Ruts* on K60, [$F(1, 24) = 0.083$, $p = 0.775$, $\eta2 = 0.003$].

Table 16a: *The impact of inter-row treatments on hydraulic conductivity at a suction of 60 mm (K_{60}) for water only flowing through pores ≤0.5 mm in a young 'Morgana' orchard.*

Inter-row treatment	Location	Year	Mean K_{60}	Std. Error	Mean Difference	*p value* (between years)
Fescue/clover	Interrow	2022	24.373	5.042	-12.571	0.048**
		2023	11.802	2.84		
	Tractor rut	2022	9.476	5.042	-7.318	0.112
		2023	2.158	2.84		
Grower mix (ryegrass/clover)	Interrow	2022	17.875	5.042	-1.249	0.831
		2023	16.627	2.84		
	Tractor rut	2022	4.342	5.042	-2.832	0.529
		2023	1.510	2.84		
Meadow mix	Interrow	2022	19.899	5.042	-1.143	0.845
		2023	18.755	2.84		
	Tractor rut	2022	5.255	5.042	-1.683	0.707
		2023	3.572	2.84		

Table 16b: *Differences in mean hydraulic conductivity at a suction of 60 mm (K_{60}) in a young 'Morgana' orchard.*

Inter-row treatment	Treatment comparison	Year	Difference in mean k_{60}	Std. Error	*P value* (within year)
Fescue/clover	Grower mix	2022	6.497	9.425	1
	Meadow mix		4.474	9.425	1
Grower mix	Fescue/clover		-6.497	9.425	1
	Meadow mix		-2.023	9.425	1
Meadow mix	Fescue/clover		-4.474	9.425	1
	Grower mix		2.023	9.425	1
Fescue/clover	Grower mix	2023	-4.825	5.443	1
	Meadow mix		-6.954	5.443	0.677
Grower mix	Fescue/clover		4.825	5.443	1
	Meadow mix		-2.129	5.443	1
Meadow mix	Fescue/clover		6.954	5.443	0.677
	Grower mix		2.129	5.443	1

The results for K_{10} in the inter-rows of the young 'Morgana' block are shown in Tables 17a and 17b.

There was no significant main effect of *Interrow Treatment* on K_{10} [$F(2, 24) = 0.291$, $p = 0.750$, $\eta 2 = 0.024$]. There was a highly significant main effect of Interrow Tractor Rut on K_{10} [$F(1, 24) = 40.877$ $p < 0.001$, $\eta 2 = 0.616$], but Interrow and Interrow Tractor Rut K_{10} were not significantly different [$F(2, 24) = 0.355$, $p = 0.705$, $\eta 2 = 0.029$].

There was a highly significant interaction effect between Time and Interrow Treatments on K_{10}, [$F(2, 24) = 8.010$, $p = 0.009$, $\eta 2 = 0.250$].

There was no significant interaction effect of Time between Interrow Tractor Ruts on K_{10} [$F(1, 24) = 0.086$, $p = 0.918$, $\eta 2 = 0.007$]. There was no significant interaction effect of Time between Interrow Treatments and Interrow Tractor Ruts on soil K_{10} [$F(2, 24) = 0.009$, $p = 0.991$, $\eta 2 = 0.001$].

Table 17a: *The impact of inter-row treatments on hydraulic conductivity at a suction of 10 mm (K_{10}) for water flowing through pores ≤3 mm in a young 'Morgana' orchard.*

Inter-row treatment	Location	Year	Mean K_{10}	Std. Error	Mean Difference	*p value* (between years)
Fescue/clover	Interrow	2022	52.999	11.716	45.698	0.013**
		2023	98.696	15.745		
	Tractor rut	2022	5.276	11.716	5.879	0.734
		2023	11.155	15.745		
Grower mix	Interrow	2022	36.553	11.716	45.289	0.014**
		2023	81.842	15.742		
	Tractor rut	2022	6.567	11.716	3.674	0.832
		2023	10.240	15.745		
Meadow mix	Interrow	2022	46.627	11.716	37.67	0.044**
		2023	84.297	15.745		
	Tractor rut	2022	12.458	11.716	0.537	0.975
		2023	12.995	15.745		

Table 17b: *Differences in mean hydraulic conductivity at a suction of 10 mm (K_{10}) in a young 'Morgana' orchard.*

Inter-row treatment	Location	Year	Difference in mean k_{10}	Std. Error	*P* value (within year)
Fescue/clover	Grower mix	2022	16.445	22.696	1
	Meadow mix		6.372	22.696	1
Grower mix	Fescue/clover		-16.445	22.696	1
	Meadow mix		-10.074	22.696	1
Meadow mix	Fescue/clover		-6.372	22.696	1
	Grower mix		10.074	22.696	1
Fescue/clover	Grower mix	2023	16.854	30.714	1
	Meadow mix		14.399	30.714	1
Grower mix	Fescue/clover		-16.854	30.714	1
	Meadow mix		-2.455	30.714	1
Meadow mix	Fescue/clover		-14.399	30.714	1
	Grower mix		2.455	30.714	1

The results for K_{60} in the inter-row of an established "Jazz' block are shown in Tables 18a and 18b.

There was no significant main effect of *Interrow Treatment* on K_{60} [$F(2, 24) = 0.280$, $p = 0.758$, $\eta2 = 0.023$].

There was a significant main effect of *Interrow Tractor Rut* on K_{60} [$F(1, 24) = 31.191$ $p < 0.001$, $\eta2 = 0.565$]. *Interrow* and *Interrow Tractor Rut* K_{60} were not significantly different [$F(2, 24) = 0.081$, $p = 0.922$, $\eta2 = 0.007$].

There was no significant interaction between *Year* and *Interrow Treatments* on K_{60} [$F(2, 24) = 0.192$, $p = 0.827$, $\eta2 = 0.16$]. The interaction between *Year* and *Interrow Tractor Ruts* was highly significant on K_{60} [$F(1, 24) = 14.932$, $p < 0.001$, $\eta2 = 0.384$].

Table 18a*: The impact of inter-row treatments on hydraulic conductivity at a suction of 60 mm (K_{60}) for water only flowing through pores ≤0.5 mm in an established 'Jazz' orchard.*

Inter-row treatment	Location	Year	Mean K_{60}	Std. Error	Mean Difference	*p value* (between years)
Grower mix	Interrow	2022	18.144	3.338	-7.965	0.004**
		2023	10.179	1.683		
	Tractor rut	2022	2.158	3.338	0.208	0.934
		2023	2.366	1.683		
Meadow mix	Interrow	2022	15.027	3.338	-5.636	0.032**
		2023	9.392	1.683		
	Tractor rut	2022	1.51	3.338	0.26	0.917
		2023	1.77	1.683		
Native mix	Interrow	2022	17.735	3.338	-8.78	0.002**
		2023	8.955	1.683		
	Tractor rut	2022	3.572	3.338	0.548	0.826
		2023	4.12	1.683		

Table 18b*: Differences in mean hydraulic conductivity at a suction of 60 mm (K_{60}) in an established 'Jazz' orchard.*

Inter-row treatment	Treatment comparison	Year	Difference in Mean K_{60}	Std. Error	*p value* (within year)
Grower mix	Meadow mix	2022	1.883	3.338	1
	Native mix		-0.502	3.338	1
Meadow mix	Grower mix		-1.883	3.338	1
	Native mix		-2.384	3.338	1
Native mix	Grower mix		0.502	3.338	1
	Meadow mix		2.384	3.338	1
Grower mix	Meadow mix	2023	0.691	1.683	1
	Native mix		-0.265	1.683	1
Meadow mix	Grower mix		-0.691	1.683	1
	Native mix		-0.957	1.683	1
Native mix	Grower mix		0.265	1.683	1
	Meadow mix		0.957	1.683	1

The results for K_{10} in the inter-row of an established "Jazz' block are shown in Tables 19a and 19b.

Interrow Treatment had no significant effect on K_{10} [$F(2, 24) = 0.613$, $p = 0.550$, $\eta2 = 0.049$], but the effect of *Interrow Tractor Rut* on K_{10} was highly significant [$F(1, 24) = 16.453$ $p < 0.001$, $\eta2 = 0.616$].

Interrow and *Interrow Tractor Rut* K_{10} were weakly different $F(2, 24) = 2.636$, $p = 0.092$ $\eta2 = 0.180$.

There were no significant interactions for K_{10} between *Year* and *Interrow Treatments* [$F(2, 24) = 0.462$, $p = 0.635$, $\eta 2 = 0.037$], or between *Year* and *Interrow Tractor Ruts* on K_{10} [$F(1, 24) = 0.581$, $p = 0.453$, $\eta 2 = 0.024$]. There was no significant interaction effect of *Year* between *Interrow Treatments* and *Interrow Tractor Ruts* on soil K_{10} [$F(2, 24) = 1.942$, $p = 0.165$, $\eta 2 = 0.139$].

Table 19a: *The impact of inter-row treatments on hydraulic conductivity at a suction of 10 mm (K_{10}) for water flowing through pores ≤3 mm in an established 'Jazz' orchard.*

Inter-row treatment	Location	Year	Mean K_{10}	Std. Error	Mean Difference	*p value* (between years)
Grower mix	Interrow	2022	29.608	6.194	12.726	0.382
		2023	42.334	14.703		
	Tractor rut	2022	3.155	6.194	7.51	604
		2023	10.666	14.703		
Meadow mix	Interrow	2022	33.767	6.194	43.074	0.006**
		2023	76.841	14.703		
	Tractor rut	2022	4.241	6.194	4.358	0.763
		2023	8.599	14.703		
Native mix	Interrow	2022	27.414	6.194	9.996	0.491
		2023	37.41	14.703		
	Tractor rut	2022	9.995	6.194	27.247	0.069*
		2023	37.242	14.703		

Table 19b: *Differences in mean hydraulic conductivity at a suction of 10 mm (K_{10}) in an established 'Jazz' orchard.*

Inter-row treatment	Treatment comparison	Year	Difference in mean k_{10}	Std. Error	*P value* (within year)
Grower mix	Meadow mix	2022	-2.622	6.194	1
	Native mix		-2.322	6.194	1
Meadow mix	Grower mix		2.622	6.194	1
	Native mix		0.3	6.194	1
Native mix	Grower mix		2.322	6.194	1
	Meadow mix		-0.3	6.194	1
Grower mix	Meadow mix	2023	-16.22	14.703	0.843
	Native mix		-10.826	14.703	1
Meadow mix	Grower mix		16.22	14.703	0.843
	Native mix		5.394	14.703	1
Native mix	Grower mix		10.826	14.703	1
	Meadow mix		-5.394	14.703	1

Tree-line treatment results for K_{60} in the young 'Morgana' block are shown in Tables 20a and 20b.

The main effect of *Year* on *Tree-line Treatment* K_{60} [$F(1, 42) = 22.628$, $p < 0.001$, $\eta 2 = 0.350$] was highly significant. There was no significant main effect of *Tree-line Treatment* on K_{60} [$F(2, 42) = 0.66$, $p = 0.936$, $\eta 2 = 0.003$].

There was no significant interaction between *Year* and *Tree-line Treatments* on K_{60} [$F(2, 42) = 1.410$, $p = 0.255$, $\eta 2 = 0.063$].

Table 20a: *The impact of tree-line treatments on hydraulic conductivity at a suction of 60 mm (K_{60}) for water only flowing through pores ≤0.5 mm in a young 'Morgana' orchard.*

Tree-line treatment	Year	Mean K_{60}	Std. Error	Mean Difference	*p value* (between years)
Compost	2022	2.446	0.407	0.10	0.175
	2023	3.409	0.586		
Hemp straw	2022	1.948	0.407	2.32	0.002**
	2023	4.263	0.586		
Mow&throw	2022	1.834	0.407	2.47	<0.001***
	2023	4.302	0.586		

Table 20b: *Differences in mean hydraulic conductivity at a suction of 60 mm (K_{60}) in a young 'Morgana' orchard.*

Tree-line treatment	Treatment comparison	Year	Difference in mean k_{60}	Std. Error	*p value* (within year)
Compost	Hemp straw	2022	0.498	0.576	1
	Mow&throw		0.612	0.576	0.881
Hemp straw	Compost		-0.498	0.576	1
	Mow&throw		0.114	0.576	1
Mow&throw	Compost		-0.612	0.576	0.881
	Hemp straw		-0.114	0.576	1
Compost	Hemp straw	2023	-0.854	0.828	0.926
	Mow&throw		-0.893	0.828	0.862
Hemp straw	Compost		0.854	0.828	0.926
	Mow&throw		-0.039	0.828	1
Mow&throw	Compost		0.893	0.828	0.862
	Hemp straw		0.039	0.828	1

The results for K_{10} in the tree-line of the young 'Morgana' block are shown in Tables 21a and 21b.

There was a highly significant main effect of *Year* on *Tree-line Treatment* K_{10} [$F(1, 42) = 30.781$, $p <$ 0.001, $\eta 2 = 0.423$].

There was no significant main effect of *Tree-line Treatment* on K_{10} [$F(2, 42) = 0.343$, $p = 0.712$, $\eta 2 =$ 0.016]. There was no significant interaction effect between *Year* and *Tree-line Treatment* on K_{10} [$F(2, 42) = 0.425$, $p = 0.656$, $\eta 2 = 0.020$].

Table 21a: *The impact of tree-line treatments on hydraulic conductivity at a suction of 10 mm (K_{10}) for water flowing through pores ≤3 mm in a young 'Morgana' orchard.*

Tree-line treatment	Year	Mean K_{10}	Std. Error	Mean Difference	*p value* (between years)
Compost	2022	11.162	2.635	38.87	0.014**
	2023	46.033	13.602		
Hemp straw	2022	7.555	2.635	43.10	0.003**
	2023	50.651	13.602		
Mow&throw	2022	9.712	2.635	52.57	<0.001***
	2023	62.284	13.602		

Table 21b: *Differences in mean hydraulic conductivity at a suction of 10 mm (K_{10}) in a young 'Morgana' orchard.*

Tree-line treatment	Treatment comparison	Year	Difference in Mean K_{10}	Std. Error	*p value* (within year)

Compost	Hemp straw	2022	3.607	3.726	1
	Mow&throw		1.449	3.726	1
Hemp straw	Compost		-3.607	3.726	1
	Mow&throw		-2.157	3.726	1
Mow&throw	Compost		-1.449	3.726	1
	Hemp straw		2.157	3.726	1
Compost	Hemp straw	2023	-4.618	19.237	1
	Mow&throw		-16.251	19.237	1
Hemp straw	Compost		4.618	19.237	1
	Mow&throw		-11.633	19.237	1
Mow&throw	Compost		16.251	19.237	1
	Hemp straw		11.633	19.237	1

The results for K_{60} in the tree-line of the established "Jazz' block are shown in Tables 22a and 22b.

There was no significant main effect of *Year* on *Treeline Treatment* K_{60} [F(1, 42) = 0.299 , *p* = 0.588, η2 = 0.007]. There was a significant main effect of *Treeline Treatment* on K_{60} [F(2, 42) = 4.861, *p* = 0.013, η2 = 0.188].

There was no significant interaction between *Year* and *Treeline Treatments* on K_{60} [F(2, 42) = 0.721, *p* = 0.492, η2 = 0.033].

Table 22a*: The impact of tree-line treatments on hydraulic conductivity at a suction of 60 mm (K_{60}) for water only flowing through pores ≤0.5 mm in an established 'Jazz' orchard.*

Tree-line treatment	Year	Mean K_{60}	Std. Error	Mean Difference	*p value* (between years)
Herbicide	2022	5.299	1.003	-0.621	0.556
	2023	4.678	0.598		
Compost	2022	2.004	1.003	1.137	0.283
	2023	3.141	0.598		
Grass/legume	2022	4.797	1.003	0.473	0.653
	2023	5.271	0.598		

Table 22b*: Differences in mean hydraulic conductivity at a suction of 60 mm (K_{60}) in an established 'Jazz' orchard.*

Tree-line treatment	Treatment comparison	Year	Difference in mean k_{60}	Std. Error	*P value* (within year)
Herbicide	Compost	2022	3.295	1.418	0.075*
	Grass/legume		0.502	1.418	1
Compost	Herbicide		-3.295	1.418	0.075*
	Grass/legume		-2.793	1.418	0.166
Grass/legume	Herbicide		-0.502	1.418	1
	Compost		2.793	1.418	0.166
Herbicide	Compost	2023	1.537	0.845	0.228
	Grass/legume		-0.593	0.845	1
Compost	Herbicide		-1.537	0.845	0.228
	Grass/legume		-2.129	0.845	0.047**
Grass/legume	Herbicide		0.593	0.845	1
	Compost		2.129	0.845	0.047**

The results for K_{10} in the tree-line of the established "Jazz' block are shown in Tables 23a and 23b.

The effect of *Year* on *Tree-line Treatment* K_{10} was highly significant [$F(1, 42) = 35.317$, $p < 0.001$, $\eta 2 = 0.457$]. There was no significant main effect of *Tree-line Treatment* on K_{10} [$F(2, 42) = 0.058$, $p = 0.944$, $\eta 2 = 0.003$].

There was no significant interaction effect between *Year* and *Tree-line Treatment* on K_{10} [$F(2, 42)$ = 0.795, *p* = 0..458, $\eta 2 = 0.036$].

Table 23a*: The impact tree-line treatments on hydraulic conductivity at a suction of 10 mm (K_{10}) for water flowing through pores ≤3 mm in an established 'Jazz' orchard.*

Tree-line treatment	Year	Mean K_{10}	Std. Error	Mean Difference	*p* value (between years)
Herbicide	2022	7.429	2.446	50.936	< 0.001***
	2023	58.365	12.318		
Compost	2022	6.263	2.446	47.523	< 0.001***
	2023	53.786	12.318		
Grass/legume	2022	15.537	2.446	30.157	0.020**
	2023	45.693	12.318		

Table 23b*: Differences in mean hydraulic conductivity at a suction of 10 mm (K_{10}) in an established 'Jazz' orchard.*

Tree-line treatment	Treatment comparison	Year	Difference in mean k_{10}	Std. Error	*P* value (within year)
Herbicide	Compost	2022	1.166	3.459	1
	Grass/legume		-8.108	3.459	0.072*
Compost	Herbicide		-1.166	3.459	1
	Grass/legume		-9.274	3.459	0.031**
Grass/legume	Herbicide		8.108	3.459	0.072*
	Compost		9.274	3.459	0.031**
Herbicide	Compost	2023	4.579	17.421	1
	Grass/legume		12.672	17.421	1
Compost	Herbicide		-4.579	17.421	1
	Grass/legume		8.093	17.421	1
Grass/legume	Herbicide		-12.672	17.421	1
	Compost		-8.093	17.421	1

Aggregate stability

Aggregate stability is a measure of the ability of soil aggregates to withstand breakdown to small fragments when quickly moistened. Aggregate stability is commonly related to soil properties, including organic carbon, texture, clay mineralogy and the proportion of monovalent verses polyvalent cations. Factors responsible for soil aggregation are understood to be size dependent. Soil organic carbon or fractions of carbon such as labile carbon and biologically active carbon are strongly associated with the stability of macro-aggregates. In contrast, particle size, mineralogy, cation ratios and cementing agents are strongly associated with the stability of micro-aggregates (Almajmaie et al. 2017b). Therefore, if the entire fraction of aggregates cannot be analysed, a commonly used analysis in soil studies that wish to achieve assessments of the aggregate stability of the range of macro and micro-aggregates that are ideal for plant health range can be attained from measuring stability in the 1 mm – 2 mm aggregate range.

The fraction of stable aggregates (soil structure) was determined using the Soil & Water Wet Sieving Apparatus (Royal Eijelkampf, Inc. Netherlands). The procedure used was somewhat similar to that used by Almajmaie et al. (2017a) using an Eijkelkamp wet sieving apparatus. However instead of the

2.00–4.75 mm aggregate fraction used by Almajmaie et al., our measurements were performed on the 1 – 2 mm aggregate fraction. The methodology is described below.

A sample was extracted from the soil under each tree-line treatment of replicates 1-5, one from the centre of each inter-row cover crop treatment replicates 1-5, and one from the tractor wheel rut of each interrow treatment from replicate 2.

The following protocol was used for sample collection in the field and preparation in the laboratory.

Field procedure

1. Dig a square hole adjacent to where you will take the sample from (between drip emitters), directly under dripline
2. From side of hole, insert square ended pan into soil horizontally at 4cm deep.
3. Using hammer, tap pan into soil.
4. Remove top 1cm with soil knife.
5. Transfer sample into a rigid-walled plastic container and store at 4°C during transport.
6. Place in large flat trays no more than 3 cm thick to air dry.

Laboratory procedure

1. Once air-dried, place samples in 50 °C oven for 48 hrs.
2. To collect aggregates from the soil sample in the range of 1-2 mm, sieve soil through a stack of two sieves, the topmost sieve with 2m mesh, the bottommost sieve 1 mm mesh — these are commonly accepted as the most relevant soil aggregates to plant health.
3. Weigh 4.0 grams of 1- to 2- mm air-dried aggregates into 0.25 um sieves.
4. Pre-wet the aggregates in distilled water (dH2O) for 10 minutes before submerging in 70ml of dH20 in a numbered can.
5. Mechanically raise and lower pre-wet 1-2 mm aggregates in the 25um sieve in the numbered cans for 3 min. ± 5 s. (stroke = 1.3 cm, approx 34 times/min).
6. Allow sieve to drip dry. Once water is no longer leaking from the sieves, take out the (numbered) cans (containing the particles and aggregate fragments that have broken loose from the aggregates and come through the sieves) on a tray.
7. Replaced cans with another set of weighed (numbered) cans
8. Filled the cans with 70ml dispersing solution (2 g sodium hexametaphosphate/L).
9. Continued sieving and submerging in dispersing solution until only sand particles (and root fragments) were left on the sieve (usually 15 minutes). At 5 minutes, if some aggregates remained stable in the dispersing solution, stopped the sieve and rubbed them across the screen with a rubber tipped rod until they disintegrated.
10. Continued raising and submerging sieves until materials smaller than the screen openings had gone through.
11. Allow sieve to drip dry. When there was no dispersion solution leaking out of the sieves, take the (numbered) cans and place them on a separate tray. These cans contain the materials from the aggregates that were stable, except for sand particles too large to get through the screen.
12. Both sets of cans were placed in a convection oven at 110 °C until the water evaporates.
13. The weight of the materials in each can is then determined by weighing the can, plus contents, and subtracting the weight of the can. In the cans were filled with dispersing solution, subtract 0.2 g from the weight of the contents to account for the dispersing solute to obtain the soil weight.
14. The fraction of stable aggregates is determined as equal to the weight of soil obtained in the dispersing solution cans divided by the sum of the weights obtained in the dispersing solution cans and distilled water cans.

A general interpretation for an aggregate stability test using 1-2 mm stable aggregates is provided in Table 24.

Table 24: *General interpretation for aggregate stability test for percentage of 1–2 mm aggregates that are stable to wetting*

1–2 mm stable aggregates (%)	Rating
<10	Very low
10–20	Low
20–30	Moderate
>30	High

An increase in % of aggregates that are stable to wetting is desirable in soil amelioration treatments.

Tables 25a,b show the results for aggregate stability for inter-row treatments in the young 'Morgana' orchard block.

There was a significant main effect of *Year* on *Interrow Treatment* percentage of Stable Aggregates [$F(1, 12) = 14.551$, $p = 0.002$, $\eta2 = 0.548$].

Interrow Treatment had no significant effect on percentage of Stable Aggregates $F(2, 12) = 0.073$, $p = 0.930$, $\eta2 = 0.012$.

The interaction between *Year* and *Interrow Treatment* was significant for the percentage of Stable Aggregates [$F(2, 12) = 0.425$, $p = 0.013$, $\eta2 = 0.516$].

Table 25a: *The impact of inter-row treatments on percentage of stable aggregates in a young 'Morgana' orchard.*

Inter-row treatment	Location	Year	Mean % Stable Aggregates	Std. Error	Mean Difference	p value for between years
Fescue/clover	Interrow	2022	59.55	4.483	18.260	<0.001***
		2023	77.81	5.073		
Grower mix	Interrow	2022	62.17	4.483	11.138	0.019**
		2023	73.31	5.073		
Meadow mix	Interrow	2022	67.47	4.483	-2.236	0.596
		2023	65.24	5.073		

Table 25b: *Mean differences in percentage of stable aggregates for soil samples from inter-row treatments in a young 'Morgana' orchard.*

Inter-row treatment	Treatment comparison	Year	Mean Difference in % Stable Aggregates	Std. Error	*p* value (within year)
Fescue/clover	Grower mix	2022	-2.624	6.34	1
	Meadow mix		-7.922	6.34	0.706
Grower mix	Fescue/clover		2.624	6.34	1
	Meadow mix		-5.298	6.34	1
Meadow mix	Fescue/clover		7.922	6.34	0.706
	Grower mix		5.298	6.34	1
Fescue/clover	Grower mix	2023	4.498	7.174	1
	Meadow mix		12.574	7.174	0.315
Grower mix	Fescue/clover		-4.498	7.174	1
	Meadow mix		8.076	7.174	0.847
Meadow mix	Fescue/clover		-12.574	7.174	0.315
	Grower mix		-8.076	7.174	0.847

In the 'Jazz' inter-row treatments (Tables 26a,b), there was a significant main effect of *Year* on *Interrow Treatment* percentage of Stable Aggregates [F(1, 12) = 11.355, *p* = 0.006, η2 = 0.486].

There was no significant main effect of *Interrow Treatment* on percentage of Stable Aggregates [F(2, 12) = 1.400, *p* = 0.284, η2 = 0.189].

There was no significant interaction effect between *Year* and *Interrow Treatment* on percentage of Stable Aggregates [F(2, 12) = 1.567, *p* = 0.249, η2 = 0.207].

Table 26a*: The impact of inter-row treatments on percentage of stable aggregates in an established 'Jazz' orchard.*

Inter-row treatment	Location	Year	Mean % Stable Aggregates	Std. Error	Mean Difference	p value (between years)
Grower mix	Interrow	2022	43.193	6.634	29.227	0.007**
		2023	72.42	4.809		
Meadow mix	Interrow	2022	58.095	6.634	15.929	0.100*
		2023	74.024	4.809		
Native mix	Interrow	2022	55.976	6.634	7	0.449
		2023	62.976	4.809		

Table 26b*: Mean differences in percentage of stable aggregates for soil samples from inter-row treatments in an established 'Jazz' orchard.*

Inter-row treatment	Treatment comparison	Year	Mean difference in % stable aggregates	Std. Error	*P* value (within year)
Grower mix	Meadow mix	2022	-14.902	9.382	0.415
	Native mix		-12.783	9.382	0.594
Meadow mix	Grower mix		14.902	9.382	0.415
	Native mix		2.119	9.382	1
Native mix	Grower mix		12.783	9.382	0.594
	Meadow mix		-2.119	9.382	1
Grower mix	Meadow mix	2023	-1.604	6.8	1
	Native mix		9.444	6.8	0.57
Meadow mix	Grower mix		1.604	6.8	1
	Native mix		11.048	6.8	0.391
Native mix	Grower mix		-9.444	6.8	0.57
	Meadow mix		-11.048	6.8	0.391

The 'Morgana' tree-line treatments (Tables 27a,b) showed a significant main effect of *Year* on *Tree-line Treatment* percentage of Stable Aggregates [F(1, 42) = 9.516 , *p* = 0.004, η2 = 0.185].

There was no significant main effect of Tree-line Treatment on percentage of Stable Aggregates [F(2, 42) = 0.086, *p* = 0.917, η2 = 0.004].

There was a highly significant interaction effect between *Year* and *Tree-line Treatment* on percentage of Stable Aggregates [F(2, 42) = 2.718, *p* = 0.078, η2 = 0.115].

Table 27a*: The impact of tree-line treatments on percentage of stable aggregates in a young 'Morgana' orchard.*

Tree-line treatment	Year	Mean % Stable Aggregates	Std. Error	Mean Difference	*p* value (between years)
Compost	2022	61.441	2.613	10.39	<0.001***
	2023	71.831	3.078		

Hemp straw	2022	65.795	2.613	4.45	0.136
	2023	70.247	3.078		
Mow&throw	2022	66.578	2.613	0.82	0.782
	2023	67.396	3.078		

Table 27b*: Mean differences in percentage of stable aggregates for soil samples from tree-line treatments in a young 'Morgana' orchard.*

Tree-line treatment	Treatment comparison	Year	Mean Difference in % Stable Aggregates	Std. Error	*p* value (within year)
Compost	Hemp straw	2022	-4.354	3.696	0.736
	Mow&throw		-5.137	3.696	0.516
Hemp straw	Compost		4.354	3.696	0.736
	Mow&throw		-0.783	3.696	1
Mow&throw	Compost		5.137	3.696	0.516
	Hemp straw		0.783	3.696	1
Compost	Hemp straw	2023	1.583	4.353	1
	Mow&throw		4.435	4.353	0.943
Hemp straw	Compost		-1.583	4.353	1
	Mow&throw		2.851	4.353	1
Mow&throw	Compost		-4.435	4.353	0.943
	Hemp straw		-2.851	4.353	1

In the 'Jazz' tree-line (Tables 28a,b), there was a significant main effect of *Year* on *Treeline Treatment* percentage of Stable Aggregates, $F(1, 42) = 35.252$, $p = <0.001$, $\eta 2 = 0.456$.

There was no significant main effect of *Treeline Treatment* on percentage of Stable Aggregates $F(2, 42) = 0.642$, $p = 0.532$, $\eta 2 = 0.030$.

There was no significant interaction effect between *Year* and *Treeline Treatment* on percentage of Stable Aggregates, $F(2, 42) = 0.763$, $p = 0.473$, $\eta 2 = 0.035$.

Table 28a*: The impact of tree-line treatments on percentage of stable aggregates in an established 'Jazz' orchard.*

Tree-line treatment	Year	Mean % Stable Aggregates	Std. Error	Mean Difference	*p* value (between years)
Herbicide	2022	63.496	2.519	15.178	<0.001***
	2023	78.674	2.482		
Compost	2022	65.865	2.439	10.073	0.015**
	2023	75.938	2.403		
Grass/legume	2022	64.579	2.607	16.875	<0.001***
	2023	81.454	2.569		

Table 28b*: Mean differences in percentage of stable aggregates for soil samples from tree-line treatments in an established 'Jazz' orchard.*

Tree-line treatment	Treatment comparison	Year	Mean difference in % stable aggregates	Std. Error	*P* value (within year)
Compost	Hemp straw	2022	-2.369	3.506	1
	Mow&throw		-1.083	3.625	1
Hemp straw	Compost		2.369	3.506	1
	Mow&throw		1.286	3.57	1

Mow&throw	Compost		1.083	3.625	1
	Hemp straw		-1.286	3.57	1
Compost	Hemp straw	2023	2.736	3.455	1
	Mow&throw		-2.78	3.572	1
Hemp straw	Compost		-2.736	3.455	1
	Mow&throw		-5.516	3.518	0.373
Mow&throw	Compost		2.78	3.572	1
	Hemp straw		5.516	3.518	0.373

Soil water retention

The soil water retention function was determined using the KuPF apparatus (UGT, Germany; ICT International, Australia) between saturation and -80 kPa, supplemented with ‘dry end’ retention data determined by pressure chamber data at -1500 kPa.

One 250 cm^3 intact core was extracted from the soil lying under each tree-line mulching treatment of replicates 1-4, one from the centre of each interrow cover crop treatments replicates 1-4, and one from the tractor wheel rut of each interrow treatment from replicate 2 - for analysis by KuPf. Pressure chamber analysis was conducted at the permanent wilting point (PWP) -1500 kPa using three replicate 20 - 30 g air dried < 2 mm soil samples obtained from the clearing preparation process of the cores taken for KupF analysis.

Volumetric soil moisture content at the PWP was determined by multiplication with bulk density determined on the 250 cm^3 cores at saturation. Following the pressure KuPF and chamber analysis, the gravimetric moisture content was determined by oven drying at 105˚C for 48 hours.

The soil water retention data was fitted for the van Genuchten equation (van Genuchten 1980) using Excel Solver software.

Saturated water content was determined as the volumetric water content following at least 3 days saturation. The saturated water content is analogous to total porosity which is derived from bulk density and equal to the Θs van Genuchten parameter.

Field capacity was determined as the volumetric moisture content at -33 kPa, which is considered to represent two days of unimpeded drainage in field soils.

The plant available water content (PAWC) was calculated as the water filled pore space between drainable porosity (DP) at -10 kPa and the permanent wilting point (PWP) at -1500 kPa (James 1988; Brady and Weil 2010).

The readily available water content (RAW) was determined as the soil moisture held between field capacity at-10 kPa and the refill point at -50 kPa. RAW represents the easily extracted portion of the PAWC between field capacity and the refill point, in which the refill point is a nominal value based on both plant and soil attributes below which growth rates slow due to moisture stress.

Drainable porosity (DP) was calculated as the pore space or moisture held between saturation at 0 kPa and -10 kPa. Water held in this range is assumed to be unavailable to plants due to rapid drainage. Drainable porosity is a measure of macroporosity represented as the proportion of air filled pore spaces after gravitational drainage, in which values less than 10 % are associated with restricted air movement and anoxic conditions (Zou et al. 2001; Hazelton and Murphy 2007).

KuPF measures can be used to interpret the availability of water to plants in the soil and data is presented in Tables 29 and 30, and Figures 7 and 8.

Unavailable water was lower in the interrow than in the tree-line. Decreases to this metric are desirable in orchard soil amelioration. In the tractor ruts, UW was close to double that in the inter-row and tree-line, ranging from 25 to 30%.

Plant available water (PAW) is hard and energy expensive for the plant to get (PAW), but it is available and will sustain plant life. Increases to this metric are desirable in orchard soil amelioration.

Readily available water(RAW) allows for rapid, vigorous growth. Increases to this metric are desirable in orchard soil amelioration.

Drainable porosity (DP) is the soil air space, the air capacity for drainage and infiltration. It serves as a measure of microporosity, and is represented as the proportion of air filed pore spaces after gravitational drainage, in which values less than 10 % are associated with restricted air movement and anoxic conditions (Zou et al. 2001; Hazelton and Murphy 2007). Increases to this metric are desirable in orchard soil amelioration. Drainable porosity range from 24 to 34% in the inter-row and tree-line plots in the 'Morgana' block, and from 18- 23% in the 'Jazz' block; results for DP in the tractor ruts were all less than 9%, ranging from 7 to 8.5% in the 'Morgana' block and as low as 3.6-5.8% in the 'Jazz block.

***Table 29**: The effect of treatments on unavailable water (UW), plant available water (PAW), readily available water (RAW), and drainable porosity (DP) in soils in a young 'Morgana' orchard block.*

Treatment	UW % (>1500 kPa)	Post-hoc comparison	PAW % (50-1500 kPa)	Post-hoc comparison	RAW% (10-50 kPa)	Post-hoc comparison	DP% (0-10 kPa)	Post-hoc comparison
(1) Grower mix								
Compost	18.50	*a*	2.50	*c*	12.90	*ns*	29.88	*ns*
Hemp	19.37	*a*	8.34	*a*	10.55	*ns*	23.95	*ns*
Mow & throw	17.99	*a*	7.20	*a*	11.28	*ns*	24.63	*ns*
Interrow	11.11	*b*	5.27	*b*	10.93	*ns*	26.81	*ns*
Tractor rut	25.70		0.92		4.24		7.15	*ns*
(2) Meadow mix								
Compost	17.86	*ns*	3.33	*a*	10.04	*ns*	29.29	*ns*
Hemp	17.06	*ns*	6.51	*a*	11.68	*ns*	29.29	*ns*
Mow & throw	16.04	*ns*	2.90	*b*	10.83	*ns*	30.27	*ns*
Interrow	15.17	*ns*	1.80	*c*	10.72	*ns*	28.28	*ns*
Tractor rut	24.94		1.12		5.03		8.85	
(3) Fescue/clover								
Compost	18.10	*a*	1.38	*c*	10.32	*b*	33.94	*ns*
Hemp	18.85	*a*	5.72	*a*	9.77	*b*	29.88	*ns*
Mow & throw	16.41	*a*	3.88	*b*	11.82	*b*	31.65	*ns*
Interrow	13.65	*b*	2.40	*c*	13.04	*a*	27.02	*ns*
Tractor rut	26.01		0.85		4.46		7.36	

***Table 30**: The effect of treatments on unavailable water (UW), plant available water (PAW), readily available water (RAW), and drainable porosity (DP) in soils in an established 'Jazz' orchard block.*

Treatment	UV % (>1500 kPa)	Post-hoc comparison	PAW % (50-1500 kPa)	Post-hoc comparison	RAW % (10-50 kPa)	Post-hoc comparison	DP % (0-10 kPa)	Post-hoc comparison
(1) Grower mix								
Bare	16.40	*ns*	10.84	*ns*	12.38	*b*	21.37	*ns*
Compost	17.16	*ns*	9.07	*ns*	13.30	*b*	21.51	*ns*
Legume	16.70	*ns*	7.91	*ns*	13.16	*b*	22.39	*ns*
Interrow	15.19	*ns*	8.24	*ns*	15.79	*a*	17.96	*ns*
Tractor rut	29.53		5.76		2.86		3.67	

(2) Meadow mix								
Bare	17.31	*a*	8.74	*ns*	12.81	*c*	21.57	*ns*
Compost	13.66	*b*	7.81	*ns*	14.53	*b*	25.01	*ns*
Legume	17.60	*a*	6.02	*ns*	12.25	*c*	23.66	*ns*
Interrow	15.13	*c*	7.69	*ns*	16.77	*a*	17.98	*ns*
Tractor rut	27.54		8.46		4.26		4.41	
(3) Native mix								
Bare	16.49	*a*	9.34	*a*	11.12	*a*	21.87	*ns*
Compost	18.23	*a*	10.35	*a*	9.91	*a*	16.67	*ns*
Legume	14.50	*b*	9.19	*a*	12.84	*a*	23.47	*ns*
Interrow	15.08	*a*	5.24	*b*	14.56	*a*	16.83	*ns*
Tractor rut	30.11		3.58		2.05		5.83	

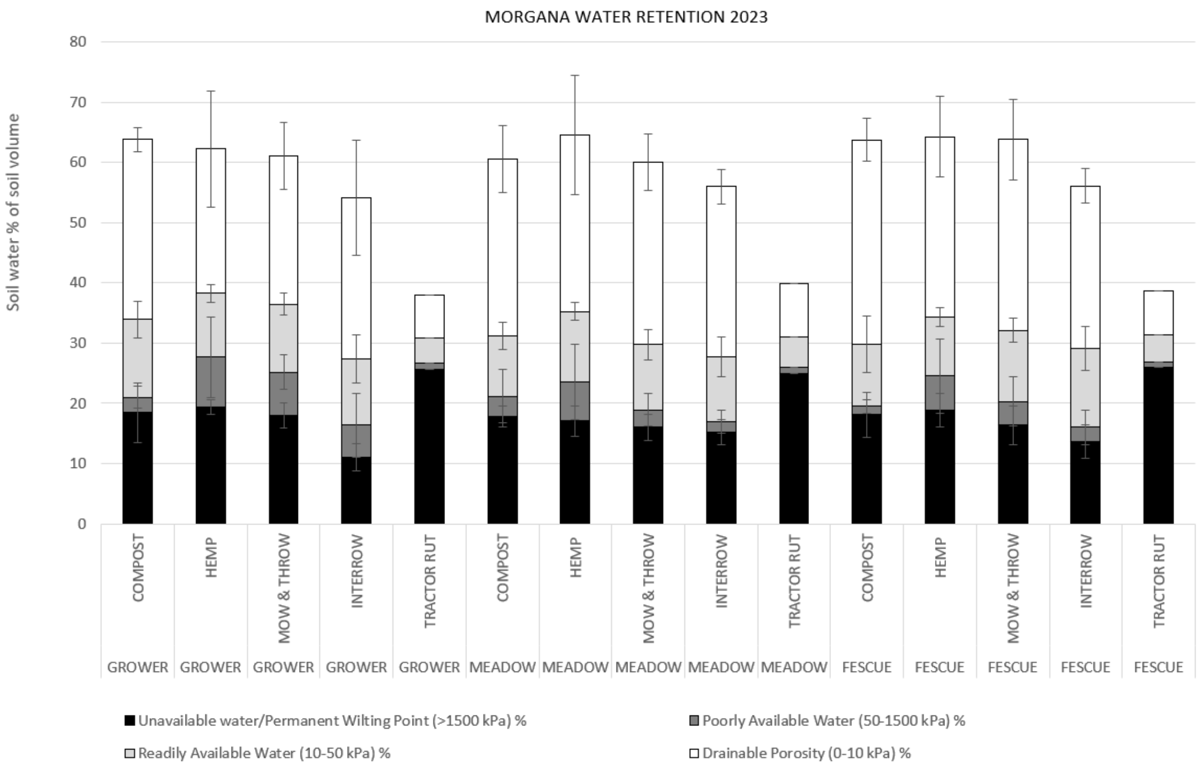

Figure 7*: The effect of treatments on unavailable water (UW), plant available water (PAW), readily available water (RAW), and drainable porosity (DP) in soils in a young 'Morgana' orchard block.*

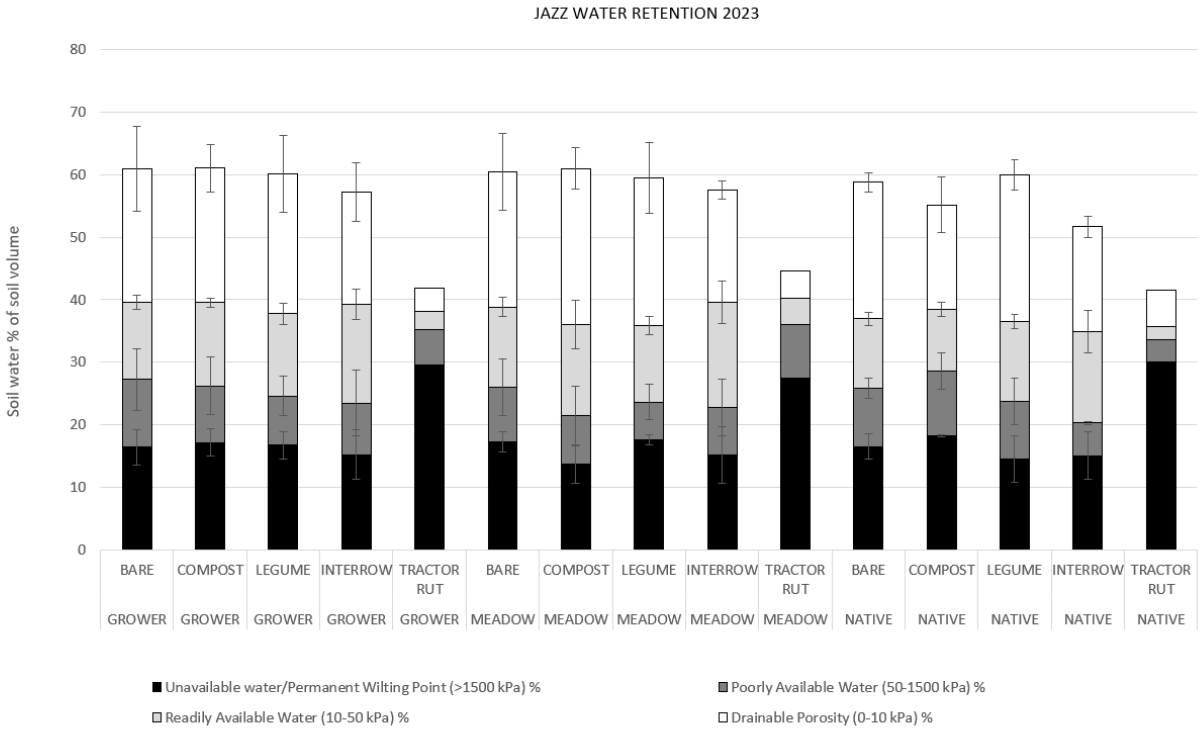

Figure 8*: The effect of treatments on unavailable water (UW), plant available water (PAW), readily available water (RAW), and drainable porosity (DP) in soils in an established 'Jazz' orchard block.*

These soil physical results demonstrate an overall trend towards an improvement in soil physical properties.

Bulk densities in the inter-row treatments were all lowered during the study period, falling into the desirable range of 1.1-1.4 g/cm^3 for sandy loams. Even the tractor ruts that started with high bulk density were brought into the desirable range. Bulk densities in the tree-line were all lower than in the inter-row, with very little variation in bulk density values for differing tree-line treatments .

Saturated hydraulic conductivity: There were reductions in K_{60} in all inter-row treatments in both the 'Morgana' and 'Jazz' blocks – a reduction represents an improvement in hydraulic conductivity. A significant large improvement was observed in K_{10} in the inter-rows in both the 'Morgana' and 'Jazz' blocks. In the tree-line treatments there was no significant difference between treatments for K_{60}, but over time all treatments showed a slight improvement (decrease). As for the inter-row treatments, there were significant large improvements to K10 in all three tree-line treatments in both blocks between 2022 and 2023 – this is a desirable finding.

Aggregate stability: all soils in the trial blocks were well structured/highly stable in the 1-2mm aggregates range. In the inter-rows aggregate stability varied from 0-10% between treatments, and improved significantly over time, from moderate to high in all but 'Morgana' Meadow mix and 'Jazz' Native mix treatments. There was 0-5% variation between the tree-line treatments, and aggregate stability improved significantly over time in all but the Hemp straw and Mow & Throw treatments.

Soil microbiology assessments

(data and interpretation provided by Morag Glen, Phil Kay and Ian Hunt)

Samples were taken from tree-line and inter-row soil in January 2022 and separated into the upper and lower halves of 150mm cores (Table 31). Subsamples were taken for the following analyses:

- Soil moisture content

- Microbial biomass carbon (extractable in K_2SO_4) and estimated by Microbiometer™
- Volatile organic compounds
- Fungal biomass, bacterial and arbuscular mycorrhizal fungal biomass (estimated by qPCR)
- Fungal and bacterial community composition

(a) (b) (c) (d)

Figure 9*: (a) enose sensor; (b, c, d) PhD student Phil Kay collecting soil samples*

Table 31*: Soil cores taken for microbial assessments (5 reps each treatment).*

Block/ cultivar	Code	Location	Treatment group*	Treatment
Jazz	JG	Inter-row	JIRL, JIRU	Grower mix
Jazz	JM	Inter-row	JIRL, JIRU	Flowering Meadow Mix
Jazz	JN	Inter-row	JIRL, JIRU	Untreated
Jazz	JGB	Tree-line	JTLL, JTLU	Bare (Grower mix inter-row)
Jazz	JGC	Tree-line	JTLL, JTLU	Compost (Grower mix inter-row)
Jazz	JGL	Tree-line	JTLL, JTLU	Legume (Grower mix inter-row)
Morgana	MG	Inter-row	MIRL, MIRU	Grower mix
Morgana	MM	Inter-row	MIRL, MIRU	Flowering Meadow Mix
Morgana	ML	Inter-row	MIRL, MIRU	Legume
Morgana	MGC	Tree-line	MTLL, MTLU	Compost (Grower mix inter-row)
Morgana	MGM	Tree-line	MTLL, MTLU	Mow & throw (Grower mix inter-row)
Morgana	MGH	Tree-line	MTLL, MTLU	Hemp (Grower mix inter-row)
Morgana	MMC	Tree-line	MTLL, MTLU	Compost (Flowering Meadow Mix inter-row)
Morgana	MMM	Tree-line	MTLL, MTLU	Mow & throw (Flowering Meadow Mix inter-row)
Morgana	MMH	Tree-line	MTLL, MTLU	Hemp (Flowering Meadow Mix inter-row)

*Samples were assigned to one of eight treatment groups based on block/cultivar, tree-line or inter-row and depth of sample.

Two of the DNA samples were lost in transit to the Australian Genomics Research Facility so microbial community assessments were not undertaken for those two samples.

No significant effects of tree-line or inter-row treatments were detected on soil moisture or microbial biomass carbon, though microbial biomass carbon was elevated under compost treatments with higher moisture levels (Figures 10, 11). PERMANOVA main test indicated that bacterial community composition differed among the soil treatments (P=0.0001), but pairwise tests did not differentiate bacterial community composition under different cover crops in the inter-row (Table 32A,B). In the Jazz block, the two tree-line treatments, compost and legume mulch, supported different bacterial communities to the bare treatment but were not significantly different from each other (Table 32C). In the Morgana block, the compost treatment differed significantly from the other two treatments (Table 32D). All tree-line treatments were significantly different from all inter-row treatments (Table 32E,F).

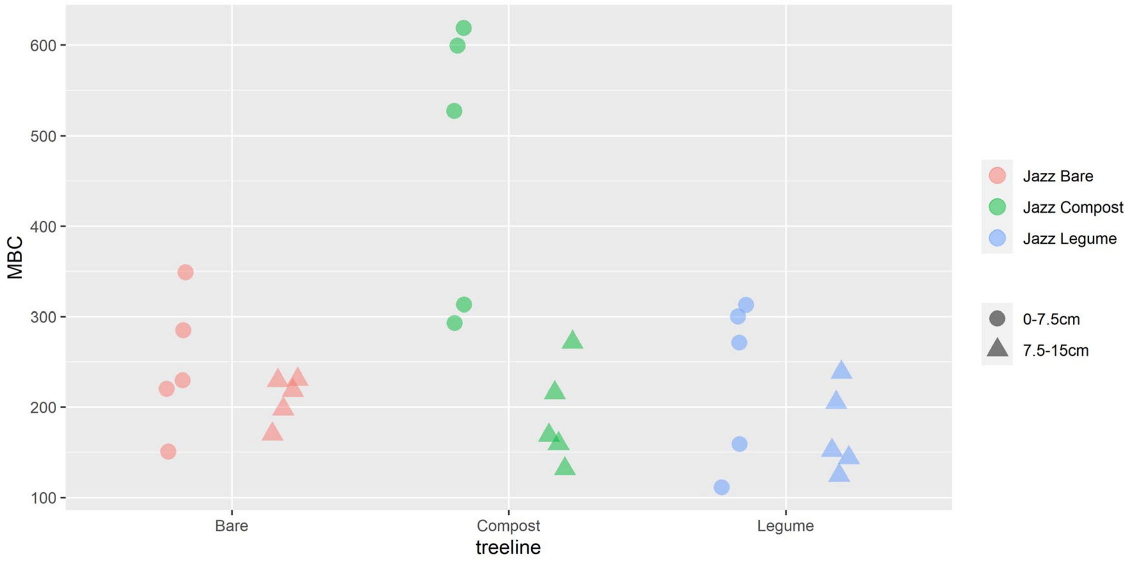

***Figure 10**: Microbial biomass carbon (MBC) in different tree-line treatments of Jazz orchard; three plots had elevated MBC in the top 75mm of soil under the compost treatment.*

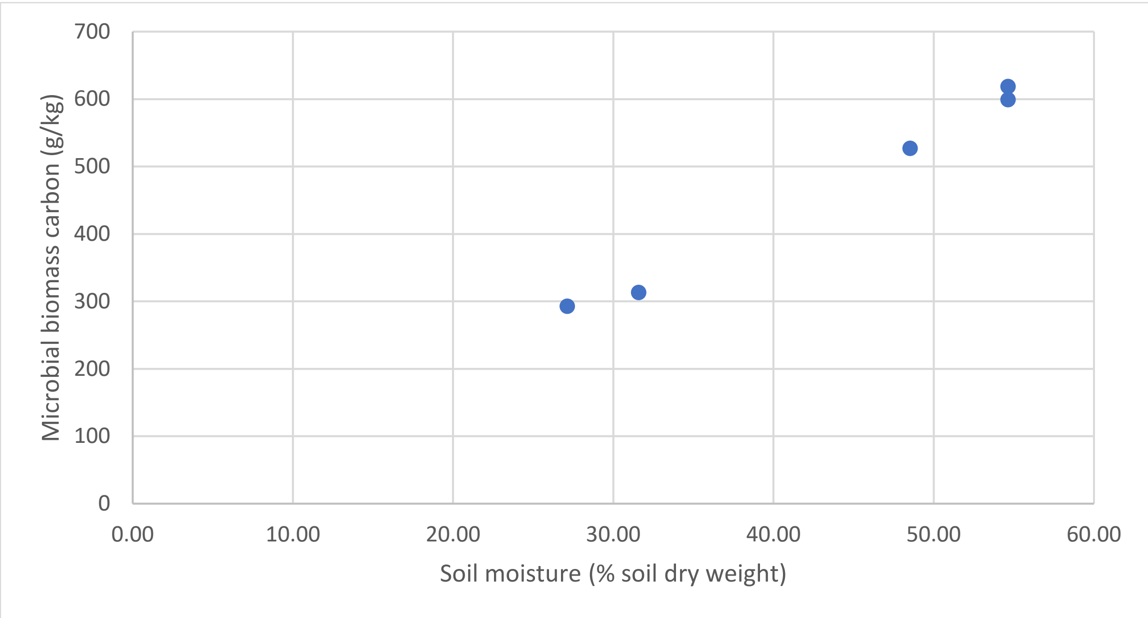

***Figure 11**: Microbial biomass carbon under compost in relation to soil moisture in the Jazz block.*

***Table 32**: PERMANOVA pairwise tests for significant difference in bacterial community composition of soil under different cover crop and mulch treatments. See Table 31 for treatment codes.*

Groups	**t**	**P(perm)**	**Unique perms**	**P(MC)**
A. Comparison of inter-row treatments in Jazz				
JG, JM	0.9139	0.6192	9911	0.5599
JG, JN	1.2071	0.0979	9897	0.1576
JM, JN	1.2742	0.074	9885	0.1147
B. *Comparison* of inter-row treatments in Morgana				
MG, MM	0.84204	0.8491	9888	0.7053
MG, ML	1.0274	0.3238	9901	0.3768
MM, ML	1.151	0.1081	9888	0.2037
C. Comparison of tree-line treatments in Jazz				
JGB, JGC	1.3976	0.0343	9929	0.061
JGB, JGL	1.3388	0.046	9921	0.0856

JGC, JGL	1.2445	0.1074	9920	0.1436
D. Comparison of tree-line treatments in Morgana				
MGM, MGC	1.5507	0.0092	9925	0.0289
MGM, MGH	0.90698	0.5061	9910	0.5219
MGC, MGH	1.3933	0.058	9914	0.0756
MMM, MMC	1.806	0.0012	9918	0.0048
MMM, MMH	1.047	0.295	9903	0.3327
MMC, MMH	1.8182	0.0005	9918	0.0058
MGM, MMM	1.0319	0.3226	9889	0.3619
MGC, MMC	1.1143	0.2328	9913	0.2615
MGH, MMH	0.90091	0.536	9933	0.5316
MGM, MMC	1.6932	0.0069	9910	0.0145
MGM, MMH	1.0792	0.2539	9920	0.2909
MGC, MMM	1.584	0.0016	9910	0.0166
MGC, MMH	1.682	0.0019	9925	0.0148
MGH, MMM	1.057	0.2926	9921	0.3123
MGH, MMC	1.7135	0.0072	9933	0.015
E. Comparison of tree-line to inter-row bacterial communities in Jazz				
JG, JGB	3.1193	0.0001	9897	0.0001
JG, JGC	2.9154	0.0001	9918	0.0001
JG, JGL	2.6184	0.0001	9921	0.0001
JM, JGB	2.7619	0.0001	9917	0.0001
JM, JGC	2.5473	0.0001	9920	0.0002
JM, JGL	2.2615	0.0001	9929	0.0004
JN, JGB	3.2424	0.0001	9924	0.0001
JN, JGC	3.0169	0.0001	9904	0.0001
JN, JGL	2.7246	0.0001	9918	0.0001
F. Comparison of tree-line to inter-row bacterial communities in Morgana				
MG, MGM	1.9058	0.0023	9906	0.0052
MG, MGC	2.1485	0.0002	9918	0.0012
MG, MGH	1.6539	0.0213	9929	0.0226
MG, MMM	1.9987	0.0001	9906	0.0008
MG, MMC	2.6025	0.0001	9922	0.0001
MG, MMH	2.1055	0.0007	9921	0.0013
MM, MGM	1.9885	0.0003	9908	0.0009
MM, MGC	2.2631	0.0001	9884	0.0002
MM, MGH	1.7542	0.0029	9903	0.0078
MM, MMM	2.0645	0.0001	9909	0.0002
MM, MMC	2.7077	0.0001	9900	0.0001
MM, MMH	2.2082	0.0001	9914	0.0003
ML, MGM	1.8746	0.0012	9910	0.0036
ML, MGC	2.1635	0.0001	9908	0.0003
ML, MGH	1.6332	0.0124	9907	0.0185
ML, MMM	1.9866	0.0001	9898	0.0004
ML, MMC	2.6751	0.0001	9922	0.0001
ML, MMH	2.1186	0.0004	9893	0.0008

Despite the significant difference among treatments, CAP analysis (Canonical Analysis of Principal Co-ordinates) had a misclassification error of 42%. The CAP graph (Figure 12) shows a closer relationship among the tree-line treatments and among the inter-row treatments in each block. Samples were combined into 8 categories (see Treatment group in Table 31) and a second CAP analysis done (Figure 13) which also separated the bacterial communities in the top 75mm of soil from those in 75-150 mm depth; the leave-one-out allocation to groups had a misclassification error of 7.4%.

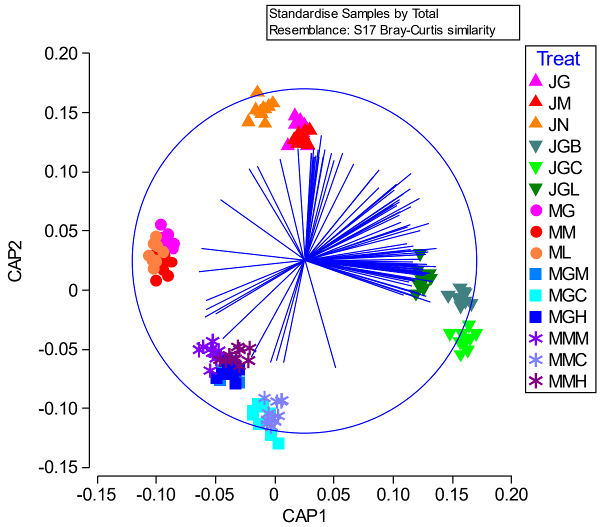

***Figure 12**: CAP analysis of bacterial communities supported the differentiation of treatments. Vectors show that many bacterial OTUs were associated (Pearson correlation coefficient >0.6) with Jazz tree-line or inter-row treatments, with fewer having a strong association with the Morgana block.*

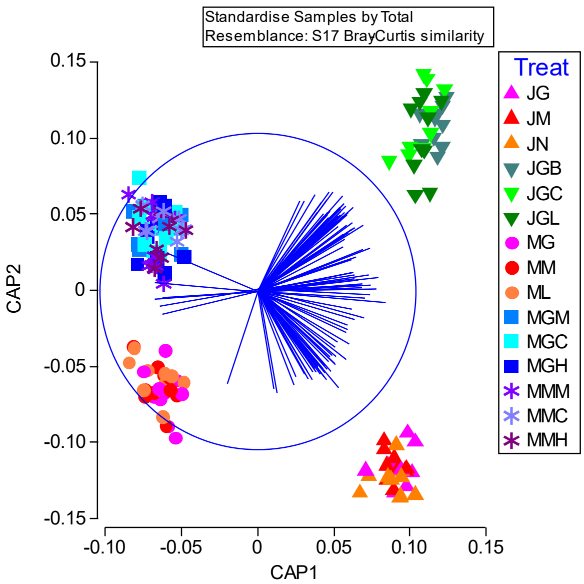

***Figure 13**: CAP analysis of bacterial communities supported the differentiation of 4 groups; Jazz tree-line, Jazz inter-row, Morgana tree-line and Morgana inter-row. The vectors represent bacterial taxa with a Pearson correlation coefficient >0.6. Most of these taxa are associated with the Jazz block which has a higher species richness than the younger Morgana block.*

Fungal communities also differed significantly among treatments. Both grower and meadow mix treatments differed from the control treatment in the Jazz inter-rows, but not from each other (Table 33A). Similarly, meadow mix differed significantly from both grower mix and legume, but the latter two were not significantly different from each other in the Morgana inter-rows (Table 33B). Among the tree-line treatments, the bare treatment was significantly different from both the compost and legume mulches, but these two were not significantly different (Table 33C). All but two of the tree-line treatments in Morgana were significantly different from each other at p<0.05(Table 33D). In addition, the fungal communities under compost mulch differed between inter-row treatments, but hemp and mow & throw did not. All inter-row fungal communities were distinct from tree-line fungal communities (Table 33E, F).

***Table 33**: PERMANOVA pairwise tests for significant difference in fungal community composition of soil under different cover crop and mulch treatments. See Table 31 for treatment codes.*

Groups	t	P(perm)	Unique perms	P(MC)
A. Comparison of inter-row treatments in Jazz				
JG, JM	0.98735	0.4566	9870	0.4478
JG, JN	1.656	0.0001	9889	0.0037
JM, JN	1.4335	0.0046	9888	0.0303

B. Comparison of inter-row treatments in Morgana				
MG, MM	1.3315	0.037	9912	0.0747
MG, ML	1.2237	0.0991	9902	0.1413
MM, ML	1.2858	0.0351	9901	0.1013
C. Comparison of tree-line treatments in Jazz				
JGB, JGC	1.3101	0.0525	9916	0.0935
JGB, JGL	1.4049	0.0419	9916	0.0633
JGC, JGL	1.312	0.0711	9908	0.0977
D. Comparison of tree-line treatments in Morgana				
MGM, MGC	1.7112	0.0005	9911	0.0072
MGM, MGH	1.4765	0.0345	9915	0.0522
MGC, MGH	1.6118	0.0048	9918	0.0164
MMM, MMC	1.628	0.0017	9910	0.0122
MMM, MMH	1.5023	0.0067	9918	0.0298
MMC, MMH	1.7383	0.0008	9914	0.0063
MGC, MMM	1.6111	0.0001	9896	0.0082
MGC, MMC	1.3793	0.0215	9910	0.0633
MGC, MMH	1.9155	0.0001	9918	0.0012
MGH, MMM	1.3989	0.0264	9896	0.0541
MGH, MMC	1.7318	0.0021	9916	0.0081
MGH, MMH	1.1086	0.2209	9911	0.2598
MGM, MMM	1.1961	0.12	9894	0.1783
MGM, MMC	1.5938	0.004	9896	0.0191
MGM, MMH	1.6663	0.0027	9904	0.0105
E. Comparison of tree-line to inter-row fungal communities in Jazz				
JG, JGB	2.5034	0.0001	9902	0.0001
JG, JGC	2.31	0.0001	9895	0.0001
JG, JGL	2.2371	0.0001	9921	0.0003
JM, JGB	2.2739	0.0001	9914	0.0001
JM, JGC	2.1183	0.0001	9898	0.0001
JM, JGL	2.0153	0.0001	9898	0.0006
JN, JGB	3.0505	0.0001	9904	0.0001
JN, JGC	2.8199	0.0001	9906	0.0001
JN, JGL	2.7937	0.0001	9913	0.0001
F. Comparison of tree-line to inter-row bacterial communities in Morgana				
MG, MGM	2.4101	0.0002	9925	0.0002
MG, MGC	2.3852	0.0001	9895	0.0001
MG, MGH	2.1375	0.0001	9913	0.0012
MG, MMM	2.1016	0.0001	9912	0.0007
MG, MMC	2.2907	0.0001	9912	0.0002
MG, MMH	2.5133	0.0001	9920	0.0001
MM, MGM	2.3552	0.0001	9911	0.0002
MM, MGC	2.4799	0.0001	9902	0.0001
MM, MGH	2.1444	0.0001	9902	0.0004
MM, MMM	2.0179	0.0001	9890	0.0005
MM, MMC	2.2103	0.0001	9906	0.0001
MM, MMH	2.416	0.0001	9893	0.0001
ML, MGM	2.3052	0.0001	9911	0.0001
ML, MGC	2.3123	0.0001	9907	0.0002
ML, MGH	2.0177	0.0001	9920	0.0012
ML, MMM	1.9423	0.0001	9885	0.0009
ML, MMC	2.2355	0.0001	9886	0.0001
ML, MMH	2.3921	0.0001	9909	0.0001

The CAP graph (Figure 14) shows a greater distance between the tree-line and inter-row treatments in the Jazz block compared to the younger Morgana. Leave-one-out allocation to treatments had a mis-classification error of 22%. When CAP was based on treatment groups (Figure 15) the mis-classification error was reduced to 12%.

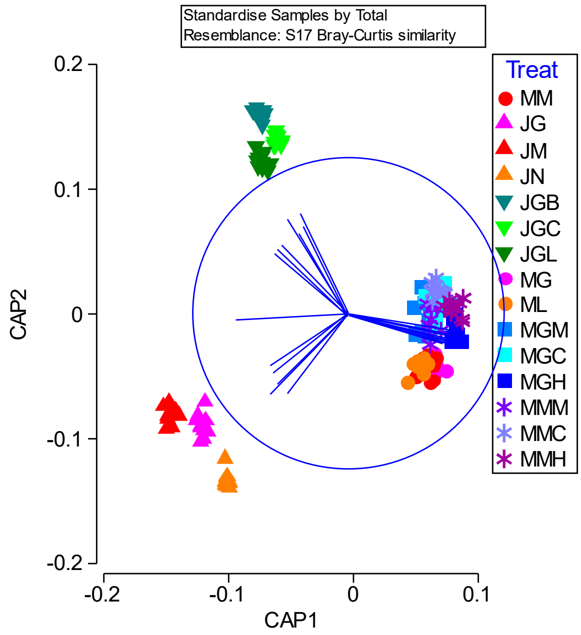

Figure 14: *CAP analysis of fungal communities supported the differentiation of treatments. Vectors show that several fungal OTUs were associated (Pearson correlation coefficient >0.6) with Jazz tree-line or inter-row treatments, with others having a strong association with the Morgana block.*

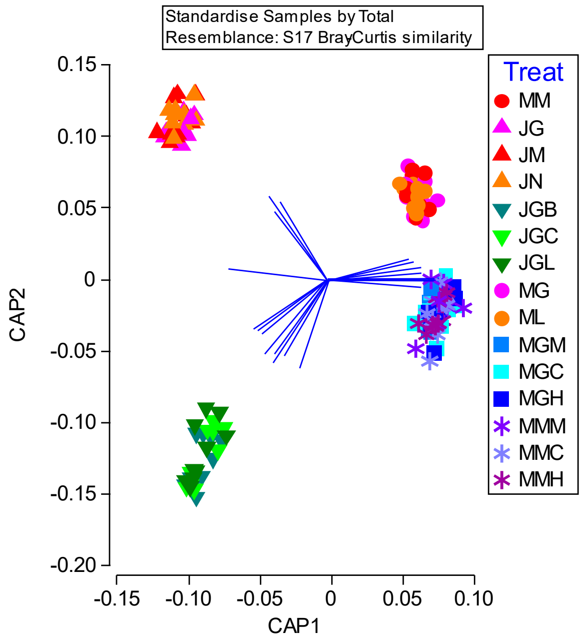

Figure 15: *CAP analysis of fungal communities supported the differentiation of 4 groups; Jazz tree-line, Jazz inter-row, Morgana tree-line and Morgana inter-row. The vectors represent fungal taxa with a Pearson correlation coefficient >0.6. Most of these taxa are associated with the tree-line samples rather than the inter-row.*

Differences among soil volatile organic compounds (VOCs) were not significant for treatments but were significant for treatment groups (Table 34). CAP analyses supported the differentiation of treatment groups (Figure 16) though the misclassification error was 20%.

Table 34: *PERMANOVA pairwise tests for significant difference in VOCs of soil in different treatment*

Groups	t	P(perm)	Unique perms	P(MC)
Comparison of samples from top 75mm				
JIRU, JTLU	2.1946	0.0095	9935	0.0093
MIRU, MTLU	3.5723	0.0001	9938	0.0001
JIRU, MIRU	3.9527	0.0001	9936	0.0001
JIRU, MTLU	3.2687	0.0001	9944	0.0001
JTLU, MTLU	4.6784	0.0001	9921	0.0001

JTLU, MIRU	7.8581	0.0001	9929	0.0001
Comparison of samples from lower75mm				
JIRL, JTLL	2.9978	0.0001	9929	0.0005
MIRL, MTLL	4.4569	0.0001	9941	0.0001
JIRL, MIRL	3.6023	0.0001	9937	0.0001
JIRL, MTLL	4.504	0.0001	9921	0.0001
JTLL, MIRL	5.2596	0.0001	9944	0.0001
JTLL, MTLL	3.7518	0.0001	9941	0.0001
Comparison of samples from upper and lower 75mm of soil in the same treatment group.				
JIRU, JIRL	3.7251	0.0001	9948	0.0001
JTLU, JTLL	5.8378	0.0001	9933	0.0001
MIRU, MIRL	2.2596	0.0012	9928	0.0021
MTLU, MTLL	2.9393	0.0001	9927	0.0001
Comparison of remaining sample pairs				
JIRU, JTLL	2.7744	0.0004	9939	0.0008
JIRU, MIRL	4.6805	0.0001	9956	0.0001
JIRU, MTLL	5.0173	0.0001	9932	0.0001
JTLU, JIRL	7.835	0.0001	9934	0.0001
JTLL, MIRU	3.871	0.0001	9936	0.0001
JTLL, MTLU	2.9005	0.0001	9930	0.0001
JIRL, MTLU	4.1598	0.0001	9934	0.0001
JIRL, MIRU	3.0241	0.0001	9942	0.0001
MIRU, MTLL	3.6339	0.0001	9932	0.0001
MTLU, MIRL	4.4999	0.0001	9920	0.0001
JTLU, MIRL	9.013	0.0001	9921	0.0001
JTLU, MTLL	8.0195	0.0001	9932	0.0001

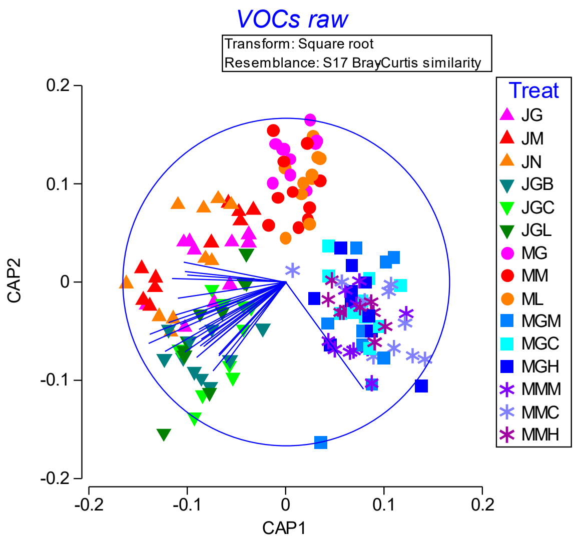

***Figure 16**: Volatile organic compounds reflected differences in microbial communities, with a more diverse volatilome in those treatments (Jazz, tree-line) with more diverse microbial communities. Vectors represent individual volatile organic compounds with a Pearson correlation coefficient >0.6*

In summary, fungal and bacterial communities were affected by both inter-row and tree-line treatments, though no increase in soil microbial carbon was as yet detectable. The increased soil microbial carbon and bacterial species richness in wetter plots with compost treatments indicates that water may be a limiting factor that reduced potential effects of the applied treatments. Additional sampling under wetter conditions may provide some clarification. Significant changes to microbial biomass carbon may take longer than the time elapsed between application of treatments and sampling, particularly where other factors may be limiting.

Earthworm counts

Worm counts of both tree-line and inter-row plots were undertaken in September 2022 in both the 15-year-old 'Jazz and 2-year-old 'Morgana' blocks (Table 35). In the older 'Jazz' block, the number of worms found in the living legume/grass mulch was 440% higher than in the compost mulch or herbicide treatments. In the 'Morgana' block there was no significant different in worm number between the compost mulch, hemp straw mulch or mow & throw mulch tree-line treatments. There was no difference in worm numbers between any of the inter-row treatments in either the 'Jazz' or 'Morgana' blocks.

Table 35: *The impact of tree-line and inter-row treatments on worm numbers in a 15-year-old 'Jazz' apple block and a young 'Morgana' apple block. Assessments undertaken Sept. 2022.*

	Herbicide	**Compost**	**Grass/legume**	**F prob**	**Lsd (p<0.05)**
Tree-line - Jazz	2.1 ^{b}	2.1 ^{b}	9.3 ^{a}	*<0.001*	*2.99*
	Grower practice	**Meadow mix**	**Native mix**		
Inter-row - Jazz	5.6	9.6	4.8	*0.105*	*ns*
	Mow & throw	**Compost**	**Hemp straw**		
Tree-line - Morgana	4.9	3.0	4.2	*0.534*	*ns*
	Grower mix	**Meadow mix**	**Fescue/clover**		
Inter-row - Morgana	6.6	5	3.6	*0.352*	*ns*

Arthropod sampling

Dr Steve Quarrell (TIA) undertook arthropod assessments in the Jazz trial block in collaboration with the PIPS3 project AP19002. Earwig traps, sticky cards, and Delta (pheromone) traps for codling moth and Light Brown Apple Moth were set up in the trees. Pitfall traps were installed in both the tree-line and inter-row (Figure 17). Traps were monitored for one week every month during the growing season.

Figure 17*: Pitfall trap in the inter-row (left); covered trap (centre); and Dr Steve Quarrell with a sticky trap in the orchard (right).*

All data for arthropod sampling are presented in the final report for AP19002.

Fruit pest damage assessments (information provided by Dr Steve Quarrell)

Fruit damage assessments were completed in Trial 1 ('Jazz') on 4th April 2022, approximately two days prior to harvest. Overall, fruit damage was relatively low across the block (mean ± SEM, 4.48 ± 0.3%). The observed damage was largely caused by weevils, apple scab (*Venturia inaequalis*), and codling moth (*Cydia pomonella*) stings with very low levels of thrip damage observed. Weevil damage was the predominant damage type (54.9%) followed by codling moth (20.5%) and apple scab (11.9%). No codling moth larvae were observed in any of the fruit assessed indicating the efficacy of the repeated organic insecticide applications (*Bacillus thuringiensis* & *Cydia pomonella granulovirus*) used in early December in preventing larval tunnelling but not fruit damage. The weevil damage is believed to have been initiated by garden weevils (*Phlyctinus callosus*) as this was the only species - all be it in relatively low numbers - observed during the production season at the 'Rookwood' conservation biocontrol field site (Figure 18).

Although preliminary analysis of fruit damage indicated no significant difference in the total damage observed between the three interrow treatments (H = 11.780, P = 0.203), differences in damage type were. Significant differences in the levels of codling moth stings (H = 5.897, P = 0.024) and apple scab lesions (H = 9.000, P = 0.028) differed between the three inter-row treatments, with higher levels of damage observed within the exotic meadow interrow treatment. No difference was observed between the standard grower sward (Huon # 2) and the native species mix.

No significant difference was observed in total damage (H = 5.048, P = 0.080), weevil damage (H = 3.140, P = 0.208) or codling moth stings (H = 3.849, P = 0.146) between the three tree-line treatments. However, a difference was observed in apple scab incidence (H = 11.083, P = 0.004) with greater scab incidence in the compost under tree treatments. No significant interaction was observed between the interrow and tree-line treatments in any of the damage types observed or total damage occurrence.

Figure 18*: Skin lesion on 'Jazz' apple characteristic of weevil damage during early development (left), and garden weevil (Phlyctinus callosus) (right). Photos courtesy of Dr Steve Quarrell.*

Tree growth

There were no significant differences between the tree-line treatments in initial tree size (measured as trunk cross-sectional area in September 2021) in either the 'Jazz' or 'Morgan' trees (Table 36). Tree-line treatments had no effect on tree growth, measure as increase in trunk circumference and trunk area in either cultivar. These results were not unexpected as this is the first full season following application of treatments, and it can take several years for the impact of soil treatments to carry through to tree growth.

Table 36*: The effect of different tree-line treatments on tree growth in Trial 1 ('Jazz') and Trial 2 ('Morgana')*

Treeline treatment	Trunk cross-sectional area (cm^2) – Sept 2021	Increase in trunk circumference (cm)	Increase in trunk area (cm^2)
Trial 1 ('Jazz')			
Herbicide	17.78	0.270	0.67
Compost	16.97	0.265	0.76
Grass/Legume	18.52	0.293	0.76
Fprob	*0.749*	*0.837*	*0.825*
Lsd (p≤0.05)	*ns*	*ns*	*ns*
Trial 2 ('Morgana')			
Mow & throw	*2.79*	*2.12*	*2.37*
Compost	*2.68*	*1.98*	*2.17*
Hemp straw	*2.65*	*1.88*	*2.07*
Fprob	*0.646*	*0.287*	*0.361*
Lsd (p≤0.05)	*ns*	*ns*	*ns*

TCSA = trunk cross-sectional area.

Fruit quality assessments

The ‘Morgana’ trees were in second leaf in the 2021/22 season and hence were not cropping; these trees carried a small crop in the 2022/23 season, but there was insufficient fruit for fruit quality assessments. Trees in the established ‘Jazz’ block were harvested at normal commercial fruit maturity in early April 2022 (2021/22 season) and 2023 (2022/23 season); fruit numbers were counted prior to harvest on two tagged trees in the centre of each trial plot (90 trees in total) and a sample of 40 fruit collected from the eastern side of these trees.

Fruit samples were returned to the laboratory, weighed and mean fruit weight determined for each sample tree. A subsample of 25 defect-free fruit was randomly selected from each tree for laboratory analysis of fruit quality and maturity. Parameters assessed included weight, diameter (D), length (L), skin chlorophyll content (DA Index), flesh firmness, total soluble solids (TSS) content, starch pattern index (SPI) and percentage dry matter content (DMC). Fruit skin colour was assessed in 2023 only due to equipment breakdown in 2022.

Fruit length (L) and diameter (D) were measured using Vernier callipers. Fruit flesh firmness was measured on pared flesh with an Effegi 11 mm penetrometer probe fitted to a Güss Model GS-20 Fruit Texture Analyser (Güss, Strand, South Africa). Juice expressed from the apples during firmness measurements was used to assess TSS concentration with an Atago PR-1 digital refractometer (Atago Co. Ltd., Tokyo, Japan). The starch-iodine test for apples was used to determine SPI; each fruit was cut transversely across the equator and the cut surface of the calyx end painted with a solution of 1 g potassium iodide plus 0.25 g iodine per 100 mL water. The resulting pattern of starch hydrolysis was compared with the ENZA 6-point starch pattern chart (ENZA International Ltd., Hastings, New Zealand) and the pattern most similar to that of the fruit recorded. For DMC, two wedges were removed from opposite sides of the stem-end of each fruit, placed in labelled paper bags, weighed, oven dried at 60°C to a constant weight, dry weight recorded, and DMC calculated. A DA meter (Model FRM01, Sinteleia, Bologna, Italy) was used to estimate the amount of chlorophyll in the outer flesh layers just under the skin using the DA index (Difference of Absorbance between 670 and 720 nm). Fruit skin colour was measured with a Chroma meter CR-400 (Konica Minolta Sensing Inc., Osaka, Japan) with output in the CIElab colour space (L*, a* and b, Figure 19). These data were used to calculate Chroma *C**and Hue angle *h*°.

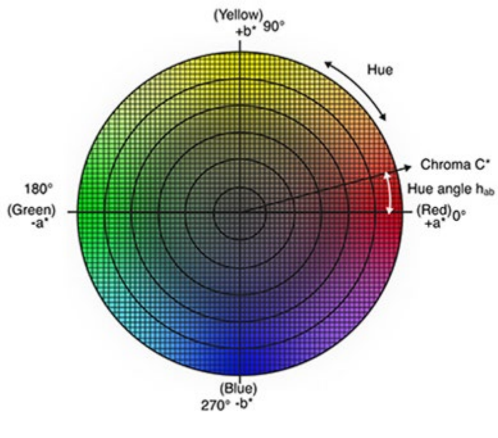

***Figure 19**: CIELAB colour chart - the colour parameters L*, a* and b* represent each of the three values used to measure objective colour and calculate colour differences. L* represents lightness from black to white on a scale of zero to 100. Colour parameters a* and hue angle relate to the “redness” of the blush and chroma quantifies the colour purity. Both a* and b* have maximum values of 60, with a* values ≤ 0 indicating no red colour, and b* ≤ 0 indicating no yellow colour. A hue angle of 0° corresponds to red, 90° to yellow, 180° to green, and 270° to blue. Chroma values range from 0–60, with lower values being less pure.*

Data were subjected to analysis of variance using Genstat release 17.1 (VSN International Ltd., Hertfordshire, UK). Data are presented as mean values for each treatment. Significance was calculated at p = 0.05 and least significant difference (LSD) used for comparison of mean values. Data were checked for normal distribution, and no data transformations were necessary.

There were no significant differences observed between the tree-line treatments for blossom density or crop load (measured as number of fruit per 100 blossom clusters and number of fruit per cm^2 trunk cross-sectional area (Table 37). These results were not unexpected as this is the first full season following application of treatments, and as noted above, it can take several years for the impact of soil treatments to carry through to tree growth and yields. There was no difference in mean fruit weight between the tree-line treatments in 2022, but in the 2023 season fruit in the grass/legume tree-line plots was 11g lighter than in the herbicide plots. One explanation for this difference is that the grass in this season was well established and growing vigorously and hence was competing with the trees for water and nutrients – potentially if these plots had been mown regularly there may have been no effect. This is worth exploring in future studies.

***Table 37**: The effect of different tree-line treatments on blossom density, crop load and fruit size growth in Trial 1 ('Jazz') and Trial 2 ('Morgana').* TCSA = trunk cross-sectional area

Treeline treatment	**Blossom density (buds cm^{-2} TCSA)**		**Fruit/100 blossom clusters**	
	2022	**2023**	**2022**	**2023**
Trial 1 ('Jazz')				
Herbicide	20.15	6.20	37.62	80.8
Compost	23.58	6.92	38.27	74.6
Grass/Legume	19.63	7.12	39.75	62.7
Fprob	*0.281*	*0.679*	*0.933*	*0.116*
Lsd (p≤0.05)	*ns*	*ns*	*ns*	*ns*
Trial 2 ('Morgana')				
Compost	-	22.7	-	54.9
Hemp straw	-	21.6	-	52.3
Mow & throw	-	22.8	-	58.2
Fprob	-	*0.754*	-	*0.469*
Lsd (p≤0.05)	-	*ns*	-	*ns*
	Fruit cm^{-2} TCSA		**Mean fruit weight (g)**	
	2022	**2023**	**2022**	**2023**
Trial 1 ('Jazz')				
Herbicide	6.37	4.57	134	136.9 a
Compost	6.61	4.84	137	139.4 a
Grass/Legume	5.97	4.60	132	125.9 b
Fprob	*0.602*	*0.930*	*0.362*	*0.001*
Lsd (p≤0.05)	*ns*	*ns*	*ns*	*7.56*
Trial 2 ('Morgana')				
Compost	-	11.97	-	-
Hemp straw	-	10.87	-	-
Mow & throw	-	12.99	-	-
Fprob	-	*0.200*	-	-
Lsd (p≤0.05)	-	*ns*	-	-

Within each column, means followed by different letters are significantly different according to the LSD means comparison test at p = 0.05.

There was no difference between treatments in fruit shape, represented by L/D ratio, in either season (Table 38). There were, however, small but significant differences in other fruit quality parameters, although these differences were not always consistent across the two seasons. Both fruit TSS and DMC were higher in the grass/legume treatments than in the compost or herbicide treated plots in the 2022 season, but in the 2023 season, TSS was lower while there was no difference in DMC. Fruit firmness was higher in the grass/legume treatment compared with the herbicide treatment in both seasons, while fruit in the compost treatment showed the lowest firmness in the 2022 season and the highest firmness in the 2023 season. Fruit chlorophyll content (DA Index) was lower in the grass/legume treatment in the 2022 season, but in the 2023 season this was higher in the grass/legume treatment compared to the herbicide control. SPI showed a slower rate of conversion of starch to sugar in the grass/legume treatment across both seasons.

Although the differences between treatments were small, it is interesting to note that grass/legume in the tree-line was not detrimental to fruit quality in the first season (2022), but rather improved most fruit quality parameters compared with the standard bare-earth herbicide treatment. The difference in fruit soluble solids content in this treatment in the second season may be due to competition as growth of the grass/legume plots was left unchecked (noted above for tree growth).

Table 38: The effect of different tree-line treatments on fruit quality parameters in Trial 1 ('Jazz' apple)

Treeline treatment	Length/diameter ratio 2022	Length/diameter ratio 2023	Soluble solids (°Brix) 2022	Soluble solids (°Brix) 2023	Dry matter content (%) 2022	Dry matter content (%) 2023
Herbicide	1.01	1.01	12.04 ^{b}	12.9 ^{a}	14.59 ^{b}	15.06
Compost	1.01	1.01	12.10 ^{b}	12.8 ^{ab}	14.63 ^{b}	15.07
Grass/Legume	1.01	1.01	12.39 ^{a}	12.7 ^{b}	14.93 ^{a}	15.02
Fprob	*0.167*	*0.697*	*<0.001*	*0.003*	*0.006*	*0.953*
Lsd (p≤0.05)	*ns*	*ns*	*0.087*	*0.13*	*0.227*	*ns*
	Firmness (kg) 2022	**Firmness (kg) 2023**	**DA Index 2022**	**DA Index 2023**	**Starch pattern index 2022**	**Starch pattern index 2023**
Herbicide	9.41 ^{b}	9.24 ^{c}	0.47 ^{b}	0.29 ^{b}	4.44 ^{a}	5.39 ^{a}
Compost	9.28 ^{c}	9.38 ^{a}	0.59 ^{a}	0.24 ^{c}	4.23 ^{b}	5.45 ^{a}
Grass/Legume	9.66 ^{a}	9.36 ^{b}	0.38 ^{c}	0.43 ^{a}	4.02 ^{c}	5.25 ^{b}
Fprob	*<0.001*	*0.028*	*<0.001*	*<0.001*	*<0.001*	*<0.001*
Lsd (p≤0.05)	*0.107*	*0.112*	*0.027*	*0.035*	*0.113*	*0.075*

Within each column, means followed by different letters are significantly different according to the LSD means comparison test at p = 0.05.
DA = delta absorbance

For fruit colour (Table 39), the L* values are in the mid-range for all treatments. Fruit from the grass/legume treatment showed slightly more redness (a* and hue angle) than the other treatments, and fruit from the compost treatments had the least redness.

Table 39: The effect of different tree-line treatments on fruit skin colour in Trial 1 ('Jazz' apple) in the intensive research trial at Ranelagh, Tasmania

	L*	a*	b*	Chroma	Hue angle
Herbicide	42.29 ^{b}	32.53 ^{b}	22.12 ^{b}	40.1 ^{b}	0.6 ^{b}
Compost	43.98 ^{a}	28.84 ^{c}	23.91 ^{a}	38.3 ^{c}	0.7 ^{a}
Grass/Legume	40.64 ^{c}	34.79 ^{a}	20.58 ^{c}	40.7 ^{a}	0.5 ^{c}
Fprob	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*
Lsd (p≤0.05)	*0.637*	*0.816*	*0.442*	*0.51*	*0.02*

Within each column, means followed by different letters are significantly different according to the LSD means comparison test at p = 0.05.

Figure 20: Harvest samples from the 'Jazz' apple trial block at Rookwood orchard, Tasmania.

Regional sites

Refer to document: AP19006 – MS190_Regional site summary-20230721.docx

Issues

- Commencing the project in late winter, with the expectation of spring plantings for trial and demonstration sites meant that there was insufficient time to prepare the soil for adequate removal of the existing weed seed bank.

- Sourcing seed for spring planting was challenging, as most suppliers were either out of stock or had limited supplies.
- Across each of the growing regions, some plantings were delayed due to wet weather and problems accessing sites.
- Poor germination of seed and poor survival through the first hot summer meant that several sites had to be replanted.
- COVID shutdowns delayed planting in some regions.
- The three-year time frame for this project was too short to assess the true impact of orchard floor treatments, particularly when the first year was spent establishing sites.

Summary and Conclusions

The knowledge gained from the intensive research trials and regional demonstration sites as well as the review of the literature has shown that it is possible to move towards a more regenerative approach in orchards by working with natural systems and processes to build optimum soil and plant health, without the need to discard the best of conventional farming methods, to maintain or improve production levels and quality. Natural systems allow for an increase in biodiversity, providing natural control of pests, and building soil health. It is evident that biodiversity, both above and below ground, is the key in the development of ecosystem services that enable a move away from reliance on synthetic fertilisers and pesticides.

The orchard floor is a complex environment that has a major influence on crop productivity and quality. The plants of the orchard floor provide a home and food source for pollinators, predators, and other beneficial insects above ground, and strongly influence the diversity of arthropods (insects, millipedes, spiders, and earth worms) and microbes at the soil boundary and below. Soil biology (macro- and meso-arthropods and micro-organisms) is the key to nutrient cycling, in addition to influencing soil physical properties such as aggregation and water infiltration. A diverse orchard floor can give the orchard resilience and balance both above and below ground, allowing the orchard to resist or rebound rapidly from disturbances or the impact of climatic events such as high rainfall or drought.

Species selected for the orchard floor, whether in the inter-row or tree-line, need to be robust and resilient to traffic, but not invasive or competitive, and provide shelter and a food source for beneficial arthropods without creating an environment conducive to pest species and disease. Understanding the importance and complexity of the interrelationships that occur within the orchard floor, both above and below ground (Figure 21), and nurturing these relationships will increase orchard resilience and long-term productivity.

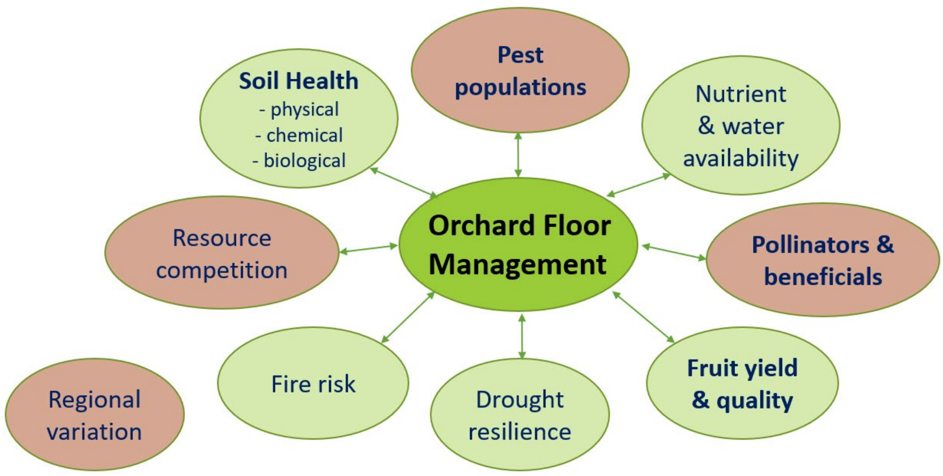

***Figure 21**: Bringing it all together – the complex inter-relationships involved in orchard floor management*

Competition

Many orchardists are concerned about competition for water and nutrients from ground cover plants on the orchard floor, particularly in the tree-line, reducing yield and fruit quality. However, the results from both the intensive research site and the regional demonstration sites suggest that the impact of cover crops in the tree-line is not necessarily detrimental to fruit quality. Further studies examining tree-line cover crop mixes and their vigour will alleviate this concern. Another option is the use of summer dormant species, however in an irrigated orchard these species do not always become dormant.

There is also concern that a vegetated tree-line provides habitat for pest species and tall vegetation growing up into the lower branches of the trees can create a humid microclimate, thus increasing disease pressure. Managing the tree-line vegetation by mowing, or even an occasional herbicide application, can ameliorate these problems.

Managing pests

Several lessons arose from this project in relation to management of pests within the orchard. These are reported in the final report for project AP19002, but include:

- arthropod species change with plant species,
- insect numbers can be altered by manipulating ground covers,
- costs and benefits for pest management can be quantified but may be site specific,
- pesticide applications can undo any improvements in numbers of beneficial insects.

Selection of orchard floor species

Any ground cover, even weeds, as a living mulch is better than bare soil, but the more diverse the plant species on the orchard floor, the greater the diversity of root architecture (fibrous, spreading and tap roots). There is evidence that the more diverse the plant species, the greater the diversity in soil organisms.

A living mulch dominated by perennials is logical in an orchard situation, and many growers have adopted a version of living mulches with a permanent sward, normally grasses and a grass/clover mix, in the inter-row, even though a bare strip under the tree row is normally still maintained. This enables the inter-row sward to be maintained without the need for reseeding each year. Use of annuals requires either reseeding every season, which adds to the costs of maintaining the orchard floor, or allowing the annuals to flower and seed. However, growers are used to maintaining a 'tidy' orchard with regular mowing and find it difficult to leave the inter-row to grow freely so plants are able to flower and seed. For a practice change such as this to succeed, a change in mind-set will be required for growers to allow the inter-row sward to grow to a height without mowing, and growers will require support to adapt.

There are multiple criteria to be considered when selecting species for planting in the orchard inter-row and/or tree-line, and these are listed in Table 40.

Table 40*: considerations when selecting plant species for living mulches in the orchard inter-row and/or tree-line.*

Inter-row	Tree-line
- easy and fast to implement	- easy and fast to implement
- rapid establishment of sward	- established rapidly
- ease of maintenance after establishment	- longevity and maintenance
- longevity	- organic matter source
- range of root architecture	- food source/habitat for beneficials
- traffic resilience	- improved soil structure & water infiltration
- provide sufficient grip for tractors	- improved water & nutrient availability
- aids in reducing soil compaction	(no competition with tree crop)
- improves water infiltration	- increased soil biology
- nutrient recycling	- maintain/improve fruit quality
- food source / habitat for beneficial arthropods	- sustainability

In this project, native species failed to establish successfully in the inter-row in all regions. One problem was the inability of native species to compete with weeds and pasture grasses due to their slow growth rate. For native grasses and herbaceous species to have any chance of success in orchard inter-rows a long lead in time of at least two years with intensive herbicide application would be required to remove the seed bank from the soil. Apart from the intensive labour requirements, this would be impractical for most orchards.

Although impractical in the orchard inter-row, there is still potential to introduce the benefits of native flowering plants in relation to habitat and food source for beneficial insects, particularly native insect species. Potential methods for introducing native flowering species include hedge rows around the orchard and/or between blocks, or in high-density orchards planting every 10th row to native species.

Increasing soil organic matter and biology

Organic matter is a vital component of healthy soils, and the amount of organic matter in a soil is determined by the balance between accumulation and loss through decomposition or oxidation. The rate of decomposition and accumulation of soil organic matter is dependent on multiple factors including soil type, temperature, moisture content, aeration, and biological activity; but conversely, soil organic matter can modify many of these soil properties. It is well recognised that soil fertility can be improved by regular additions of organic matter and that microbial biomass is central to organic matter cycling in soils - the higher the level of microbial activity the higher the rate of mineralisation of organic matter.

As well as providing a food source for soil microbes, organic matter acts a sponge, aiding in water infiltration and increasing drought resilience. Incorporation/addition of organic matter is a proven method of building the soil.

In new orchards the process of increasing soil organic matter can be started by incorporation of a high-quality compost prior to planting. In established orchards the following practices can aid in increasing soil organic matter levels:

- Addition of composts in both the inter-row and tree-line. Specialised spreaders for application to the tree-line will aid in minimising labour input.
- Application of coarse mulches or straw in the tree-line.
- Cover crops in the inter-row.
- Permanent sward in the inter-row – perennial species avoid the need for annual resowing.
- Living mulches, ideally a mix of grasses and legumes in the tree-line.
- Throwing the mowing clippings onto the tree-line.

As root exudates from actively growing plants provide a food source for soil microbes, the abundance and diversity of the soil microbial community is likely to be increased by ensuring full ground cover with a range of plant species. There is normally a decline in carbon availability with increasing soil depth, and this has been attributed to the vertical soil distribution of microbial communities. The dominant factor influencing microbial biomass and activity at different depths appears to be plant root distribution, with the presence of deeper rooting species resulting in higher microbial populations and diversity deeper in the soil profile.

In the short two years that our treatments were established in this project, differences were observed in both fungal and bacterial communities between the inter-row and tree-line treatments. While there were no measurable treatment effects on soil microbial carbon, there was an increase in soil microbial carbon and bacterial species richness in the wetter compost plots, indicating that water may be a limiting factor that reduced potential effects of the applied treatments.

The different components of this project are all in agreement that soil life can be increased by increasing organic matter in soil. Practices such as reducing herbicide use and adding organic matter to the soil will aid in increasing soil life. While addition of compost and/or mulches such as straw or mower clippings plays an important role, actively growing plants are critical to healthy microbial populations and an active food web within the soil that provides a high level of nutrient cycling and an adequate supply of plant available nutrients.

Have we seen an improvement in soil health?

While there is no set definition of what constitutes the optimum 'healthy soil,' we know that soil health is related to factors such as physical structure, aggregate size, water retention and infiltration, soil chemistry and availability of nutrients, and biodiversity including microbe and invertebrate (arthropod) populations.

Building up good soil health is a gradual process. Depending on the soil type and initial state of 'health', some benefits to any management changes aimed at improving soil health and resilience may be observed within the first 12 months, but it often takes several years before noticeable improvements can be observed. Healthy soil attributes to work towards include:

- good levels of organic matter,
- good populations of earthworms, macro- and meso-arthropods,
- thriving populations of micro-organisms - bacteria, fungi, protozoa, and nematodes,
- nutrient cycling to provide plant available nutrients,
- 100% ground cover with a diverse mix of species,
- small & large pore spaces for air & water,
- good soil aggregation,
- good water infiltration rates (>100 mm/hr),
- absence of a compaction or crusting layer.

In spite of the relatively short time frame that treatments were implemented, there were differences in soil microbiology observed between treatments, and soil physical characteristics such as soil bulk density, hydraulic conductivity and aggregate stability improved. There were also increases in level of several nutrients observed in some of the tree-line treatments, with the compost and grass/legume treatments appearing to be the most beneficial. However more time is needed to quantify these changes.

What can growers do to check the state of their soils ?

Whatever the state of your soil, there are many simple ways of keeping track of your soil health, from commercially available soil test kits to simple tests using everyday equipment. What you are looking for is change (hopefully positive!) over time. Remember that if you change the way you manage your orchard floor, results won't be seen immediately – so to know whether the change was beneficial you need to monitor what is happening over time.

Make sure that you are consistent in the time of year that you take your samples, the way you take a soil sample and the lab you use if you are sending samples for laboratory analysis. But there are multiple tests that you can do yourself, including looking at biological activity using simple field kits, such as Solvita, that measure soil respiration or carbon dioxide production.

And most importantly, remember that a spade is one of your most valuable tools to see what is happening in your soil - dig a hole so you can see the subsoil:

- Are old inactive roots decomposing (evidence of bacteria and fungi);
- Does the soil smell earthy (actinomycetes);
- Is the soil dark in colour (soil organic carbon);
- Is the soil well structured (soil aggregation);
- Is there evidence of bioturbation (macrofauna – earthworms and beetles);
- store a representative sample of soil in an ice cream container – do the same in subsequent seasons to see how the physical character of your soil changes.

Look for evidence of organisms

- Count earthworms – 10-12 per spadeful indicates good soil health;

- Set pitfall traps for macro and mesofauna;
- Examine nodules on legume (clover) roots – a bright pink/red colour indicates active nitrogen fixing bacteria;
- Rapid deterioration of wooden stakes is a good indicator of fungal activity (the cellulose in the wood provides a food source for fungi), or bury some cotton undies and check for decomposition after 8-10 weeks.

Recommendations for further studies

1. Continue monitoring the existing PIPS3 intensive trial sites, with a focus on tree-line treatments.
2. Examine tree-line cover crops and their vigour for effective on tree growth, crop yield and fruit quality.
3. Examine inter-row mixes that support a self-sustaining population of flowering annual and perennial species that encourage insect guilds that provide pollination and predatory services.
4. Identify optimal mowing times / methods (eg alternate rows) to support beneficial insect guilds.
5. How do we shift the orchard from a bacteria dominated environment (changes to bacterial populations) to a mycorrhiza dominated environment (what species, rates of colonisation?).
6. What influence do changes to soil health have on fruit quality?
    - What are the influences beyond simple and traditional fruit quality measures?
    - Apply research tools such as e tongue and e nose to fruit quality evaluation.
7. Tree physiological impacts:
    - Cover crops and compost addition should improve tree water availability over time due to increased soil carbon/organic matter and benefits to soil structure and water infiltration/retention.
    - Potential effects of orchard floor treatments on fruit and leaf tissue carbon isotope ratios may indicate improved resilience of the growing system to tree water deficit.
8. Develop a soil health tool kit for growers:
    - Advance the BMPs for cover crops to growers determining benefits/changes simply and cost effectively
    - Easy to adopt methods and how to monitor benefits/changes.
9. Form distinctions between the functional purposes of cover crops in the tree-line vs inter-row
    - Tree-line: tree health, accessibility to water, soil water holding capacity, nutrient recycling, mycorrhizal activity;
    - Interrow: attract beneficials, alterative food source for pollinators, habitat for predatory insects, overcoming soil compaction issues, holding soil together on slopes.
10. Economic analysis: cost benefits of cover cropping, modelling of soil carbon changes and benefits, determining resilience and economic benefit of a more resilient orchard.

AP19006 - Improved Australian apple & pear orchards soil health and plant nutrition

MS190: Final report – Regional sites

Sally Bound, Jessica Fearnley, Susie Murphy-White, Paul James and Susie Green

Regional demonstration sites were established in different growing regions across Australia to support the intensive trial work undertaken in Tasmania. It also provided the opportunity for local examples accessible to growers that showcased how different orchard floor management practices influenced soil health, tree health and nutrition, fruit yield and quality, The demonstration sites, with limited data collection, were established in New South Wales, South Australia and Western Australia, the Victorian site was part of the PIPS3 project *AP19002 – Strengthening cultural and biological management of pests and diseases on apple and pear*.

The treatments established in each region included a range of tree-line cover crops, composts, mulches and herbicide bare-earth strip; inter-row plantings included native herbaceous and/or grass mix, flowering meadow mix, and grass/legume mixes.

Treatments and species used reflected regional priorities and soil, climatic and management system differences to assist with:

- identification of the biological, structural and chemical indicators for soil health, including relationship to regional and soil type differences, and assessment methods;
- improving understanding of the interaction between management practices, soil health, nutrient availability, water availability, pest and disease control and fruit productivity/quality;
- measuring the impact of sustainable orchard floor management on the presence and function of mycorrhizal fungi and the organic carbon content of the soil;
- providing a better understanding of the relationships between soil health, tree health, growth and fruit yield, productivity and quality; and
- addressing grower perceived impediments to adoption including water requirements, herbicide and fungicide use, tractor movements and fire risk.

This document describes the regional sites in NSW, SA and WA. The Victorian site is reported in the final milestone report for *AP19002 – Strengthening cultural and biological management of pests and diseases on apple and pear.*

New South Wales regional site

The NSW demonstration site was established at NSW Department of Primary Industries' Orange Agricultural Institute as this is an ideal location to hold workshops and orchard walks. Complete access and control of the site means a thorough demonstration plot can be established and maintained.

Three rows of ordinary strain Pink Lady apples, each with 20 trees that are trellised and on 4 × 1.5 m tree spacing were used for the demonstration block, allowing for a buffer tree in between each treatment.

***Table 1**: Treatments applied at the NSW Orange demonstration site.*

Inter-row Treatments	Tree-line Treatments
Control	Herbicide strip
Flowering Meadow	Compost/mulch
Native Pastures	Legume/grass

Inter Row Treatments

In preparation for sowing, the inter-rows were sprayed with glyphosate and cultivated to ensure a weed-free strip for planting (Figure 1).

Figure 1:*Cultivation of the inter-row to ensure a weed-free planting strip.*

<u>(i) Grower practice</u>

Most growers in the Orange area choose to have a grass/legume inter-row and this formed the control for this trial. The orchards at Orange Agricultural Institute are sown with a clover/ryegrass mix and one row in the trial site was left with this mix.

<u>(ii) Flowering meadow mix</u>

The focus of the flowering meadow mix was to bring bees and beneficial insects to the row. Two mixes (Beneficial Insect Mix and Bee Friendly Mix) were purchased from Meadow Flowers Australia. Species in these mixes are listed in Table 1.

Table 1*. Plant species in the flowering meadow mix*

Bee Friendly Mix	Beneficial Insect Mix
Blanketflower (*Gaillardia pulchella*)	**Blanket Flower** (*Gaillardia aristata)*
Blue Flax (*Linum perenne*)	**California Poppy** (*Eschscholzia californica*)
Blue-thimble-flower (*Gilia capitate*)	**Candytuft** (*Iberis umbalatta*)
California Poppy (*Eschscholzia californica*)	**Common Dill** (*Anethum graveolens*)
China aster (*Callistephus chinensis*)	**Coriander** *(Coreopsis sativum*)
Chinese hound's tongue (*Cynoglossum amabile*)	**Dense Blazing star** *(Liatris spicata)*
Common Poppy (*Papaver Rhoeas*)	**Garden/Dwarf Cosmos** *(Cosmos bipinnatus)*
Garden Tickseed (*Coreopsis tinctoria*)	**Mayfield Giants** (*Coreopsis lanceolate)*
Korean Mint (*Agastache rugose*)	**Menzies' baby blue eyes** (*Nemophila menziesii*)
Lance-leaved coreopsis (*Coreopsis lanceolate*)	**Queen Anne's Lace** *(Ammi majus)*
Menzies' baby blue eyes (*Nemophila menziesii*)	**Rock Cress** *(Aubrieta hybrid)*
Moroccan Toadflax (*Linaria maroccana*)	**Shasta Daisy** (*Chrysanthemum maximum)*
Purple coneflower (*Echinacea purpurea*)	**Sweet alyssum** *(Alyssum benthamii)*
Sweet alyssum (*Lobularia maritima*)	**Wallflower** *(Cheirianthus Chieri)*
Tidy tips (*Layia platyglossa*)	**Wild bergamot** (*Monarda fistulosa*)
Wallflower (*Cheiranthus allionii*)	
Wild bergamot (*Monarda fistulosa*)	

Seed was sown on 22 April 2020 using a manual seeder. Germination was good, (Figure 3) and this mix was very successful in the inter-row (Figure 2).

The flowering meadow mix re-established successfully in the following season after setting seed in the first season of the project. However, there were limited species flowering during the apple pollination window (Figure 2). The flowering meadow mix treatment continued to flower throughout the 2022-23 season, with Baby Blue Eyes and Coriander the most prominent species.

Figure 2: Flowering meadow mix in the inter-row (a) season 1 (spring 2020), and (b) during apple pollination in October 2022. Photo: Aphrika Gregson, NSW DPI

(iii) Native herbaceous mix

Seed for the native herbaceous mix was sourced from Native Seeds Australia. This mix contained:

Burra Weeping grass *(Microlaena Stipoides var. Burra)*
Common Tussock grass *(Poa labillardieri)*
Curly Mitchell grass *(Astrebla lappacea)*
Evans Wallaby grass *(Rytidosperma caespitosa)*
Griffin Weeping grass *(Microlaena Stipoides var. Griffin)*
Kangaroo grass (*Themeda triandra)*
Native Wheat grass *(Anthosachne scabra)*
Oxley Wallaby grass *(Rytidosperma bigeniculata)*
Purple Wire Grass *(Aristida personata)*
Scent Top grass *(Capillipedium spicigerum)*
Silky Bluegrass *(Dichanthium sericeum)*
Silky top Lemon Scented grass *(Cymbopogon obtectus)*

The native seeds were sown on 22 April using a manual seeder. Germination in the native seed row was very poor, with only 5% of seeds establishing successfully. As this native pasture treatment was difficult to establish in the field from seed, seeds were planted in seedling trays and placed into a glasshouse. Once seeds had germinated and formed a healthy root system, they were planted in the orchard on 11 November 2021. The seedlings were protected by a layer of sugar cane mulch.

However, the survival rate was poor and the native species were unable to compete with other grasses and weedy species, hence was left to become naturalised in the final season. By the end of the trial, there were no native species left in this treatment.

Tree-line treatments

The common tree-line management in the Orange region is bare earth or herbicide strip under the tree line. This treatment was adopted in the demonstration site for comparison with the other two treatments.

(i) Herbicide strip

The herbicide strip plots were treated with glyphosate (Roundup®) on 11 November 2021 and weeds were also chipped throughout the growing season. It was difficult to keep these plots weed-free and they required several sprays throughout the season to keep clean. This may have been exacerbated by the wet season in 2022-23, but constant chemical application is a large expense for the grower, a health risk for workers and herbicide resistance can occur.

Figure 3*: Herbicide free strip where weeds were treated with glyphosate (Roundup®).*

(ii) Compost

The third tree-line treatment was a mix of compost and pine bark mulch sourced from Australian Native Landscapes (ANL). ANL 'Greenlife Mulch and Compost' is a common and easily accessed compost commonly used in orchards.

The ANL 'Greenlife Mulch and Compost' was applied to the tree line in November 2020 and incorporated into the soil at a rate of 1000 m3/ha (Figure 4). This compost/mulch treatment was effective in suppressing weeds, however broke down significantly during the season and had to be re-applied in November of each season (Figure 4). Success of this treatment was dependant on the amount of coverage and 'thickness' of application - in areas that didn't get an even coverage, weeds and grasses were able to establish under the trees.

Figure 4*: Compost/mulch tree-line treatment, Orange NSW. Photo: Jessica Fearnley, NSW DPI.*

(iii) Grass/legume cover crop

The grass/legume cover crop was a turf-based mix with added legumes. This was established in autumn 2021 directly under the tree line. Plots were hand sown on 24 March 2021, using a hand spreader and seed roller, then irrigated to promote germination. The seed mix was applied at a rate of 3-4 kg per ha or 30 grams of seed per tree.

The grass/legume plots established well, although natural grasses also invaded these plots. These grasses were kept as part of the cover crop (Figure 5)

At the end of the 2021-22 season, the crop was cut with a whipper snipper as it was encroaching onto the trees. Cuttings were left on the crop to increase mulching. The cover crop growing at heights that reach the bottom branches of the tree can create an easy access for pests, create a more humid environment for trees and can pose a significant bushfire risk.

Figure 5: *Tree-line grass/legume cover crop with natural grasses (a) season 1, (b) December 2022. Photo: Jessica Fearnley, NSW DPI.*

Soil tests

Soil microbial analysis

A soil microbe analysis was performed on the three tree line treatments for the Future Orchards field day in spring 2021. While all treatments had a high microbial respiration rate, it was highest in the cover crop treatment (Figure 6).

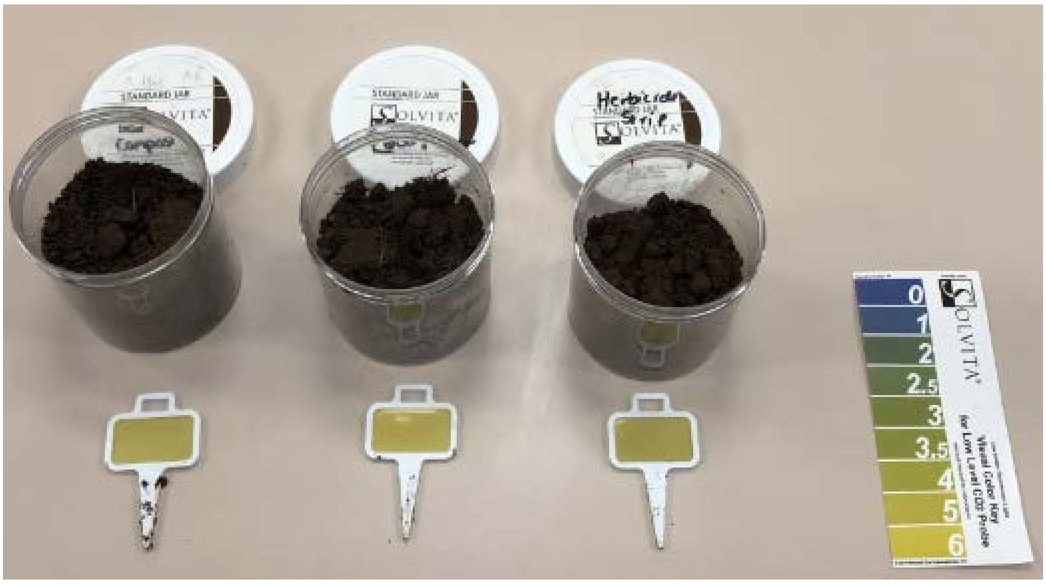

Figure 6: *Microbial respiration test on the tree line treatments.*

Soil chemical analysis

Soil samples were collected in May 2021 and 2023. Samples were forwarded to CSPB Soil and Plant Analysis Laboratory in 2021 and the NSW DPI Wollongbar Environmental Laboratory in 2023 for major soil nutrients and components:

Almost all treatments displayed acceptable levels of total N, an important nutrient for crop growth and fruit development. Interestingly, the cover crop treatment which contained legumes, had low levels of total N present. This could be linked to the very low sulfur levels indicated across all treatments. Sulfur is an essential nutrient for biological nitrogen fixation processes and without it, legumes are unable to fix nitrogen easily. Fertilising treatments with sulfur will ensure that these processes can occur effectively.

An important characteristic that improves soil health is the amount of organic carbon in the soil. The mulch/compost and cover crop treatments in the tree-line were a physical addition of organic material, which would breakdown to organic carbon in the system. Soil carbon can improve the activity and biodiversity of microorganisms in the soil. All treatments had an acceptable level of organic carbon in the soil, except for the herbicide strip, which was expected. Keeping the soil bare exposes organisms to temperature fluctuations and soil erosion. This demonstration trial showed the importance of having ground cover in tree-line to protect soil microbes.

Table 1*: Orange demonstration site soil sample results for May 2023.*

Treatment	Electrical conductivity	Total Nitrogen (%)	Colwell Phosphorus (mg/kg)	Organic Carbon (%)	Sulfur (mg/kg)
Control (interrow)	Acceptable	Acceptable	Low	Acceptable	Very low
Flowering meadow (interrow)	Acceptable	Acceptable	Low	Acceptable	Very low
Grass/legume (tree-line)	Acceptable	Low	High	Acceptable	Very low
Herbicide strip (tree-line)	Acceptable	Low	High	Low	Very low
compost/mulch (treeline)	Acceptable	Acceptable	High	Acceptable	Very low

Full soil analysis results for the Orange demonstration site for all treatments are presented in Tables 4a and 4b.

Table 4a*: Soil analysis results for the inter row treatments*
(2021 = CSBP Laboratories; 2023 = Wollongbar Environmental Laboratory)

	Grower practice		Flowering meadow	
	2021	**2023**	**2021**	**2023**
pH (CaCl2)	6.4	6.6	6.8	6.8
pH (H2O)	7.3	7.4	7.6	7.6
Conductivity (dS mm-1)	0.095	0.072	0.133	0.062
CEC $_{(effective)}$ (meq/100g)	-	13	-	14
ECe Calculation Result**	-	0.62	-	0.53
ESP Exchangeable (%)	0.1	-	0.1	-
Organic carbon (%)	2.03	1.5	1.91	1.1
Total C (%)	2.55	-	2.55	-
Ammonium N (mg/kg)	8	-	5	-

Nitrate N (mg/kg)	5	-	25	-
Total N (%)	0.21	0.18	0.22	0.16
Colwell P (mg/kg)	27	17	31	14
Colwell K (mg/kg)	262	-	320	-
Exchangeable Al (meq/100g)	0.03	<0.1	0.02	<0.1
Exchangeable Ca (meq/100g)	13.5	12	14.8	13
Exchangeable Mg (meq/100g)	0.57	0.6	0.58	0.55
Exchangeable K (meq/100g)	0.63	0.65	0.72	0.57
Exchangeable Na (meq/100g)	0.02	<0.03	0.02	<0.03
S (mg/kg)	3.8	3.8	5.8	2.5
B (mg/kg)	0.81	0.64	0.86	0.58
Cu (mg/kg)	5.84	3	5.75	2.5
Fe (mg/kg)	22.8	14	22.1	9.5
Mn (mg/kg)	37.95	20	38.56	19
Zn (mg/kg)	7.28	4.5	6.91	2.9
Calcium/ Magnesium (% of ECEC)	-	19	-	23
Exch. Calcium Percent (% of ECEC)	-	90	-	92
Exch. Potassium Percent (% of ECEC)	-	5.1	-	4.2
Exch. Magnesium Percent (% of ECEC)	-	4.7	-	4

***Table 4b**: Soil analysis results for tree-line treatments*
(2021 = CSBP Laboratories; 2023 = Wollongbar Environmental Laboratory)

	Herbicide Strip		**Compost/Mulch**		**Cover Crop**	
	2021	**2023**	**2021**	**2023**	**2021**	**2023**
pH (CaCl2)	**7.0**	**7.6**	**6.6**	**7.6**	**6.8**	**7.2**
pH (H2O)	**7.8**	**6.8**	**7.4**	**6.6**	**7.7**	**6.5**
Conductivity (dS mm^{-1})	**0.092**	**0.057**	**0.118**	**0.056**	**0.131**	**0.064**
CEC $_{(effective)}$ (meq/100g)	**-**	**12**	**-**	**13**	**-**	**13**
ECe Calculation Result**	**-**	**0.49**	**-**	**0.48**	**-**	**0.55**
ESP Exchangeable (%)	**0.3**	**-**	**0.4**	**-**	**0.4**	**-**
Organic carbon (%)	**1.60**	**1.0**	**1.97**	**1.3**	**1.90**	**1.1**
Total C (%)	**1.87**	**-**	**2.69**	**-**	**2.24**	**-**
Ammonium N (mg/kg)	**4**	**-**	**5**	**-**	**7**	**-**
Nitrate N (mg/kg)	**3**	**-**	**4**	**-**	**4**	**-**
Total N (%)	**0.15**	**0.13**	**0.21**	**0.16**	**0.18**	**0.14**
Colwell P (mg/kg)	**59**	**51**	**52**	**64**	**49**	**50**
Colwell K (mg/kg)	**271**	**-**	**226**	**-**	**232**	**-**
Exch. Al (meq/100g)	**0.02**	**<0.1**	**0.05**	**<0.1**	**0.02**	**<0.1**
Exch. Ca (meq/100g)	**11.55**	**11**	**13.47**	**11**	**12.69**	**11**
Exch. Mg (meq/100g)	**1.34**	**1.3**	**2.54**	**1**	**2.10**	**0.88**
Exch. K (meq/100g)	**0.61**	**0.41**	**0.51**	**0.86**	**0.52**	**0.57**
Exch. Na (meq/100g)	**0.05**	**<0.03**	**0.07**	**<0.03**	**0.07**	**<0.03**
S (mg/kg)	**4.3**	**<2**	**6.3**	**2.5**	**22.3**	**3.9**
B (mg/kg)	**0.64**	**0.43**	**0.64**	**0.7**	**0.75**	**0.5**

Cu (mg/kg)	**6.06**	**2.8**	**11.13**	**3.4**	**6.45**	**3.7**
Fe (mg/kg)	**23.3**	**10**	**29.5**	**11**	**27.9**	**13**
Mn (mg/kg)	**40.3**	**17**	**45.1**	**21**	**40.5**	**20**
Zn (mg/kg)	**9.2**	**4.8**	**17.8**	**6.2**	**11.9**	**6**
Calcium/ Magnesium	**-**	**8**	**-**	**11**	**-**	**13**
Exch. Ca Percent (% of ECEC)	**-**	**86**	**-**	**86**	**-**	**89**
Exch. K Percent (% of ECEC)	**-**	**3.3**	**-**	**6.5**	**-**	**4.4**
Exch. Mg Percent (% of ECEC)	**-**	**11**	**-**	**7.8**	**-**	**6.9**

Fruit quality

Fruit samples were harvested from all trial plots in 2022 and assessed for diameter, weight, firmness, total soluble solids (TSS) content, background colour and starch pattern index (SPI). Due to major hail storms in 2023, there was no suitable fruit for quality assessments.

Data were subjected to analysis of variance using Genstat release 17.1 (VSN International Ltd., Hertfordshire, UK). Data are presented as mean values for each treatment. Significance was calculated at p = 0.05 and least significant difference (LSD) used for comparison of mean values.

Compared with the herbicide strip, fruit from the grass/legume plots was 11g lighter in weight, but there was no difference in diameter, firmness or sugar content between the three tree-line treatments (

***Table 5**: Fruit quality assessments (2022 harvest) from the NSW regional demonstration site*

Treeline treatment	**Diameter (mm)**	**Mean fruit weight (g)**	**SPI**	**Firmness (kg)**	**TSS (°Brix)**	**Background colour**
Herbicide strip	71.15	208 ab	4.57	8.63	12.26	3.0
Compost	72.95	212 a	5.30	8.45	12.11	2.9
Grass/legume	70.98	197 b	4.47	8.49	12.25	3.4
Fprob	*0.088*	*0.034*	*<0.001*	*0.193*	*0.363*	*<0.001*
Lsd (p≤0.05)	*ns*	*12.1*	*0.238*	*ns*	*ns*	*0.144*

Within each column, means followed by different letters are significantly different according to the LSD means comparison test at p = 0.05.
SPI = starch pattern index; TSS = total soluble solids.

Insect monitoring

The block was monitored for pests and disease throughout the growing season. Woolly apple aphid was detected in small numbers and the affected branches were removed during pruning.

Sticky traps and pheromone traps were used to monitor codling moth and other insects. Queensland fruit fly traps with pheromones were checked every two weeks. Routine mite monitoring was undertaken weekly.

Various bee species were sighted in the flowering meadow mix.

In 2022, trees and inter-row treatments were assessed once a week, at 10 am, from late September through to mid-October, capturing flowering stages from pink to petal fall. To assess the type and frequency of pollinators visiting the inter-row treatments, four randomly selected 1 m^2 quadrats were monitored for insect visitors for 5 minutes each in both the flowering meadow and control inter-row. Insects were recorded according to order: Hymenoptera (bees, ants and wasps), Diptera (flies), lepidoptera (moths and butterflies) and coleoptera (beetles). Where known, species were also recorded. At each quadrat and replicate, the flowering plant species present and an approximation of the quadrant area was recorded. The control inter-row had a variety of flowering plants, recognised as common agricultural weeds. Several species, such as dandelion (*Taraxacum officinale*), and common clover (*Trifolium repens*) were captured in transects, however, additional species such as scarlet pimpernel (*Anagallis arvensis*) were also present. Ants, wasps and European honeybees were the predominant visitors to both apple flowers and flowering species in the inter-row and control treatments.

***Table 6**: Flowering species and insect visitors in the control and flowering meadow inter-row treatments during apple pollination.*

Flowering species		**Insect visitors to inter-row treatments**	
Scientific name	Common name	Scientific name	Common name
Veronica arvensis	Speedwell	*Apis mellifera*	European honeybee
Cynoglossum amabile	Chinese houndstooth	Tiphiidae	Flower wasp
Nemophila sp.	Baby blue eyes	Formicidae	Ant
Trifolium repens	Clover		
Taraxacum officinale	Dandelion		
Viola spp.	Pansy		

To assess the type and frequency of insect visitors to flowering apples, 4 trees were selected in the inter-row trial area and 4 trees in a neighbouring row outside of the trial area as a control. Weekly from pink to petal fall, each tree was observed for 5 minutes, and the number and type of insect visitors recorded. The highest number of insect visitors observed was 42 during full bloom, on 19 of October.

At each assessment, weather data including temperature, humidity, wind speed and direction and general comments were noted. Temperatures during observations remained cool, ranging from 12 °C to 16 °C, and relative humidity from 75% to 96%. Due to the cool, wet summer (La Nina), most observations were undertaken on cloudy, overcast days. One observation day during early apple flowering had clear sunny weather, with 14 of the 21 insect visitors being European honeybees.

Challenges

In December 2021, a hailstorm caused some damage to the trial block. This block is not under hail net and the leaves of the canopy sustained damage. Fortunately, due to the size of the fruit, there was little fruit damage; the damaged fruit was thinned and removed, resulting in a good fruit size for the remaining fruit.

The 2022- 2023 apple season had extreme wet weather conditions throughout NSW, with growing regions such as Orange experiencing some of the highest monthly rainfall averages in decades. The Orange growing region had a cool, wet season, with hail and snow events making good fruit quality challenging. The NSW demonstration site was impacted heavily by a hailstorm in late November, which resulted in extremely poor fruit quality and high black spot pressure. Unfortunately, this meant we were unable to collect fruit quality samples for this season.

Conclusions

The demonstration site has provided growers with a basic understanding of the impact of different soil ameliorants on soil health and nutrition. Further investigation into the establishment of these treatments and how they may impact growers economically would be beneficial. There is a definite improvement in soil when introducing mulch, compost and cover crops, but it is unknown how viable they are in a grower's bottom line.

South Australia regional site

The SA demonstration site was established at Flavells Fruit Sales, Stentiford Road, Forest Range. The demonstration block was situated in a 5-year old block of Kanzi™ apples grown on M9 rootstock trained to a single leader in duplex soils. The orchard rows run in a south-east to north-west direction up and down a fairly uniform slope. It is covered with permanent hail netting.

Three inter row and three tree-line treatments were applied across the block. Each treatment combination was replicated four times over six rows, and each treatment plot consisted of a panel of 10 trees.

Inter row treatments

Due to the sloping soils and relatively wet conditions experienced in Spring, the grower did not want the ground inter-row cultivated and seeded during spring.

Soil preparation for autumn sowing of the inter-row sward was delayed until the opening rains. The inter-rows sprayed out with a systemic herbicide applied in late May. The herbicide was very effective, controlling >90% of active grasses. The soils were then lightly scarified. A follow up contact weed-spray application was applied on the 4th June. There was approximately 50 mm of rain received on the following day, with follow-up light rain persisting for several days after. A window of opportunity prevailed to seed on 11th June. The soils had mostly dried, however access of machinery on the sloping site was still challenging in some places.

<u>(i) Grower practice</u>

Grower own practice consisted of a Lenswood Orchard mix of perennial grasses.

***Figure 7**: Trial site, looking south-east up the slope. Typical grower practice of inter-row sward and bare weed-spray strip with grass mulch from mower. Right September 2022*

<u>(ii) Flowering meadow mix</u>

The flowering meadow mix was seeded by hand, using a hand lawn seeder. The seed was mixed with vermiculite as per supplier specifications (Meadow Flowers Australia), to assist with dispersal, soil contact and moisture uptake. The “beneficial insect” mix was sown at a rate of 2 g/m^2.

***Table 7**: Species in the flowering meadow mix*

Alyssum benthamii	Sweet alyssum
Ammi majus	Queen Anne’s Lace
Anethum graveolens	Common Dill
Aubrieta hybrida	Rock Cress
Cheirianthus chieri	Wallflower
Chrysanthemum maximum	Shasta Daisy
Coreopsis lanceolate	Mayfield Giants
Coreopsis sativum	Coriander
Cosmos bipinnatus	Garden/Dwarf Cosmos
Eschscholzia	California Poppy
Gaillardia aristate	Blanket Flower
Iberis umbalatta	Candytuft
Liatris spicata	Dense Blazing Star
Monarda fistulosa	Wild Bergamot
Nemophila menziesii	Menzies’ Baby Blue Eyes

The flowering meadow mix established well, with some early annuals commencing to flower in early spring.

***Figure 8**: (Left) Flowering meadow mix in late November 2021; (right) Meadow mix after mowing*

With both inter-row seeding treatments, there were some challenges with seed not establishing well in the wheel ruts. This was exacerbated due to the fairly wet spring conditions. Being a commercial orchard, the grower was unwilling to avoid tractor traffic on the seeded rows, needing to keep sprays onto the orchard. Even in the well-grassed areas of grower’s own practice, wheel damage was difficult to avoid in the first season.

Following on from the spring seeding of the inter-row sward, the meadow mix established generally quite well. The native mix was slower to get going, but by late spring there were signs of some of the native grasses pushing through.

Unfortunately, in late spring, the grower inadvertently mowed the full trial block, including the meadow mix and native grass mix sites. While there was good flowering of some of the earlier flowering annuals in the meadow mix, the summer flowering perennials did not have the opportunity to flower and set seed into the soil. Also, the mowing knocked down any flowers that may have supported an IDPM benefit through the summer period. After a fairly wet early spring, there was an extended dry period through late spring into summer, so there was very little new growth of the inter-row sward after mowing.

This meant that it was difficult to see the full benefits of the inter-row sward treatments. A key learning from this is that it is a change in mind-set for growers to allow the inter-row sward to grow to a height without mowing, and an informative process will need to happen to support growers to adapt in practice change in this regard.

Figure 9*: Meadow mix September 2022 – mixture of flowering plants returning this spring, some tall grasses showing through as well*

<u>(iii) Native grass mix</u>

The native seed mix was sown by Seeding Natives Incorporated, using machinery adapted by them specifically for seeding native grasses and seeds. The seed was mixed with wood shavings to help with the dispersal. This mix consisted of the species listed in Table 8.

Table 8*: Native species mix*

Rytidosperma geniculatum	Kneed wallaby grass
Rytidosperma caespitosum	Wallaby grass
Microlaena stipoides	Weeping grass
Chloris truncata	Windmill grass
Bothriochloa macra	Red-leg grass
Vittadinia Gracilis	Woolly New Holland daisy
Calocephalus citreus	Lemon Beauty Heads
Chrysocephalum apiculatum	Yellow buttons

Figure 10*: Seeding of the native seed mix.*

The native seed mix was very slow to establish. Some grasses came through, but there was quite a bit of competition from weeds and the grass sward that was previously in place re-established.

Figure 11*: Native grass inter row plots – the native grasses did not establish, species now present are primarily clover, grasses and plantain. Several weed species such as Sow Thistle and Marshmallow are present in significant numbers.*

Tree-line treatments

(i) Herbicide strip (grower practice)

The Grower's practice consisted of a bare weed spray strip with mulch from inter-row mowing.

Figure 12a*: Herbicide strip in September 2022*

Figure 12b*: Herbicide strip in May 2023*

(ii) Compost

Compost was Cultured Compost sourced from Peats Soil & Garden Supplies. It was applied in early December as a 100 mm deep layer in the tree line.

Figure 13a*: Cultured compost applied in the tree-line*

Figure 13b*: Compost plots in September 2022*

Figure 13c*: compost plot in May 2023*

(iii) Grass/legume mix

The tree-line grass/legume treatment was sown on 11th December 2020. Prior to sowing, residual weeds in the weed-spray strip were hoed out by hand and the soil was lightly scarified by hand.

The seed mixture used comprised the following:

- Convoy Cocksfoot
- Creeping Red Fescue
- Riesling White Clover
- Palestine Strawberry Clover

This sowing time was later than ideal due to site access and then a COVID-19 lockdown. Immediately after sowing, the soil was raked over and seed was watered in using a fire-fighting system on the back of a tractor to ensure even water application across the entire under-tree area. The under-tree drip irrigation system did not provide sufficient coverage to fully water the seeded area.

Repeat watering was carried out by the grower, however the conditions in December 2020 were very dry and the seed did not successfully germinate.

Soil preparation for re-seeding of the grass/legume plots was conducted through autumn and winter of 2021. The site was hand weeded to remove any residual weeds then lightly scarified with a rake. The site was re-seeded on 8th September 2021 by hand. Seed was mixed with vermiculite to assist with soil contact. The soil was lightly tamped down by hand after sowing.

Establishment of the grass/legume plots after re-sowing was good.

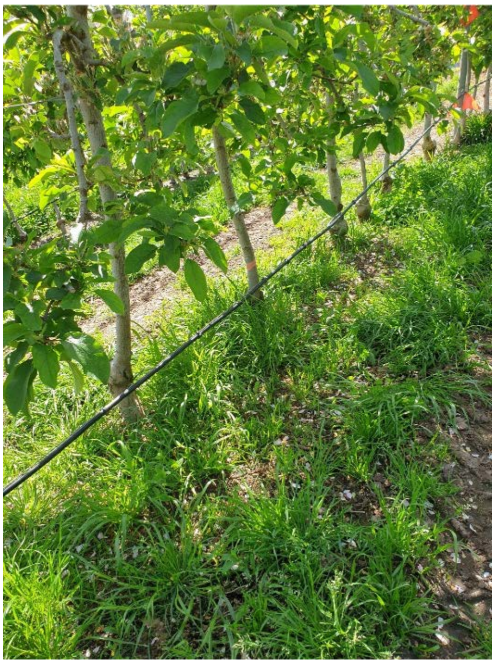

Figure 14a*: Hand seeding tree-line grass/legume mix (left), and plots in early November 2021 after germination (right)*

Figure 14b*: Tree-line grass/legume plots in September 2022*

Figure 14c*: Tree-line grass/legume plots in May 2023*

Soil chemical analysis

Soil samples were collected in May 2021 and 2023. Samples were forwarded to CSPB Soil and Plant Analysis Laboratory for the following tests:

- Phosphorus (Colwell), Potassium (Colwell), Sulfur (KCl 40), Organic Carbon
- (Walkley-Black), Nitrate Nitrogen, Ammonium Nitrogen, Electrical Conductivity, pH (water), pH ($CaCl_2$),
- Boron, Trace Elements (DTPA) - Copper, Zinc, Manganese, Iron, Exchangeable Cations without pre-wash
- Calcium, Magnesium, Sodium, Potassium, Aluminium, Texture (In-house method)
- Total C, Total N
- ECEC calculation, Exchangeable Sodium Percentage (ESP calculation)

Replicate samples were collected in 2023, but only one composite sample per treatment was sent to the laboratory in 2021.

There were no significant differences between the inter-row treatments (Table 9).

***Table 9**: Soil analysis results for the SA demonstration site inter row treatments.*

	pH (CaCl2)		**pH (H2O)**		**Conductivity (dS mm^{-1})**	
	2021	**2023**	**2021**	**2023**	**2021**	**2023**
Grower practice	6.1	6.20	6.8	6.80	0.181	0.1045
Meadow mix	6.1	6.25	6.8	6.85	0.181	0.1265
Fprob	-	*0.874*	-	*0.874*	-	*0.340*
Lsd (p≤0.05)	-	*ns*	-	*ns*	-	*ns*
	ESP Exchangeable (%)		**Organic carbon (%)**		**Total C (%)**	
	2021	**2023**	**2021**	**2023**	**2021**	**2023**
Grower practice	0.9	0.6	4.50	3.14	6.68	4.415
Meadow mix	0.9	0.6	4.50	3.05	6.68	4.535
Fprob	-	*1.000*	-	*0.366*	-	*0.609*
Lsd (p≤0.05)	-	*ns*	-	*ns*	-	*ns*
	Ammonium N (mg/kg)		**Nitrate N (mg/kg)**		**Total N (%)**	
	2021	**2023**	**2021**	**2023**	**2021**	**2023**
Grower practice	59	2.50	30	34	0.55	0.31
Meadow mix	59	2.50	30	43	0.55	0.32
Fprob	-	-	-	*0.266*	-	-
Lsd (p≤0.05)	-	*ns*	-	*ns*	-	*ns*
	Colwell P (mg/kg)		**Colwell K (mg/kg)**			
	2021	**2023**	**2021**	**2023**		
Grower practice	145	83.5	707	292		
Meadow mix	145	94.0	707	308		
Fprob	-	*0.307*	-	*0.763*		
Lsd (p≤0.05)	-	*ns*	-	*ns*		
	Exchangeable Al (meq/100g)		**Exchangeable Ca (meq/100g)**		**Exchangeable Mg (meq/100g)**	
	2021	**2023**	**2021**	**2023**	**2021**	**2023**
Grower practice	0.140	0.022	19.23	14.21	3.22	2.11
Meadow mix	0.140	0.018	19.23	15.10	3.22	2.19
Fprob	-	*0.421*	-	*0.398*	-	*0.910*
Lsd (p≤0.05)	-	*ns*	-	*ns*	-	*ns*
	Exchangeable K (meq/100g)		**Exchangeable Na (meq/100g)**			
	2021	**2023**	**2021**	**2023**		
Grower practice	1.45	0.63	0.21	0.105		
Meadow mix	1.45	0.68	0.21	0.115		
Fprob	-	*0.644*	-	*0.500*		
Lsd (p≤0.05)	-	*ns*	-	*ns*		
	S (mg/kg)		**B (mg/kg)**		**Cu (mg/kg)**	
	2021	**2023**	**2021**	**2023**	**2021**	**2023**
Grower practice	16.3	6.15	2.10	1.66	16.0	17.0
Meadow mix	16.3	8.70	2.10	1.71	16.0	13.9
Fprob	-	*0.270*	-	*0.769*	-	*0.395*
Lsd (p≤0.05)	-	*ns*	-	*ns*	-	*ns*
	Fe (mg/kg)		**Mn (mg/kg)**		**Zn (mg/kg)**	
	2021	**2023**	**2021**	**2023**	**2021**	**2023**
Grower practice	92.5	100	21.91	5.94	23.77	6.79
Meadow mix	92.5	88	21.91	4.95	23.77	6.23
Fprob	-	*0.717*	-	*0.388*	-	*0.057*
Lsd (p≤0.05)	-	*ns*	-	*ns*	-	*ns*

Within each column, means followed by different letters are significantly different according to the LSD means comparison test at p = 0.05.

In the tree-line treatments, most parameters measured were higher in the compost plots compared to the herbicide and grass/legume plots. However Fe, MN and ESP exchangeable percentage were lower in the compost plots, while there was no difference between treatments for Cu, Zn, exchangeable Al and exchangeable Na.

***Table 10**: Soil analysis results for the SA demonstration site tree-line treatments.*

	pH (CaCl2)		**pH (H2O)**		**Conductivity (dS mm^{-1})**	
	2021	**2023**	**2021**	**2023**	**2021**	**2023**
Herbicide	6.3	6.263	6.8	6.925	0.190	0.116
Compost	6.6	6.663	7.3	7.487	0.613	0.164
Grass/Legume	6.3	6.413	6.8	7.025	0.190	0.122
Fprob	-	*<0.001*	-	*<0.001*	-	*<0.001*
Lsd (p≤0.05)	-	*0.1303*	-	*0.2065*	-	*0.0155*
	ESP Exchangeable (%)		**Organic carbon (%)**		**Total C (%)**	
	2021	**2023**	**2021**	**2023**	**2021**	**2023**
Herbicide	2.1	1.65	3.87	2.79	4.50	4.08
Compost	4.7	0.86	3.70	3.51	5.80	5.68
Grass/Legume	2.1	1.55	3.87	2.77	4.50	4.03
Fprob	-	*0.030*	-	*<0.001*	-	*0.001*
Lsd (p≤0.05)	-	*0.608*	-	*0.3267*	-	*0.842*
	Ammonium N (mg/kg)		**Nitrate N (mg/kg)**		**Total N (%)**	
	2021	**2023**	**2021**	**2023**	**2021**	**2023**
Herbicide	21	2.25	25	28.2	0.38	0.286
Compost	24	2.75	52	37.1	0.51	0.458
Grass/Legume	21	2.50	25	26.9	0.38	0.289
Fprob	-	*0.185*	-	*0.011*	-	*<0.001*
Lsd (p≤0.05)	-	*ns*	-	*6.70*	-	*0.0849*
	Colwell P (mg/kg)		**Colwell K (mg/kg)**			
	2021	**2023**	**2021**	**2023**		
Herbicide	181	191.8	564	343		
Compost	246	245.9	1452	492		
Grass/Legume	181	163.1	564	411		
Fprob	-	*0.006*	-	*<0.001*		
Lsd (p≤0.05)	-	*45.99*	-	*57.4*		
	Exch. Al (meq/100g)		**Exch. Ca (meq/100g)**		**Exch. Mg (meq/100g)**	
	2021	**2023**	**2021**	**2023**	**2021**	**2023**
Herbicide	0.030	0.021	16.13	14.67	3.05	2.51
Compost	0.040	0.025	19.27	20.40	3.94	3.51
Grass/Legume	0.030	0.021	16.13	14.30	3.05	2.63
Fprob	-	*0.373*	-	*<0.001*	-	*<0.001*
Lsd (p≤0.05)	-	*ns*	-	*2.239*	-	*0.29*
	Exch. K (meq/100g)		**Exch. Na (meq/100g)**			
	2021	**2023**	**2021**	**2023**		
Herbicide	1.13	0.736	0.44	0.295		
Compost	3.19	1.065	1.29	0.211		
Grass/Legume	1.13	0.907	0.44	0.281		
Fprob	-	*<0.001*	-	*0.235*		
Lsd (p≤0.05)	-	*0.1165*	-	*ns*		
	S (mg/kg)		**B (mg/kg)**		**Cu (mg/kg)**	
	2021	**2023**	**2021**	**2023**	**2021**	**2023**
Herbicide	19.7	9.3	1.84	1.608	18.05	16.85
Compost	111.7	15.5	2.98	2.266	16.15	15.49
Grass/Legume	19.7	10.9	1.84	1.566	18.05	17.60
Fprob	-	*0.001*	-	*<0.001*	-	*0.349*
Lsd (p≤0.05)	-	*2.881*	-	*0.245*	-	*ns*
	Fe (mg/kg)		**Mn (mg/kg)**		**Zn (mg/kg)**	
	2021	**2023**	**2021**	**2023**	**2021**	**2023**
Herbicide	85.1	95.5	18.88	4.85	26.1	16.0
Compost	82.7	80.7	17.89	4.04	29.1	16.0
Grass/Legume	85.1	87.5	18.88	5.48	26.1	9.9
Fprob	-	*0.011*	-	*0.029*	-	*0.113*
Lsd (p≤0.05)	-	*8.89*	-	*1.023*	-	*ns*

Within each column, means followed by different letters are significantly different according to the LSD means comparison test at p = 0.05.

Tree growth and fruit quality

Trunk girth was measured 15 cm above ground level in spring of 2022 and 2023 and used to calculate trunk cross-sectional area. Fruit numbers were counted prior to harvest and a sample of 20 fruit taken from five trees in each treatment for fruit quality assessments. Assessments included weight, background colour (Kanzi colour chart), starch pattern index (SPI), flesh firmness and total soluble solids (TSS). Fruit dry matter content (DMC) was also measured in 2023.

Data were subjected to analysis of variance using Genstat release 17.1 (VSN International Ltd., Hertfordshire, UK). Data are presented as mean values for each treatment. Significance was calculated at p = 0.05 and least significant difference (LSD) used for comparison of mean values.

In the 2022 harvest season (Table 11) there were no differences between treatments for crop load (number of fruit cm^{-2} TCSA), fruit weight, background colour, firmness or TSS. The only fruit quality parameter to show significant differences between treatments was SPI with fruit from the grower practice of a herbicide strip along the tree row showing an increased rate of starch conversion compared to the other treatments. The overall lack of effect of treatments is not unexpected as changes in orchard floor management can take 2-3 years before effects are seen on tree growth and/or fruit quality.

Table 11*: Crop load and fruit quality assessments (2022 harvest) in the South Australia regional demonstration site*

Treeline treatment	Fruit cm^{-2} TCSA	Mean fruit weight (g)	Background colour	SPI	Firmness (kg)	TSS (°Brix)
Grower practice	8.77	163.5	3.19	4.8 [a]	8.64	13.72
Compost	8.55	170.6	3.35	4.2 [b]	8.65	14.35
Grass/legume	8.42	163.8	3.22	4.3 [b]	8.63	13.82
Fprob	*0.917*	*0.326*	*0.465*	*0.013*	*0.994*	*0.171*
Lsd (p≤0.05)	*ns*	*ns*	*ns*	*0.38*	*ns*	*ns*

Within each column, means followed by different letters are significantly different according to the LSD means comparison test at p = 0.05.
TCSA = trunk cross-sectional area; SPI = starch pattern index; TSS = total soluble solids.

In the 2023 season, tree growth was lowest in the compost treatment, but this treatment had the highest crop load (Table 12). There was no difference between treatments for fruit weight (Table 12), SPI, TSS or DMC (Table 13). Background colour was greener in the compost treatment (Table 13). Fruit firmness was increased in the grass/legume treatment (Table 13).

Table 12*: Tree growth, crop load and fruit size (2023 harvest) in the South Australia regional demonstration site*

Treeline treatment	Increase in trunk girth (cm)	Increase in trunk area (cm^2)	Fruit cm^{-2} TCSA	Mean fruit weight (g)
Grower practice	1.62 ab	4.21 ab	6.57 b	177.4
Compost	0.74 b	1.74 b	7.98 a	180.3
Grass/legume	2.14 a	5.65 a	5.51 b	181.5
Fprob	*0.015*	*0.012*	*<0.001*	*0.732*
Lsd (p≤0.05)	*0.936*	*2.508*	*1.228*	*ns*

Within each column, means followed by different letters are significantly different according to the LSD means comparison test at p = 0.05.
TCSA = trunk cross-sectional area.

***Table 13**: Fruit quality assessments (2023 harvest) in the South Australia regional demonstration site*

Treeline treatment	Background colour	SPI	Firmness (kg)	TSS (°Brix)	Dry matter content)%)
Grower practice	2.63 a	4.5	9.53ab	13.64	0.169
Compost	2.20 b	4.2	9.15 b	13.31	0.170
Grass/legume	2.84 a	4.0	10.00 a	13.70	0.175
Fprob	*0.005*	*0.259*	*0.004*	*0.297*	*0.379*
Lsd (p≤0.05)	*0.379*	*ns*	*0.483*	*ns*	*ns*

Within each column, means followed by different letters are significantly different according to the LSD means comparison test at p = 0.05. SPI = starch pattern index; TSS = total soluble solids.

Monitoring

IPDM monitoring continued through the season with the one-minute observations. No sticky traps were set out. There were very little pests or diseases of concern detected in any of the treatment blocks. Of different note, high levels of leaf hopper were observed throughout the trial site.

Project delays

Due to the sloping soils and relatively wet conditions experienced in Spring, the grower did not want the ground inter-row cultivated and seeded during spring. Therefore, soil preparation for the interrow was delayed until the following autumn.

A state-wide lockdown in South Australia due to COVID-19 also delayed the application of compost and under-tree seeding by a few weeks

Due to a lack of seed establishment and the delay in the inter-row plantings, there were insufficient treatments in place to warrant pest monitoring and fruit quality and yield analysis being undertaken in this first season.

Western Australia regional site

The WA regional demonstration site was established in Spring of 2020 at Ladycroft Orchard, an established large conventional orchard in Manjimup. The demonstration block consists of Lady in Red apples on M26 rootstock and is situated on Karri loam soils. The trees were in their 3rd leaf, planted on a 2D trellis at 3.5m row spacing and 0.8m tree spacing.

Treatments included three inter-row and three tree-line treatments. Prior to seed sowing plots were sprayed with a knockdown herbicide followed by cultivation 10 days after spraying. Sourcing seed in spring was challenging, hence seed choice was limited. Native seeds and seedlings were unable to be sourced in time for spring planting, so the plots were sown with a green manure mix to control weeds until the native species were available for planting.

Inter Row Treatments

(i) Grower practice

The grower's normal inter row practice of a grass, clover and weed strip was retained as the control treatment.

(ii) Flowering meadow mix

The seed mix used for the flowering meadow mix treatment was an Equine Mix from Bells Pasture Seeds, a local pasture seeds supplier. In addition, 100g of Phacelia scorpion weed, 200g Coriander and some marigold seeds were added to the equine mix. The equine mix (12kg/600m2) included Ryecorn cereal, Everlast ryegrass, Fescue, Cocksfoot, Balansa clover, Arrowleaf crimson clover, Cadiz serradella, Chicory, and Phalaris.

This mix was sown on 25 September 2020 by hand with broadcast spreaders at a rate of 20kg/ha. A cool wet spring provided ideal conditions for pasture establishment. The flowering meadow treatment was reseeded in July 2021 to encourage more clover and ryegrass flowering during apple flowering and to bulk up the diversity of species in the inter row during the growing season. The grasses established well but the clovers and other species did not establish after reseeding and the inter row has remained very weedy with not much diversity, mainly grasses.

***Figure 15**: Grower standard practice of established grass, clovers and weeds that is mowed during the season (left). Flowering meadow mix on 2nd December 2020 showing good establishment of all species (right).*

(iii) Native mix

As noted above, native species were not available for spring at the commencement of the project, so plots were sown with a green manure mix to control weeds. This inter-row mix was sourced from Irwin Hunter Seeds and planted on 2 October 2020. Species included: Avolon Perennial Ryegrass, AusVic Perennial Ryegrass, Roper Perennial Ryegrass, Annual Ryegrass, Saia Oats, Trikkala subterranean clover, Arrowleaf crimson clover, White Clover, and Tillage Radish.

The following species were ordered from local native seed suppliers and planted out as tube stock in July 2021. The inter row was sprayed off with a knock down herbicide prior to planting.

Wallaby grass	*Austrodanthonia caespitosa*
Weeping grass	*Microlaena stipoides*
Spear grass	*Austrostipa sp*
Running postman	*Kennedia prostrata*
Pink everlastings	*Rhodanthe chlorocephala*
Fan flower	*Scaevola crassifolia*
Slender Lobelia	*Lobelia tenuior*
Native Bluebell Creeper	*Billardiara fusiformis*

 

Figure 16*: Green manure mix planted in Native treatments inter row in December 2020 (left), and .native seedlings just after planting in July 2021 (right).*

Plants in the native mix did not survive, and the plots became very weedy after planting in July 2021. The interrow was very dry during the summer and weeds out completed the seedlings. The inter row now consists mainly of grass weeds and rye grass.

Figure 17*: Grower standard practice in the inter row, bare herbicide strip under tree 5 Dec 202.*

Figure 18*: Native inter row and compost under tree treatment, 5 December 2022.*

***Figure 19**: Flowering meadow inter row and grass legume under tree, 5 December 2022.*

The inter row treatments are mown regularly as part of the normal orchard mowing.

Tree-line treatments

(i) Bare herbicide strip

The tree-line treatment of herbicide application has occurred as the growers standard practice. Herbicide was applied annually.

***Figure 20**: Grower standard practice of bare herbicide strip.*

(ii) Mushroom compost

The mushroom compost, used in the viticulture industry as a dual purpose fine mulch and soil conditioner, was sourced from C-Wise in Nambelup, and contained 60% organic matter and 35% organic carbon.

The compost was applied at one metre width and 10 cm depth under the trees on 23rd October 2020. Weeds growing through the compost have been sprayed out a couple of times during each year.

Figure 21: *Mushroom compost in the treeline.*

(iii) Grass/legume mix

The tree-line legume grass mix was a crimson, Balansa clover (15%) and annual and perennial rye grass (80%) viticulture inter row mix from Cowaramup Agencies. This was sown by hand on 25 September 2020. This treatment was cut back in late spring 2021 to reduce the growth into the trees and potential for disease risk. The grasses dominate in these tree-line plots and have remained green throughout the season due to the drip irrigation.

Figure 22*: Grass legume tree-line treatment. December 2020 (left) and November 2021 (right)*

Soil chemistry

Compost samples were analysed by CSBP Laboratories for pH (Water, CaCl2), Electrical Conductivity), Total Nitrogen (Leco), Total Carbon (Leco), Acid Wash TOC, Soluble Nutrients, Compost Total Nutrients, Compost Available Nutrients.

***Table 15**: laboratory analysis of compost samples*

		Compost	Mulch Compost			Compost	Mulch Compost
Conductivity	dS/m	10.563	0.989	Compost Sat Paste Mn	mg/kg	30.3	1.5
pH Level (CaCl2)		6.1	6.3	Compost Sat Paste Na	mg/kg	3827.6	588.5
pH Level (H2O)		6.5	7.3	Compost Sat Paste NH4N	mg/kg	4744	34
Total Nitrogen	%	2.25	0.39	Compost Sat Paste NO3N	mg/kg	31	4
Total Carbon	%	33.74	30.04	Compost Sat Paste P	mg/kg	354.3	11.1
Total Organic Carbon (Acid Wash)	%	32.44	29.62	Compost Sat Paste pH		6.7	7.8
Compost EC 1:5	dS/m	14.72	1.48	Compost Sat Paste S	mg/kg	10118.2	80.1
Compost pH 1:5		6.7	7.7	Compost Sat Paste Zn	mg/kg	12.9	0.1
Compost Soluble NH4N	mg/kg	1191	9	Compost Total B	mg/kg	35.84	11.26
Compost Soluble NO3N	mg/kg	8	2	Compost Total Ca	%	6.51	1.64
Compost Soluble PO4P	mg/kg	93	5	Compost Total Cu	mg/kg	84.26	6.38
Compost Sat Paste Al	mg/kg	1.6	1.6	Compost Total Fe	mg/kg	1287.72	36183.00
Compost Sat Paste B	mg/kg	6.8	0.6	Compost Total K	%	2.01	0.23
Compost Sat Paste Ca	mg/kg	6151.1	379.0	Compost Total Mg	%	0.47	0.14
Compost Sat Paste Cu	mg/kg	3.9	0.2	Compost Total Mn	mg/kg	350.91	122.54
Compost Sat Paste ECe	dS/m	3.12	0.30	Compost Total Na	%	0.40	0.09
Compost Sat Paste Fe	mg/kg	24.0	9.0	Compost Total P	%	0.49	0.04
Compost Sat Paste K	mg/kg	16486.0	1083.3	Compost Total S	%	2.37	0.07
Compost Sat Paste Mg	mg/kg	2664.9	126.2	Compost Total Zn	mg/kg	271.92	22.62

Soil samples were collected from the different treatment plots in May 2021 and 2023. Samples were forwarded to CSPB Soil and Plant Analysis Laboratory for the following tests:

- Phosphorus (Colwell), Potassium (Colwell), Sulfur (KCl 40), Organic Carbon
- (Walkley-Black), Nitrate Nitrogen, Ammonium Nitrogen, Electrical Conductivity, pH (water), pH (CaCl2),
- Boron, Trace Elements (DTPA) - Copper, Zinc, Manganese, Iron, Exchangeable Cations without pre-wash
- Calcium, Magnesium, Sodium, Potassium, Aluminium, Texture (In-house method)
- Total C
- Total N
- ECEC calculation
- Exchangeable Sodium Percentage (ESP calculation)

While there were some significant differences (Table 16) between the inter row treatments in 2021 for conductivity, ESP, Nitrate N, Colwell P, Exchangeable Al, Exchangeable Mg, Exchangeable Na, S Fe and Zn, after two years under these treatments there were no longer any differences in these parameters.

***Table 16**: Soil analysis results for the inter row treatments at the WA demonstration site*

	pH (CaCl2)		pH (H2O)		Conductivity (dS mm^{-1})	
	2021	**2023**	**2021**	**2023**	**2021**	**2023**
Flowering mix	5.4	5.5	6.2	6.1	0.108	0.067
Grower practice	5.4	5.5	6.2	6.1	0.153	0.065
Native mix	5.4	5.5	6.2	6.2	0.138	0.054
Fprob	*1.000*	*0.929*	*0.875*	*0.250*	*0.037*	*0.508*
Lsd (p≤0.05)	*ns*	*ns*	*ns*	*ns*	*0.0273*	*ns*
	ESP Exchangeable (%)		**Organic carbon (%)**		**Total C (%)**	
	2021	**2023**	**2021**	**2023**	**2021**	**2023**
Flowering mix	1.5	2.4	3.39	2.86	4.26	4.71
Grower practice	1.9	2.0	4.31	3.22	4.90	4.59
Native mix	1.8	1.6	3.74	2.88	4.72	4.48
Fprob	*0.016*	*0.188*	*0.203*	*0.555*	*0.227*	*0.902*
Lsd (p≤0.05)	*0.18*	*ns*	*ns*	*ns*	*ns*	*ns*
	Ammonium N (mg/kg)		**Nitrate N (mg/kg)**		**Total N (%)**	
	2021	**2023**	**2021**	**2023**	**2021**	**2023**
Flowering mix	7	6	37	10	0.35	0.32
Grower practice	8	6	48	8	0.41	0.34
Native mix	6	6	52	4	0.39	0.33
Fprob	*0.571*	*1.000*	*0.030*	*0.206*	*0.295*	*0.813*
Lsd (p≤0.05)	*ns*	*ns*	*8.0*	*ns*	*ns*	*ns*
	Colwell P (mg/kg)		**Colwell K (mg/kg)**			
	2021	**2023**	**2021**	**2023**		
Flowering mix	25	30	317	146		
Grower practice	29	28	401	225		
Native mix	30	32	398	272		
Fprob	*0.045*	*0.500*	*0.003*	*0.035*		
Lsd (p≤0.05)	*3.5*	*ns*	*15.6*	*73.4*		
	Exch. Al (meq/100g)		**Exch. Ca (meq/100g)**		**Exch. Mg (meq/100g)**	
	2021	**2023**	**2021**	**2023**	**2021**	**2023**
Flowering mix	0.110	0.104	5.69	3.97	0.58	0.43
Grower practice	0.165	0.150	6.28	4.33	0.67	0.56
Native mix	0.125	0.112	5.51	4.93	0.56	0.65
Fprob	*0.030*	*0.659*	*0.066*	*0.003*	*0.028*	*0.139*
Lsd (p≤0.05)	*0.0304*	*ns*	*ns*	*0.173*	*0.061*	*ns*
	Exch. K (meq/100g)		**Exch. Na (meq/100g)**			
	2021	**2023**	**2021**	**2023**		
Flowering mix	0.70	0.36	0.11	0.11		
Grower practice	0.86	0.54	0.15	0.11		
Native mix	0.80	0.68	0.13	0.11		
Fprob	*0.009*	*0.044*	*0.038*	*0.750*		
Lsd (p≤0.05)	*0.046*	*0.207*	*0.030*	*ns*		
	S (mg/kg)		**B (mg/kg)**		**Cu (mg/kg)**	
	2021	**2023**	**2021**	**2023**	**2021**	**2023**
Flowering mix	21.3	13.2	0.96	0.78	0.93	0.97
Grower practice	15.2	9.9	1.20	0.90	1.07	1.07
Native mix	17.2	10.4	1.09	0.89	1.03	1.25
Fprob	*0.025*	*0.214*	*0.189*	*0.245*	*0.300*	*0.390*
Lsd (p≤0.05)	*3.05*	*ns*	*ns*	*ns*	*ns*	*ns*
	Fe (mg/kg)		**Mn (mg/kg)**		**Zn (mg/kg)**	
	2021	**2023**	**2021**	**2023**	**2021**	**2023**
Flowering mix	3090	33.00	1.77	1.99	0.46	0.81
Grower practice	35.45	34.75	2.35	2.44	0.86	0.89
Native mix	39.80	30.35	2.25	2.12	0.67	0.82
Fprob	*0.041*	*0.087*	*0.122*	*0.352*	*0.044*	*0.922*
Lsd (p≤0.05)	*5.580*	*ns*	*ns*	*ns*	*0.260*	*ns*

Within each column, means followed by different letters are significantly different according to the LSD means comparison test at p = 0.05.

In the tree-line treatments (Table 17), the compost treatment showed significantly higher values for most parameters compared to the herbicide and grass/legume treatments.

***Table 17**: Soil analysis results for the tree-line treatments at the WA demonstration site*

	pH (CaCl2)		**pH (H2O)**		**Conductivity (dS mm^{-1})**	
	2021	**2023**	**2021**	**2023**	**2021**	**2023**
Herbicide	5.4	5.2	6.2	5.9	0.364	0.215
Compost	6.4	6.4	6.8	7.0	4.648	0.371
Grass/Legume	5.3	5.4	6.1	6.0	0.232	0.155
Fprob	*0.006*	*0.014*	*0.010*	*0.029*	*<0.001*	*0.491*
Lsd (p≤0.05)	*0.49*	*0.67*	*0.35*	*0.74*	*1.2471*	*ns*
	ESP Exchangeable (%)		**Organic carbon (%)**		**Total C (%)**	
	2021	**2023**	**2021**	**2023**	**2021**	**2023**
Herbicide	8.3	8.1	3.60	2.76	4.32	4.51
Compost	5.5	2.0	4.41	4.36	11.14	9.84
Grass/Legume	6.0	5.9	3.58	2.99	4.30	4.39
Fprob	*0.338*	*0.008*	*0.021*	*0.006*	*0.002*	*0.059*
Lsd (p≤0.05)	*ns*	*2.70*	*0.539*	*0.701*	*2.38*	*4.901*
	Ammonium N (mg/kg)		**Nitrate N (mg/kg)**		**Total N (%)**	
	2021	**2023**	**2021**	**2023**	**2021**	**2023**
Herbicide	5	6	31	10	0.34	0.38
Compost	20	8	240	61	1.13	0.83
Grass/Legume	5	7	17	3	0.35	0.31
Fprob	*0.001*	*0.284*	*0.005*	*0.342*	*0.003*	*0.050*
Lsd (p≤0.05)	*4.6*	*ns*	*98.0*	*ns*	*0.312*	*0.415*
	Colwell P (mg/kg)		**Colwell K (mg/kg)**			
	2021	**2023**	**2021**	**2023**		
Herbicide	104	76	495	174		
Compost	389	383	5396	200		
Grass/Legume	65	107	373	228		
Fprob	*0.030*	*0.017*	*0.002*	*0.674*		
Lsd (p≤0.05)	*225.1*	*182.2*	*1697.7*	*ns*		
	Exch. Al (meq/100g)		**Exch. Ca (meq/100g)**		**Exch. Mg (meq/100g)**	
	2021	**2023**	**2021**	**2023**	**2021**	**2023**
Herbicide	0.140	0.247	6.46	4.63	0.91	1.17
Compost	0.087	0.054	35.78	32.64	7.98	4.74
Grass/Legume	0.143	0.118	5.72	5.35	0.94	1.15
Fprob	*0.496*	*0.026*	*<0.001*	*0.021*	*0.003*	*0.101*
Lsd (p≤0.05)	*ns*	*0.1193*	*8.564*	*18.329*	*2.595*	*ns*
	Exch. K (meq/100g)		**Exch. Na (meq/100g)**			
	2021	**2023**	**2021**	**2023**		
Herbicide	1.06	0.41	0.76	0.60		
Compost	14.45	0.48	3.38	0.67		
Grass/Legume	0.84	0.55	0.47	0.42		
Fprob	*<0.001*	*0.723*	*0.006*	*0.351*		
Lsd (p≤0.05)	*1.335*	*ns*	*1.315*	*ns*		
	S (mg/kg)		**B (mg/kg)**		**Cu (mg/kg)**	
	2021	**2023**	**2021**	**2023**	**2021**	**2023**
Herbicide	113.9	69.1	2.07	1.43	1.07	1.45
Compost	76.8	87.2	5.69	2.09	4.55	3.51
Grass/Legume	4386.3	26.4	2.18	1.56	1.13	3.93
Fprob	*0.002*	*0.521*	*0.011*	*0.687*	*0.001*	*0.539*
Lsd (p≤0.05)	*1504.2*	*ns*	*1.941*	*ns*	*1.022*	*ns*
	Fe (mg/kg)		**Mn (mg/kg)**		**Zn (mg/kg)**	
	2021	**2023**	**2021**	**2023**	**2021**	**2023**
Herbicide	35.07	35.67	3.85	5.37	1.35	1.93
Compost	46.60	37.63	27.00	17.86	47.08	43.94
Grass/Legume	41.77	43.53	2.93	5.43	1.13	2.80
Fprob	*0.264*	*0.189*	*<0.001*	*0.031*	*0.004*	*0.007*
Lsd (p≤0.05)	*ns*	*ns*	*4.205*	*9.216*	*18.730*	*20.093*

Within each column, means followed by different letters are significantly different according to the LSD means comparison test at p = 0.05.

Fruit quality assessments

There was some variation between the two seasons in most the impact of treatments on the measured fruit quality parameters (Tables 18 and 19). In 2022 the compost treatment resulted in the lowest fruit weight and firmness. The grass/legume treatments had the highest fruit firmness in both years and the highest fruit weight and TSS in 2023.

***Table 18**: Fruit quality assessments (2022 harvest) in the WA regional demonstration site*

Treeline treatment	Fruit diameter (mm)	Mean fruit weight (g)	SPI	Firmness (kg)	TSS (°Brix)
Grower practice	70.4	163 ab	4.78 b	10.41 b	14.75 a
Compost	70.6	159 b	5.01 a	9.19 c	14.18 b
Grass/legume	70.3	164 a	4.81 b	10.67 a	14.28 b
Fprob	*0.618*	*0.044*	*<0.001*	*<0.001*	*<0.001*
Lsd (p≤0.05)	*ns*	*4.2*	*0.0637*	*0.156*	*0.182*

Within each column, means followed by different letters are significantly different according to the LSD means comparison test at p = 0.05.
SPI = starch pattern index; TSS = total soluble solids.

***Table 19**: Fruit quality assessments (2023 harvest) in the WA regional demonstration site*

Treeline treatment	Fruit diameter	Mean fruit weight (g)	SPI	Firmness (kg)	TSS (°Brix)
Grower practice	67.2 b	147 c	3.99 c	9.87 b	13.41 a
Compost	68.5 a	153 b	4.08 b	8.96 c	13.08 b
Grass/legume	69.1 a	158 a	4.22 a	10.02 a	13.54 a
Fprob	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*
Lsd (p≤0.05)	*0.80*	*4.8*	*0.063*	*0.132*	*0.145*

Within each column, means followed by different letters are significantly different according to the LSD means comparison test at p = 0.05.
SPI = starch pattern index; TSS = total soluble solids.

Monitoring

Tree inspections were completed in December, January and March and leaves assessed for mite damage. Flower tapping undertaken at full bloom in late October 2020. All treatments were very clean with no pest damage seen during the season. Final fruit counts, insect damage assessment on fruit and TCA were completed just prior to picking. Rosy Glow apples were picked on 11 May 2021.

Conclusions from the regional sites

All sites experienced difficulties in treatment establishment due to adverse weather and COVID-19 lockdowns. However, once the sites were established there were several lessons learnt.

- It is extremely difficult to establish natives in the orchard without a long lead in time (at least two years of intensive work to remove the seed bank) as their slow growth rate makes it difficult for them to compete. Ensuring adequate irrigation in the establishment phase is critical.
- Autumn is preferable for sowing of both inter-row and tree-line treatments as access in Spring can be difficult due to wet soil conditions, and growers cannot avoid tractor traffic in the inter-rows in Spring.

- The compost and grass/legume treatments in the tree-line were a physical addition of organic material, which break down to organic carbon in the system. Soil carbon can improve the activity and biodiversity of microorganisms in the soil.
- The tree-line grass/legume treatments showed the highest microbial respiration rate. Keeping the soil bare exposes organisms to temperature fluctuations and soil erosion; ground cover in the tree-line is important to protect soil microbes.
- Herbicide needs to be applied regularly throughout the season to maintain a bare strip in the tree-line - constant chemical application is a large expense for the grower, a health risk for workers and herbicide resistance can occur.
- Compost/mulch treatment is effective in suppressing weeds, but success of this treatment was dependant on the amount of coverage and 'thickness' of application - in areas that didn't get an even coverage, weeds and grasses were able to establish under the trees.
- One drawback of compost is the rapid break down and need to re-apply each season, which is costly for the grower.
- Tall tree-line cover crops that grow to heights reaching the bottom branches of the tree can create an easy access for pests, create a more humid environment for trees and can pose a significant bushfire risk.
- Growers found it difficult to allow the inter-row to grow freely and allow plants to flower and seed. This meant that it was difficult to see the full benefits of the inter-row sward treatments. A key learning from this is that it is a change in mind-set for growers to allow the inter-row sward to grow to a height without mowing, and an informative process will need to happen to support growers to adapt in practice change in this regard.

The demonstration sites in each region have provided growers with a basic understanding of the impact of different soil ameliorants on soil health and nutrition. Further investigation into the establishment of these treatments and how they may impact growers economically would be beneficial. There is a definite improvement in soil when introducing mulch, compost and cover crops, but it is unknown how viable they are in a grower's bottom line.

PIPS3 (AP19006)

Improved Australian Apple & Pear Orchards Soil Health and Plant Nutrition

SWAN Systems and SINATA

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Summary

Apple crop yield and quality depend on irrigation and fertiliser application. A Strategic Irrigation & Nitrogen Assessment Tool for Apples (SINATA) was developed in Microsoft Excel by TIA to aid with pre-season planning of these inputs for key apple growing region in Australia. SWAN Systems is a web-based application that facilitates fertiliser and irrigation planning for any crop. SWAN also ingests live data feeds from a wide range of devices and analyses the data based on crop water usage models, soil type and irrigation system characteristics to provide daily recommendations of irrigation requirements. SWAN tracks key metrics such as soil moisture status and drainage. SWAN systems has a crop library that includes industry-standard crop coefficient models for apples, and these can readily be customised for different season lengths and locations.

This study formed part of the AP19006 project (Improved Australian Apple & Pear Orchards Soil Health and Plant Nutrition) of the PIPS3 program[1]. The goal was to investigate whether the SINATA pre-season planning tool could be implemented via SWAN to provide growers with the added benefit of current season, real time tools for irrigation and nutrient management of apples. This report compares SINATA and SWAN for features and outputs. Analysis of user engagement during the trial is presented along with a discussion of options for growers who would like to adopt the technology.

[1] https://apal.org.au/programs/more-industry-programs/pips3program/ap19006/

Improved Australian Apple & Pear Orchards Soil Health and Plant Nutrition: SWAN Systems and SINATA

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Introduction

The timing of irrigation and nitrogen application, and the amounts applied, are key determinants of fruit quality and yield in apple production. The University of Tasmania, along with leading industry bodies, developed SINATA (Strategic Irrigation & Nitrogen Assessment Tool for Apples) to help apple growers with irrigation and nitrogen planning[2]. SINATA is an Excel-based tool that considers apple variety, age, orchard layout, and irrigation strategy to provide estimates of weekly irrigation requirements for major apple growing regions based on historical climatic data. It also provides a nitrogen balance calculation for a range of local soil types based on inputs (fertiliser, leaf fall, mineralisation, etc.) and outputs (offtake in fruit, leaching, and volatilisation).

SWAN Systems (Scheduling Water and Nutrients) is a web-based irrigation and nutrient management program that includes water and nutrients pre-season planning tools, and live data collection from in-field devices to track in-season weather, soil moisture, water use, and drainage.

SINATA and SWAN are complementary and share some similar models. Like SINATA, SWAN is fully configurable for soil type, irrigation system, and crop characteristics. SWAN is generally applicable to all crop types, including apples. On the irrigation side, the primary difference is that SINATA is a pre-season planning tool based on seasonal averages, while SWAN uses live data to calculate daily soil moisture balance and provides a soil moisture forecast to facilitate irrigation decision support for the week ahead. For nutrients, SWAN allows full nutrient program planning based on targets for each element and users can record actual nutrient applications for comparison and reporting against the budgets. SINATA is unique in providing an estimate of likely annual Nitrogen-balance via models based on climatic averages and intended irrigation strategies.

SWAN partnered with the University of Tasmania to investigate the synergies between the two platforms and investigate options for implementing SINATA via SWAN so as to make the apple-specific SINATA planning tools accessible via SWAN's universal interface and to provide growers with current season, real time tools for irrigation and nutrient management of apples.

This report presents the findings from the first year of the study. A review of the season's data is presented along with commentary on usage and accessibility of the packages to growers.

Orchards and data collection

Five orchards in different apple-growing regions were selected for the project (Table 1). The Shepparton farm (Plunkett) was devastated by hail in December 2022 and will not be analysed further. The remaining orchards provided complete irrigation records either by feeds collected automatically by SWAN from irrigation controllers (Fontanini and Oakleigh) or by manual upload of flow data to SWAN (Squibb and Tingira). All the farms had soil moisture probes installed in two or more blocks and onsite rainfall records were obtained via existing manually read gauges or automatic weather stations.

Table 1. Orchards participating in the SWAN trial for PIPS3.

State, Region	Orchard	Blocks	Ha	Irrigation data	Devices
WA, Manjimup	Fontanini	8	11.8	Controller (MAIT)	2 probes, rain gauge
SA, Lenswood	Oakleigh	14	8.6	Controller (Netafim)	2 probes, AWS
Tas, Launceston	RW Squibb	19	19.5	Manual records	3 probes, rain gauge
NSW, Batlow	Tingira	23*	22.3	Manual records	2 probes, rain gauge, AWS
Vic, Shepparton	Plunkett	10	30.5	n/a	n/a

* The blocks were areas that were managed as units for purposes of irrigation and fertiliser, rather than areas irrigated by single valves.

[2] https://www.horticulture.com.au/growers/help-your-business-grow/research-reports-publications-fact-sheets-and-more/ap14023/

Growers followed their normal nutrient programs. The nutrient applications were recorded in SWAN. SWAN was used to compare the timing of nutrient application with irrigation, rainfall, and predicted drainage. SWAN's outputs were derived from live data for the current season. The actual Nitrogen applications and crop yields were added into the SINATA sheet at the end of the season. SINATA was configured to match the blocks being analysed (location, weather source, soil type, crop age, irrigation system details, spacings). The SINATA output was thus based on inputs of actual yields and fertiliser applications analysed against long-term weather averages.

Results: Irrigation and nitrogen application

Water use

Due to rainfall, there was no significant irrigation at any of the properties before December 2022. Irrigation had typically finished by late March or early April 2023. Water use and rainfall during the period of irrigation is shown in Table 2.

Table 2. Water use and rainfall during period of irrigation (Dec 2022 – Apr 2023)

State, Region	Orchard	Rain (mm)	Irrig (kL/ha)	Min (kL/ha)	Max (kL/ha)
WA, Manjimup	Fontanini*	187	3600	3225	3730
SA, Lenswood	Oakleigh§	189	2950	1935	3553
Tas, Launceston	RW Squibb	257	1650	1300	2020
NSW, Batlow	Tingira	418	540	80	1400

*There was a small amount of irrigation during Oct & Nov.
§Two blocks with aberrant (high) flow data excluded

Drainage

Understanding drainage plays a key role in ensuring that fertiliser (nitrogen in particular) and irrigation are applied at appropriate times. Excessive drainage following fertiliser application may result in environmental discharge of nutrients which is both an unnecessary cost and not in keeping with best-practice environmental stewardship. Rainfall and irrigation both potentially contribute to drainage. However, the timing of irrigation was appropriate for all the orchards. Only rainfall potentially contributed to drainage.

The SINATA tool provides an annual estimate of drainage for each location based on historical weather data, soil types and other variables. This can help to inform planning of the timing and quantity of fertilizer application, but actual timing will depend on the specific season. SWAN calculates drainage daily based on actual weather, irrigation, crop water use and daily soil moisture balance. Table 3 summarises the drainage data estimated or calculated by the different methods. This data highlights the variability of rainfall (and resultant drainage) from season to season.

Table 3. Average drainage (mm) for each location estimated by SINATA (long term annual average) and calculated by SWAN for the 2022-23 season, and for the period of fertilizer application during the 2022-23 season.

State, Region	Orchard	SINATA (annual)	SWAN (season)	SWAN (fert app.)	Fert apply Period
WA, Manjimup	Fontanini*	277	700	300	Aug – Apr
SA, Lenswood	Oakleigh§	300	130	0	Dec – Apr
Tas, Launceston	RW Squibb	175	130	79	Sep – Apr
NSW, Batlow	Tingira	315	1150	315	Oct – Apr

Nitrogen fertilizer applications

The N applications were recorded in SWAN on a weekly basis, either from fertigation system records, or manually from grower-reported records. Two of the four farms provided fertiliser records after the season had concluded. N applications were then aggregated into five main periods of application to conform to the SINATA input requirement, which allows five applications for planning purposes. In some cases, this meant that continuously or frequently applied fertilizer was aggregated to a date corresponding to the middle of an interval of application. A sample of SWAN's nutrients recording and reporting pages, from which the summaries used in this report were derived is shown in Figure 1.

The amount of nitrogen applied varied greatly between orchards and varieties. This was presumably driven by agronomic recommendations (tree age, variety, yield targets, soil type, etc.), historical practice, and capacity to apply the fertiliser under the conditions. The data are summarised in Table 4 for key varieties grown in each orchard.

All of the orchards were irrigated appropriately given the weather and evaporative demand. The timing of rainfall cannot be predicted but the SWAN's soil moisture forecast can give some indication of whether irrigation will be required, and also whether drainage may occur following specific rain forecasts. This in turn might guide the timing of N application, particularly where large quantities of N were applied during or prior to periods that are typically wet.

Table 4. Nitrogen application and predicted leaching for orchards by variety, tree age and yield. The N leaching estimates were estimated by SINATA based on actual orchard characteristics, actual N application, and reported yields for 2022/23, but were derived using weather data and drainage estimates from long term climatic averages.

Orchard	Variety	Age	Yield (T/ha)	N Applied (kg/ha)	N Leached (kg/ha)
Fontanini	Kanzi	10	54	58	43
	Bravo	8	91	58	35
	Granny Smith	>13	106	100	60
Oakleigh	Rosy Glow	22	75	25	29
	Rockit	9	50	41	40
	Bravo	6	45	8	17
Squibb	Royal Gala	25	36	50	25
	Smitten	5	22	50	33
	Pink Lady	9	45	50	22
Tingira	Royal Gala	15	55	9	11
	Pink Lady	15	47	3.3	8
	Fuji	30	40	4	8

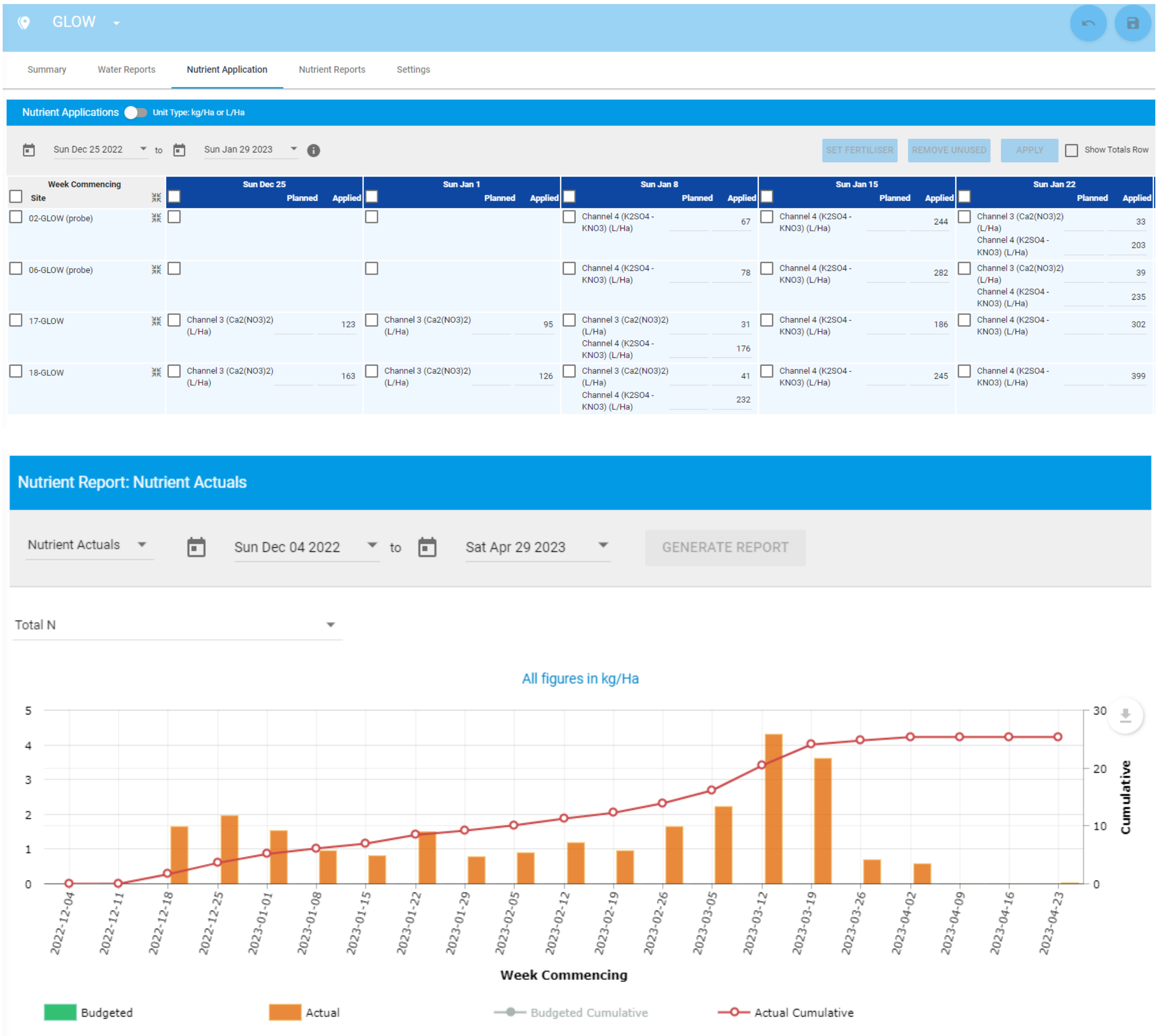


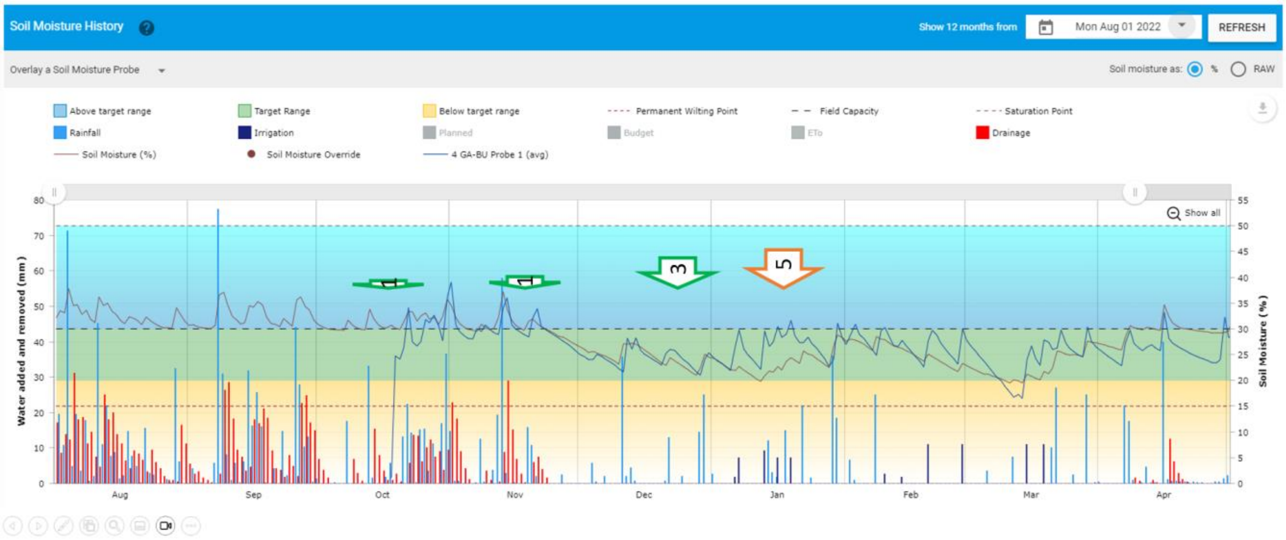
Figure 1. Fertilizer application recording form in SWAN (TOP), and SWAN reporting showing timing and quantity of Nitrogen application (BOTTOM) for Rosy Glow apples.

The timing of Nitrogen application varied substantially between farms and varieties. This is illustrated in the pair of charts below (Figure 2) that depict the irrigation season in SWAN, and the SINATA output for the corresponding block/variety. Paired charts showing this analysis for key varieties from all of the orchards are provided in Appendix 1. The SINATA output chart shows the final tab of the Excel tool, including the crop N dynamics, and soil N balance. The SWAN chart presents daily soil moisture predictions for key blocks in each orchard from August 2022 to April 2023. Each chart has a detailed legend identifying all the components. In particular, the key features to note in each SWAN chart are:

- Daily soil moisture balance calculated by SWAN (brown line)
- Daily average soil moisture balance measured by a probe if present (blue line)
- Daily irrigation amounts (dark blue columns)
- Daily rainfall (light blue columns)
- Calculated drainage (red columns)
- Superimposed applied N (either as fertigation or granular spread)

Tingira: Gala

N-Applications kg/ha
Fertigation/Spread
Foliar Spray



Tingira
Gala

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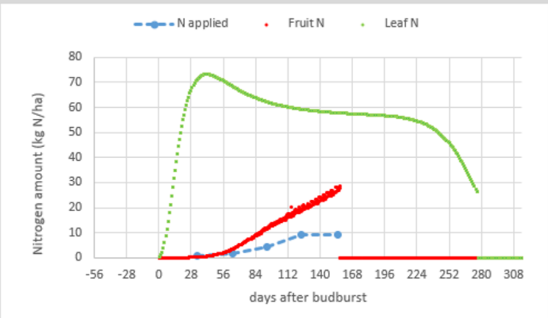


17 yr-old Gala at an Batlow on Batlow "Red Dermosol" (NSW)

Budburst occurs on 13-Sep

the target yield is 55 T/ha

Select Nitrogen inputs by changing values in the green boxes

Variety	Gala
Expected yield (T/ha)	55
Application method	Fertigation

DABB	Date	Product	Rate (kg/ha)	N (kg/ha)
33	15-Oct	Calcium Nitrate	4.00	0.62
64	15-Nov	Calcium Nitrate	7.00	1.09
94	15-Dec	Calcium Nitrate	17.00	2.64
124	15-Jan	Urea	10.00	4.70
155	15-Feb	Calcium Nitrate	0.50	0.08

Annual Nitrogen balance (kg N/ha)			
Leaf fall (kg N/ha)	30	crop N (kg N/ha)	27
Mineralization of soil N (kg/N/ha)	-9	volatization (kg N/ha)	0
		nitrate leaching (kg N/ha)	11
Fertilizer N (kg/ha)	9.1	denitrification (kg N/ha)	0

Nitrogen INPUTS (Fertilizer-N + soil mineralization + leaf fall)	30	NO3- uptake from the soil	12
Nitrogen OUTPUTS (volatilization + denitrification + leaching + uptake)	34	NH4 uptake from the soil	10
difference (Nin - N out)	-4	change in soil min-N	-3

Figure 2. Sample SWAN and SINATA output. The top chart shows the soil moisture for the 2022-23 season represented in SWAN, with actual N applications overlayed on the chart. The second chart shows the final page from the SINATA spreadsheet, including the N-balance estimated as described in the text.

Discussion: Grower engagement with the technology

SWAN set up and training

SWAN maintained regular contact with growers. This involved calls with the growers to discuss the data and recommendations the system was producing, and at least three detailed reviews with each grower during the season. SWAN support was available at any time to answer questions or check data feeds.

The detailed reviews were conducted at strategic times in the season via Teams conference calls and used screen-sharing. The first detailed review was in December and was conducted to discuss and review the setup of the sites, irrigation system parameters, data feeds, etc. This review was to ensure the account was calibrated and "ground-truthed" against probes, grower feedback, etc. This first session was also the first training session, familiarising the grower in the key aspects of the SWAN program, namely SWAN's soil moisture modelling principles, interpreting the soil moisture charts, and using SWAN for daily scheduling. This session occurred prior to commencement of irrigation in 3 of the 4 farms.

The second review was timed to occur 2-3 weeks after irrigation-proper had begun. The session reinforced the subjects and training provided in the first and was also used to cover more advanced questions from the growers, and for SWAN to fine tune crop water use modelling to fit the timings of varieties in each block.

The final session was a post-season wrap-up with the Tasmanian Institute of Agriculture represented by Nigel Swartz. This session took in a detailed analysis of the season's data, reviewed water usage, timing of fertiliser application, drainage and the SINATA predictions for the N-balance of selected sites, as shown in the report. It included a discussion about the usage of SWAN during the season, which is covered below. A full review of the season's data and settings typically forms the basis for rolling over the SWAN setup for the next season. The initial season thus forms the blueprint, and subsequent seasons require much less direct support.

Usage patterns

All of the growers regularly logged into and reviewed their accounts in SWAN, though the frequency of logging in varied. SWAN's login data (anonymised below, and in no particular order), shows the number of distinct days on which each of the growers logged into the platform. Logins were concentrated in the irrigation months.

There were different approaches to using the system. A common theme was that the growers reported they were keen to see how the system worked and to be sure they trusted it before directly following the irrigation recommendations. All reported that SWAN represented an accurate model of the irrigation requirements for their blocks and that seeing SWAN's outputs gave them confidence in the decisions they were making. Likewise, they stated that they would have greater confidence to use the system to guide irrigation in subsequent seasons.

Grower 1 logged into SWAN almost daily and reported great confidence in the SWAN dashboard, and that it provided good guidance and confirmation that he was on the right track for his irrigation practice. Grower 2 ran his standard approach for the season and reported being happy to monitor progress with SWAN and see how it compared with the standard approach. He logged into SWAN about once per week during the irrigation period and regretted being especially time-poor this season due to various infrastructure issues. He was very interested to run SWAN for another year and use SWAN more fully to inform irrigation decisions.

Grower 3 reported being satisfied with the accuracy of SWAN's soil moisture predictions and regularly accessed the system to confirm moisture status. Irrigation requests were communicated to staff via the app. His aim would be to follow SWAN's recommendations fully next season. Similar to the others, Grower 4 acknowledged the confidence that SWAN Systems gave him in irrigation decisions. This grower was the only one who had attempted to engage with SINATA directly, but did not work through all the steps, citing complexity. Some support with SINATA would have assisted.

Table 5. User Engagement: Frequency of logging in to SWAN Systems. The main months of irrigation are indicated by blue text.

Month	Farm 1	Farm 2	Farm 3	Farm 4
Sep-22	14	0	2	0
Oct-22	13	0	1	1
Nov-22	22	0	3	0
Dec-22	23	2	11	9
Jan-23	24	6	20	13
Feb-23	25	3	12	16
Mar-23	19	3	2	11
Apr-23	10	0	2	3
Total unique days	150	14	53	53
Total logins	183	20	91	74
% total via webapp	100%	100%	26%	45%
% total via mobile	0%	0%	74%	55%

Costs

Key parameters required for a successful SWAN Systems experience are:

- Setup
  - Soil types
  - Irrigation system characteristics (spacings, valve flow rate table, etc.)
  - Crop characteristics (crop coefficients)
- Reliable data
  - Accurate flow data or records
  - Good local weather observations and forecasts
  - Soil moisture probes (optional)
  - Nutrient records
- Training and user engagement

Ideally for horticultural accounts, all of a grower's blocks would be configured in the system for accurate soil moisture balance predictions. The latter requires automated data collection, or regular upload of flow data records (there is a dedicated function for this in SWAN). Typically, weather data will be available from a nearby public source (BoM, NRM, etc.) or a private rain gauge. While potentially useful for calibrating the soil moisture model, probe data is optional but can be automatically collected from most devices. SWAN is currently developing automated nutrient data collection to take advantage of fertigation systems that record this data. Surface spread or foliar spray nutrients are very easy to log in SWAN, which may be appealing to growers who are currently keeping hand-written records.

The cost of SWAN Systems depends on the level of service required. The standard package includes all the components required to run SWAN as it was during this trial, namely:

- set up and configuration of blocks
- establishment of data collection from farm devices (controllers, probes, weather stations)
- configuration of the crop water use modelling
- soil moisture predictions and irrigation recommendations
- nutrients planning and recording tools
- access to pre-configured reports for water and nutrient usage
- satellite imagery at 10 x 10 m every 5 days (Sentinel)
- sufficient support for training and basic trouble-shooting for a season

Add-ons to the service include:

- detailed, custom reports prepared by SWAN support
- extra support
- high resolution satellite imagery
- direct integration of SWAN's irrigation recommendations with controllers
- additional sensors hosted on the data hub at a granular level

SWAN has a pricing matrix that is used to provide a quote, factoring in the required specific functions and level of support. As an example, we have prepared a typical quotation for three different scale operations, 10, 30 and 100 hectares (Table 6). The setup fees are one-off, hence the difference in total price between year 1 and year 2+. Each SWAN account comes with 10 hours of support as standard, but we strongly recommend having additional support to ensure maximum benefit from the system. For the 2022-23 project, additional time was spent in running the project, including adding flow and fertiliser data manually where required, attending field days, producing reports etc., estimated at 100 hours.

We have a partnership with AgLogic in Tasmania who can assist with this support, and if the grower has a preferred advisor, we are happy to explore collaborating with them in a similar manner.

Table 6. Indicative pricing matrix for SWAN Systems

SWAN systems **Quotation: Jul-15-2023** **Tasmanian Institute of Agriculture**

Notes			Level 1			Level 2			Level 3		
Package for apple and pair growers			10 hectare farm, basic package			30 hectare farm, basic package			100 hectare farm, basic package		
				Total Year 1	$3,480		Total Year 1	$5,640		Total Year 1	$9,700
				Total Year 2	$2,980		Total Year 2	$4,640		Total Year 2	$7,700
Item/feature	**Unit**	**Price/unit A$**		**Quantity**	**Price**		**Quantity**	**Price**		**Quantity**	**Price**
Account fee (includes 10 hrs support)	Subscription	$1,000.00	Yes	1	$1,000	Yes	1	$1,000	Yes	1	$1,000
Setup	Hours	$100.00	Yes	5	$500	Yes	10	$1,000	Yes	20	$2,000
Extra support	Hours	$100.00	Yes	10	$1,000	Yes	15	$1,500	Yes	20	$2,000
Scheduling & water budgeting			Yes		$900	Yes		$1,900	Yes		$3,900
Nutrients	Hectare	$8.00	Yes	10	$80	Yes	30	$240	Yes	100	$800

Outcomes for SINATA

This project represents a first step to incorporating the SINATA planning tool into SWAN. Table 7 below provides a comparison of the functionality of the tools. Both systems incorporate the irrigation design, local weather, water budgeting, crop water use models and fertiliser planning based on plant nutrient uptake curves. SWAN would require the apple nutrient uptake model to be added to its library for full planning functionality. There are two fundamental differences:

1. SINATA is a pre-season planning and scenario-testing tool, whereas SWAN covers some planning functions, but is intended to be used daily (or frequently) for live monitoring and decision support.
2. SINATA has a model for calculating soil nitrogen balance; SWAN does not.

Table 7. Comparison of SINATA and SWAN features

Variable	SINATA	SWAN
CONFIGURATION		
Irrigation system specific setup	Yes	Yes
Soil type / moisture holding	Yes	Yes
Weather data	Historical	Live
Water budgeting	Based on long term average, not customisable	Based on long term average, fully customisable
Budget based on expected yield	Yes, inbuilt	Via crop coefficient (Kc)
SOIL MOISTURE		
Soil moisture modelling	Historical	Live
Drainage modelling	Historical	Live
Irrigation planning	Generic planning strategy	Live, daily
Scheduling decision support	No	Yes
NUTRIENTS		
Fertiliser planning	Coarse (5 applications/ season)	Detailed (weekly)
Nutrient uptake model	N only	All nutrients (including N)
Annual nitrogen balance	Yes	No

The first difference is just a matter of purpose – essentially planning can only be done based on averages. Growers must then adapt to each season's unique challenges (weather events, water availability etc.). SWAN potentially covers both sides of the divide here.

The second difference is that SWAN does not currently provide for soil nutrient analysis or modelling of soil nitrogen balance. SWAN's estimates of drainage may be sufficient to give an indication of the timing of fertiliser application relative to actual drainage events, and thus also of environmental costs of N-application. SWAN is already developing a data hub to collect, store and analyse a wide range of data feeds and facilitate custom display options. With this tool in place it will be relatively straightforward for SWAN to provide a native overlay of nutrient applications on the annual soil moisture history chart (e.g. Figure 2).

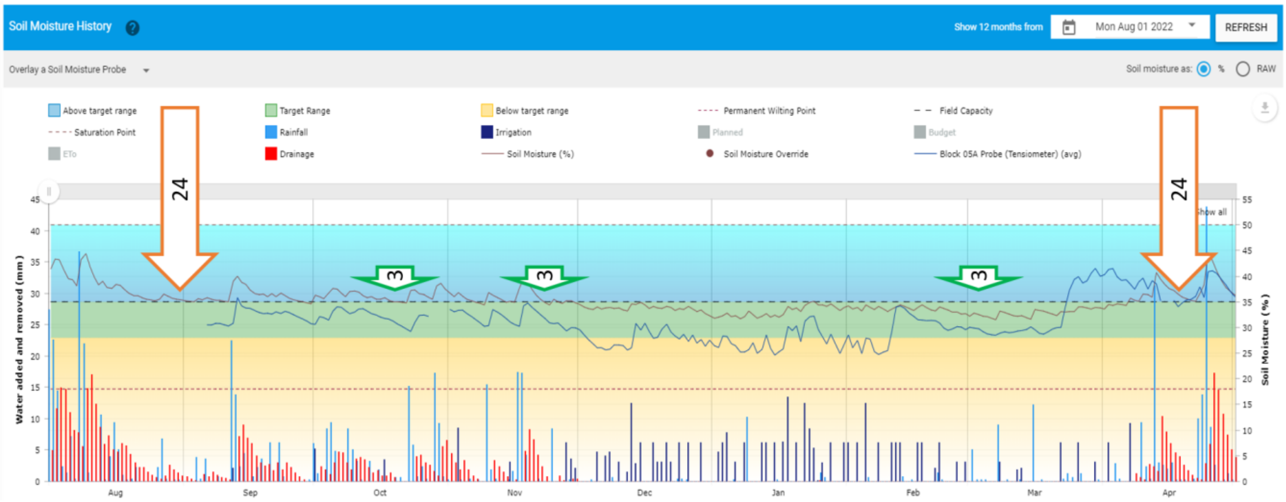
To include the full SINATA functionality in SWAN would require dedicated human resources to increase the capacity of SWAN's development pipeline. The models for N-balance calculations would need to be built into SWAN (e.g. N in crop offtake, leaf-fall, mineralisation and volatilisation dynamics of specific soils, the leached N fraction, etc.) Development on SWAN's side would need to consider the system architecture to house the data, including soil nutrient analysis, and the ability to add base data for new regions. The combination of planning tools and calculation of N-balance models based on current season live data would be a unique and powerful tool for the management of pome orchard soil health and plant nutrition.

Appendix 1: SWAN soil moisture and SINATA N-balance sheets.

Fontanini

Fontanini: Kanzi

N-Applications kg/ha
Fertigation/Spread
Foliar Spray



Fontanini Kanzi	Plant & Food Research Rangahau Ahumāra Kai; University of Tasmania TIA Tasmanian Institute of Agriculture; apal Apple & Pear Australia Ltd; pips Apples & Pears; Hort Innovation Strategic levy investment; Apple and Pear Fund

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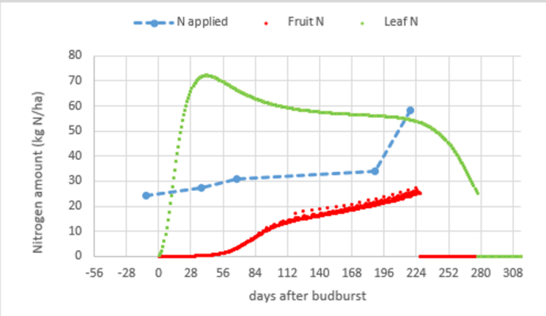


13 yr-old Pink at an Manjimup on Manjimup Brown Chromosol (WA)

Budburst occurs on 09-Sep

the target yield is 54 T/ha

Select Nitrogen inputs by changing values in the green boxes

Variety	Pink
Expected yield (T/ha)	54
Application method	Fertigation

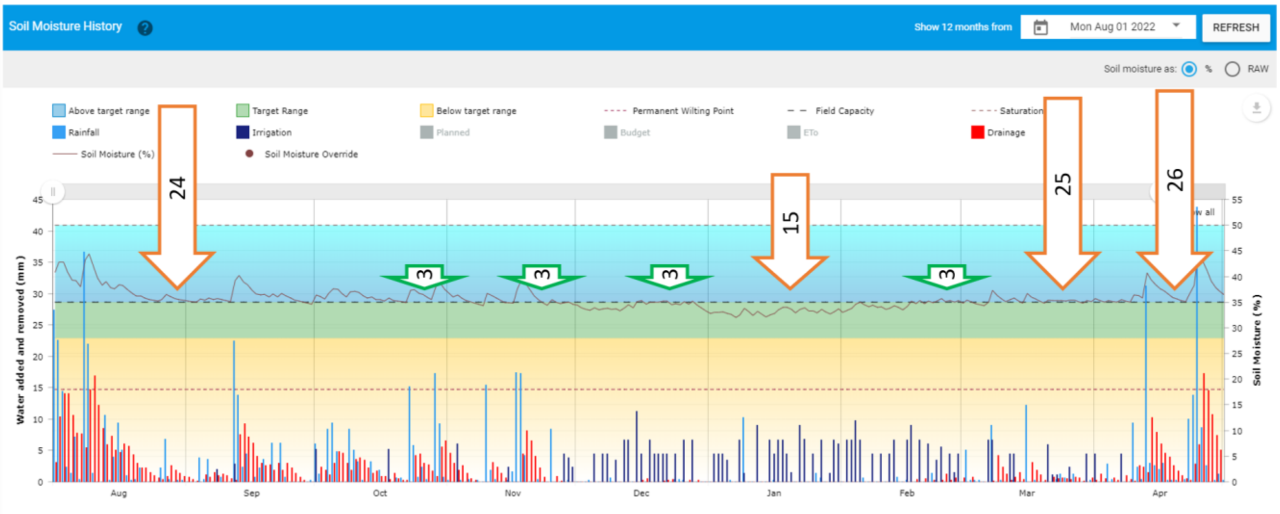
DABB	Date	Product	Rate (kg/ha)	N (kg/ha)
354	28-Aug	CAN	90	24.3
37	15-Oct	Urea	6	2.8
68	15-Nov	Calcium Nitrate	23	3.6
188	15-Mar	Calcium Nitrate	20	3.1
219	15-Apr	CAN	90	24.3

Annual Nitrogen balance (kg N/ha)			
Leaf fall (kg N/ha)	29	crop N (kg N/ha)	26
Mineralization of soil N (kg/N/ha)	9	volatization (kg N/ha)	2
		nitrate leaching (kg N/ha)	43
Fertilizer N (kg/ha)	58	denitrification (kg N/ha)	0

Nitrogen INPUTS (Fertilizer-N + soil mineralization + leaf fall)	96	NO3- uptake from the soil	36
Nitrogen OUTPUTS (volatilization + denitrification + leaching + uptake)	97	NH4 uptake from the soil	16
difference (Nin - N out)	-1	change in soil min-N	3

Fontanini: Granny Smith

N-Applications kg/ha
Fertigation/Spread
Foliar Spray



Fontanini
Granny Smith

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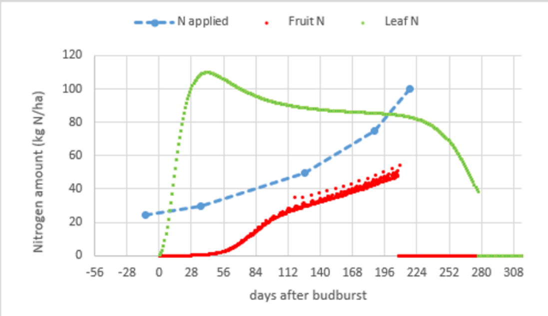


15 yr-old Granny at an Manjimup on Manjimup Brown Chromosol (WA)

Budburst occurs on 10-Sep

the target yield is 106 T/ha

Select Nitrogen inputs by changing values in the green boxes

Variety	Granny
Expected yield (T/ha)	106
Application method	Fertigation

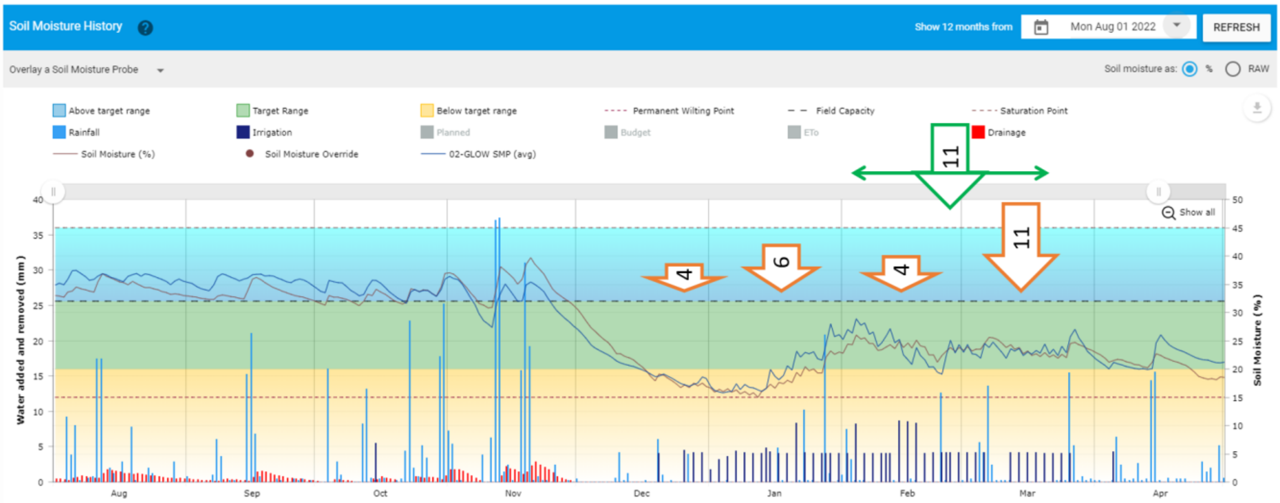
DABB	Date	Product	Rate (kg/ha)	N (kg/ha)
353	28-Aug	CAN	90	24.3
36	15-Oct	Urea	11	5.2
127	15-Jan	Calcium Nitrate	130	20.2
187	15-Mar	Urea	53	24.9
218	15-Apr	CAN	95	25.7

Annual Nitrogen balance (kg N/ha)			
Leaf fall (kg N/ha)	44	crop N (kg N/ha)	49
Mineralization of soil N (kg/N/ha)	5	volatization (kg N/ha)	4
		nitrate leaching (kg N/ha)	60
Fertilizer N (kg/ha)	100	denitrification (kg N/ha)	1

Nitrogen INPUTS (Fertilizer-N + soil mineralization + leaf fall)	149	NO3- uptake from the soil	57
Nitrogen OUTPUTS (volatilization + denitrification + leaching + uptake)	150	NH4 uptake from the soil	29
difference (Nin - N out)	-1	change in soil min-N	7

Lenswood: Rosy Glow

N-Applications kg/ha
Fertigation/Spread
Foliar Spray



Lenswood Rosy Glow

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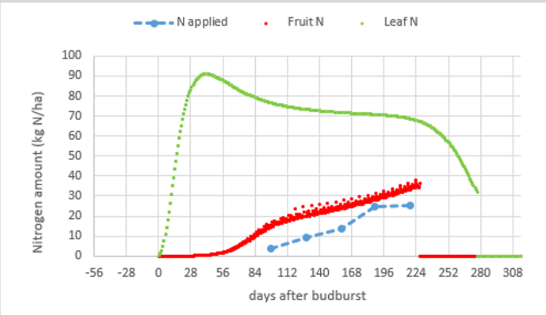


15 yr-old Pink at an Lenswood on Lenswood "Brown Chromosol" (SA)

Budburst occurs on 09-Sep

the target yield is 75 T/ha

Select Nitrogen inputs by changing values in the green boxes

Variety	Pink
Expected yield (T/ha)	75
Application method	Fertigation

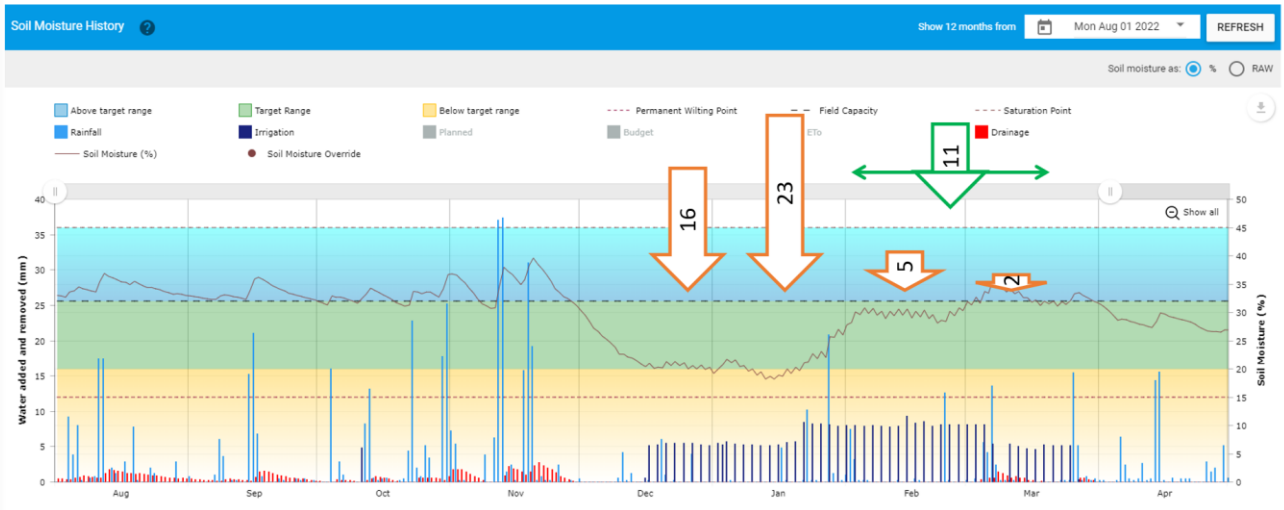
DABB	Date	Product	Rate (kg/ha)	N (kg/ha)
98	15-Dec	Calcium Nitrate	24	3.7
128	15-Jan	Calcium Nitrate	36	5.6
159	15-Feb	Calcium Nitrate	30	4.7
188	15-Mar	Calcium Nitrate	70	10.9
219	15-Apr	Calcium Nitrate	4	0.6

Annual Nitrogen balance (kg N/ha)			
Leaf fall (kg N/ha)	37	crop N (kg N/ha)	36
Mineralization of soil N (kg/N/ha)	4	volatization (kg N/ha)	0
		nitrate leaching (kg N/ha)	29
Fertilizer N (kg/ha)	25	denitrification (kg N/ha)	1

Nitrogen INPUTS (Fertilizer-N + soil mineralization + leaf fall)	66	NO3- uptake from the soil	23
Nitrogen OUTPUTS (volatilization + denitrification + leaching + uptake)	69	NH4 uptake from the soil	15
difference (Nin - N out)	-2	change in soil min-N	-2

Lenswood: Rockit

N-Applications kg/ha
Fertigation/Spread
Foliar Spray



Lenswood Rockit

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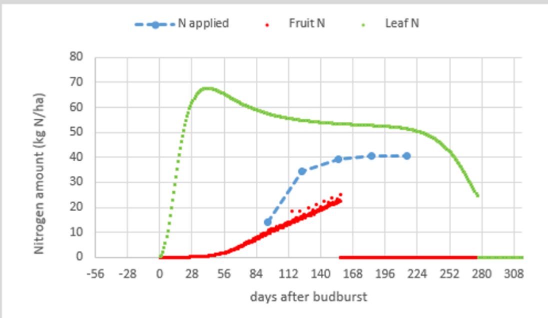


8 yr-old Gala at an Lenswood on Lenswood "Brown Chromosol" (SA)

Budburst occurs on	13-Sep	
the target yield is	50	T/ha

Select Nitrogen inputs by changing values in the green boxes

Variety	Gala
Expected yield (T/ha)	50
Application method	Fertigation

DABB	Date	Product	Rate (kg/ha)	N (kg/ha)
94	15-Dec	Calcium Nitrate	90	14.0
124	15-Jan	Potassium Nitrate	150	20.4
155	15-Feb	Potassium Nitrate	35	4.8
184	15-Mar	Potassium Nitrate	12	1.6
215	15-Apr	Potassium Nitrate	0	0.0

Annual Nitrogen balance (kg N/ha)			
Leaf fall (kg N/ha)	28	crop N (kg N/ha)	23
Mineralization of soil N (kg/N/ha)	4	volatization (kg N/ha)	0
		nitrate leaching (kg N/ha)	40
Fertilizer N (kg/ha)	41	denitrification (kg N/ha)	2

Nitrogen INPUTS (Fertilizer-N + soil mineralization + leaf fall)	73	NO3- uptake from the soil	20
Nitrogen OUTPUTS (volatilization + denitrification + leaching + uptake)	74	NH4 uptake from the soil	12
difference (Nin - N out)	-1	change in soil min-N	-1

Squibb

N-Applications kg/ha

Fertigation/Spread

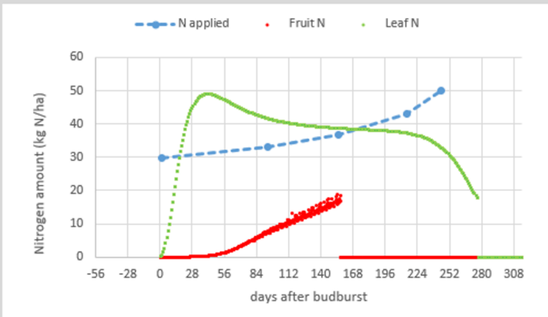
Foliar Spray

Squibb: Royal Gala

*All blocks/varieties were treated the same

Squibb Royal Gala	Plant & Food Research Rangahau Ahumāra Kai · TIA Tasmanian Institute of Agriculture · apal · pips · Hort Innovation · APPLE AND PEAR FUND

- SINATA is a **S**trategic **I**rrigation & **N**itrogen **A**ssessment **T**ool for **A**pples



25 yr-old Gala at an Spreyton on Lucaston silty clay loam (TAS)

Budburst occurs on	13-Sep	
the target yield is	36	T/ha

Select Nitrogen inputs by changing values in the green boxes

Variety	Gala
Expected yield (T/ha)	36
Application method	Broadcast

DABB	Date	Product	Rate (kg/ha)	N (kg/ha)
2	14-Sep	ASN	115	29.9
94	15-Dec	Calcium Nitrate	20	3.1
155	15-Feb	CAN	14	3.8
215	15-Apr	Urea	13	6.1
245	15-May	Urea	15	7.1

Annual Nitrogen balance (kg N/ha)			
Leaf fall (kg N/ha)	20	crop N (kg N/ha)	17
Mineralization of soil N (kg/N/ha)	-8	volatization (kg N/ha)	4
		nitrate leaching (kg N/ha)	25
Fertilizer N (kg/ha)	50	denitrification (kg N/ha)	0

Nitrogen INPUTS (Fertilizer-N + soil mineralization + leaf fall)	62	NO3- uptake from the soil	23
Nitrogen OUTPUTS (volatilization + denitrification + leaching + uptake)	63	NH4 uptake from the soil	11
difference (Nin - N out)	-1	change in soil min-N	-2

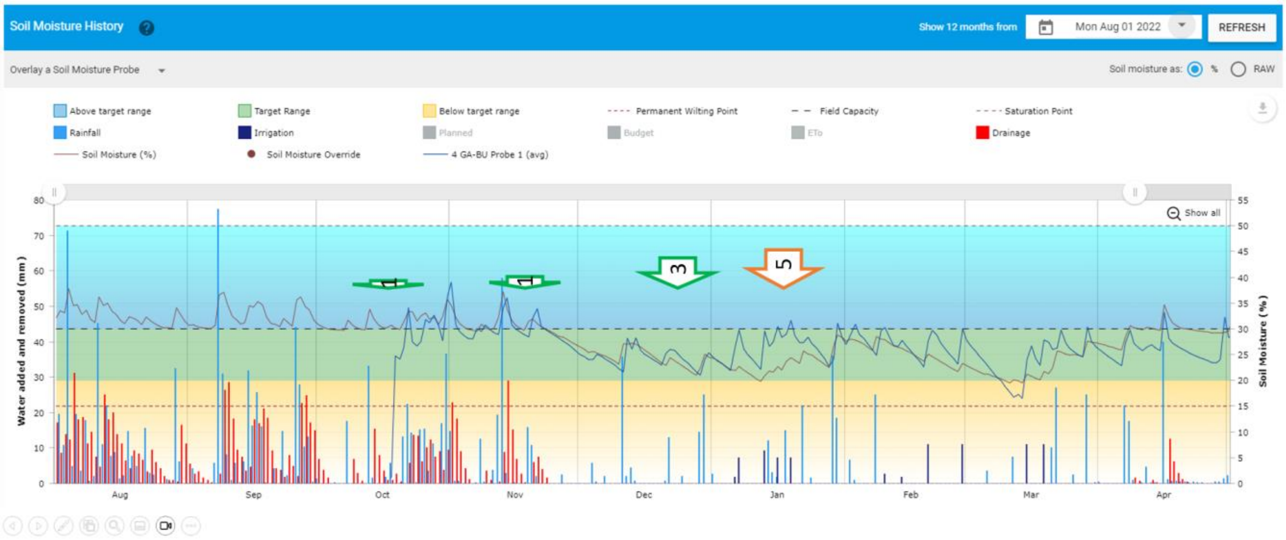
Tingira

Tingira: Gala

N-Applications kg/ha

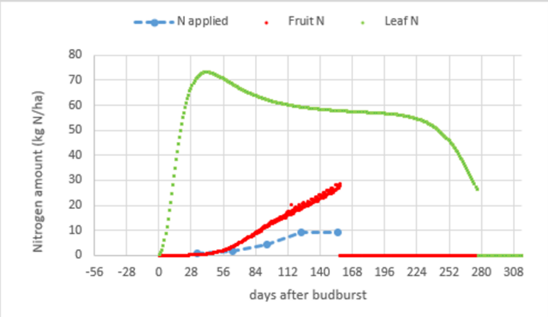
Fertigation/Spread

Foliar Spray



Tingira Gala

- SINATA is a **S**trategic **I**rrigation & **N**itrogen **A**ssessment **T**ool for **A**pples



17 yr-old Gala at an Batlow on Batlow "Red Dermosol" (NSW)

Budburst occurs on 13-Sep

the target yield is 55 T/ha

Select Nitrogen inputs by changing values in the green boxes

Variety	Gala
Expected yield (T/ha)	55
Application method	Fertigation

DABB	Date	Product	Rate (kg/ha)	N (kg/ha)
33	15-Oct	Calcium Nitrate	4.00	0.62
64	15-Nov	Calcium Nitrate	7.00	1.09
94	15-Dec	Calcium Nitrate	17.00	2.64
124	15-Jan	Urea	10.00	4.70
155	15-Feb	Calcium Nitrate	0.50	0.08

Annual Nitrogen balance (kg N/ha)

Leaf fall (kg N/ha)	30	crop N (kg N/ha)	27
Mineralization of soil N (kg/N/ha)	-9	volatization (kg N/ha)	0
		nitrate leaching (kg N/ha)	11
Fertilizer N (kg/ha)	9.1	denitrification (kg N/ha)	0

Nitrogen INPUTS (Fertilizer-N + soil mineralization + leaf fall)	30	NO3- uptake from the soil	12
Nitrogen OUTPUTS (volatilization + denitrification + leaching + uptake)	34	NH4 uptake from the soil	10
difference (Nin - N out)	-4	change in soil min-N	-3

Monitoring and evaluation

The PIPS3 Program Final Evaluation interview process was conducted in June and July 2023.

Overall, forty-three (43) telephone interviews were undertaken by the PIPS3 Program Coordinator, each interview averaging a 20 minute in duration. Eleven questions were asked, seven of these structured with a rating response required between 1 (most negative) and 5 (highly positive), with an opportunity to provide an extended comment to support the rating response. Most often, the respondents were highly motivated to expand upon the ratings provided. Four questions were open-ended to gain feedback and insight in a less formal and structured approach. These responses were particularly important in identifying areas for continuous improvement.

The stakeholder groups represented in the interviews were:

- Research team (n = 8)
- Growers (n = 20)
- Service Providers (n = 15)

The service provider stakeholder group included agency extension, commercial advisors, private advisors, and technical collaborators.

Some interviewees provided a response based upon their involvement across multiple projects of the program. This resulted in fifty-four (54) possible responses when quantifiably analysing results on a project basis. The following is a break-down of possible responses per project:

- Whole-of-program relationship (n = 6)
- AP19002 (n = 10)
- AP19003 (n = 6)
- AP19005 (n = 8)
- AP19006 (n = 24; Researcher (n =2), Grower (n = 13), Service Provider (n = 9))

Although the spread of project respondents appears to be disproportionate, with AP19006 having 24 respondents, this reflects the large geographic spread of this project. The interviews conducted for this project ensured good representation across the regional areas in which both trial and demonstration activities were being conducted.

The interview process of both quantifiable and qualitative questions was used to evaluate **effectiveness**, **relevance**, **process appropriateness**, **efficiency** and **legacy** KEQ of the PIPS3 Program, and the specific program/project questions underpinning these (refer to the table below for questions that were specifically developed by the AP19006 project). The design of the questions enables analysis of responses at both a program and project level so that all users of the evaluation report can apply findings to both program and individual project level questions. A table of the interview questions used to assess performance of the program/ projects against the Key Evaluation Questions (KEQ) is provided in the final report for AP19007 (Independent Coordination).

AP19006 achieved a "Strong" performance rating across all KEQ from the final evaluation interview process, although the long-term legacy rating was borderline at an overall rating of 3.8, with a moderate rating for likelihood of adoption in the next ten years rated as medium (3.7).

Table 1. Stakeholder interview quantitative response ratings to determine final performance.

Stakeholder interview result	Evaluation criteria
Strong	Rating of between 3.8 to 5
Moderate	Rating of between 2.4 to 3.7
Weak	Rating of between 1 to 2.3

Table 2. AP19006 Key Evaluation Questions and performance results

AP19006 Key Evaluation Questions	Project performance	Example Feedback from respondents.
EFFECTIVENESS: *To what extent has the PIPS3 Program addressed the objectives, research agreement achievement criteria and identified outcomes/ outputs?*		
• To what extent did the project increase grower and front-line advisor knowledge and understanding of sustainable orchard management practices? • Did the project produce sustainable orchard management guidelines and the SINATA Irrigation & Nutrition web app?	**AP19006 effectiveness rating achieved:** 4.1 (n=24) **Overall program effectiveness:** 4.3 (n=43) Respondents were confident that the project achieved its objectives and activities were executed as expected, however the delayed establishment of the soil health sites in season one had an impact upon the overall outcomes of the project. There was substantial caution expressed on the practicalities of certain interrow (native species) treatments and cost of tree line (mulch/compost) treatments trialed, and an underling belief that other industries had already conducted extensive research into these strategies, and these needed to be looked at more thoroughly. Whilst most respondents understood the need and soil/nutrient benefits in improving soil health, they expressed the economics need to be further understood. Both advisors and growers highlighted that the project had certainly facilitated new conversation amongst industry stakeholders on the need for more sustainable management practices in the orchard and sharing of ideas on this. Integration of SINATA into the Swan Systems online platform has been well received by the trial farmers for it's ease of use, accuracy (alignment with "what I thought") and support provided by the company. Respondents in NSW, SA and WA valued having local	***Researcher*** *All activities were implemented but it's going take us longer to identify and realise the soil health impacts. The practicalities of soil health management are really not realised yet and it's what we need to work through. Also, the economics need to be fully evaluated.* *Implemented but not sure that the results are there for industry. Project design was good but time constraints in the beginning for consultation was limited. We needed more time and research understanding of the treatments and what growers are looking for.* ***Grower*** *I don' t think that the concepts had been thought out enough - i.e., tractability. Implementation did get better…find it frustrating that [name omitted] exploits potential benefits in fruit- but we have never seen the evidence. Unless the growers can understand it and have confidence, it is wasted money.* *I give 4 for SINATA as it's very relevant…only 3 for cover cropping- no data as yet, need to see this.* *I used to predict my irrigation for the whole year- actually used it and compared it to tensiometers I had in the ground. Lots of confidence in it and will continue to use it. [SINATA]* ***Service Provider*** *The project utilising someone on the ground in WA and with a relationship with growers is a valued way to go.*

	demonstration and local coordinators of those sites who knew them well.	*[Soil health] is extremely relevant to move forward to softer chemicals and more sustainable nutrient use and need more production from our poor soils. Interrow and tree line knowledge is good & leads to intensification, but it wasn't executed well. The SINATA tool- would be good to have them all using it. As an agronomist we don't have time to do this for growers, but they can easily share this [platform] with an advisor.*
RELEVANCE: *How relevant were the research outcomes/ outputs to the needs of apple and pear growers, advisors, and industry stakeholders?*		
• Is there evidence that outcomes/ outputs of the project have inspired growers to implement sustainable orchard management practices? • To what extent has the project met the needs of growers and front-line advisors to provide information and guidance on soil health management strategies and the impact of these upon soil health, production and profitability?	**AP19006 relevance rating achieved:** 4.4 (n=24) **Overall program relevance:** 4.4 (n=43) The project was considered strongly relevant to both growers and advisors who support them. There was certainly interest expressed on the desire to be more sustainable and having demonstratable evidence to show consumers. It was evident that growers and advisors appreciated the "theoretical" information extended by the project on the importance and likely benefits of good soil health. However, the project did not provide <u>tangible</u> information to growers on how the soil health treatments benefited fruit yield and quality, some respondents expressing that the project needs to concentrate on the soil, nutrient, water, and insect/pollinator benefits, and leave fruit parameters out. Many respondents acknowledged that soil health is an area of research requiring a much longer timeframe than three years. The SINATA tool integrated into Swan Systems was immediately relevant to the irrigators who trialed the tool.	***Researcher*** *I am comfortable…I really do think this is really critical and we are on-track to deliver this understanding long-term- what the growers need to do and how to do it into PIPS4.* *Trial work not long enough, good starter to get the right information out.* ***Grower*** *A shift in thinking about soil health and chemical use. How we can do things more beneficial for the environment, and then how this links to the consumer experience* *Good trial to see the grasses that were growing. But more understanding on benefits and management. Needs 3-5 years to see what may die off etc. Over different seasonal conditions- this year was extremely wet.* *I think they have been really relevant projects that provide results continuously. The people are very decent people who know what they are doing.* *Definitely. SINATA is for everyone. It's what you do with the knowledge you get from the walks and resources. For a single operators maybe SINATA not needed but for those with staff excellent for communication.*

		Growers have more confidence in work done in their district. Although I can see how things are relevant in Tas, not all growers can see that. The actual content and aims are relevant and expose people to the right information. ***Service Provider*** *What you are doing is talking to growers which is the right way to go to get grower input. Making sure we have reflected WA growers and their growing conditions.* *Soil health all really relevant due to implications on soil disease. Cover crops- already a lot done in this space and maybe just look to other industries.*
APPROPRIATENESS: *How well have intended audiences been engaged in the project?* *To what extent was the PIPS3 Program Communications and Extension Plan appropriate and had an impact upon the target audience?*		
No specific AP19006 within M&E plan.	**AP19006 appropriateness rating achieved:** 4.5 (n=24) **Overall program appropriateness:** 4.6 (n=43) The project was considered strong in developing materials and engaging with the industry, especially through local demonstration and the final roadshow events, or where programmed in Future Orchards® walks. However, respondents expressed that the general information on soil health and likely benefits now needs to be underpinned by resources and extension that is backed by data relevant to them, including the economics. In Tasmania, there is acknowledgement that the local TIA team is very accessible to the industry, and many will "pick-up the phone" to ask a question when the need arises. Ongoing contacts list restriction for *Industry Juice* prevail. There are growers and advisors who do	***Researcher*** *I'm very comfortable in just standing-up and talking with growers- it's the best thing. We get direct feedback, but they get the opportunity to give their input and discuss.* ***Grower*** *Been to the field days and read what's important to me in AFG & IJ. I'll look locally and nationally for information.* *E-newsletters- I always click on these. By building a personal relationship with the researchers, I'll pick-up the phone and talk to them. The articles get me thinking, then I'll follow-up. Everyone has the opportunity to do this.* *The guys you had talking at the event were really fascinating. I pulled out what was relevant to me. Also, when we were in the orchard, those specialists were so knowledgeable, and I really paid attention to what they had to say. To have the specialists in the*

	not receive IJ, but they receive local organizational materials (i.e., FGT, FGV, Pomewest). While the volume and content of information was regarded as high quality, issues with grower time pressures to read and engage is a concern, primarily raised by advisors.	*orchard who are experts in certain aspects is so good- nitrogen input, IPDM- a group in the orchard and available to ask questions. It was awesome to have that opportunity.* *Mixed approach. Roadshow was great timing.* ***Service Provider*** *Needs much more engagement with the local agronomists [in treatments imposed]. Hemp compost being used was an issue and is costly. Mow & throw is the most benefit that we see, and growers are doing.* *More people at the field day [Roadshow] than I would have thought. The ones who came are those who are "fiddling around" at home and are ready to do stuff.* *FGT conference, PIPS Roadshow, FO with Nigel involved. IJ & AFG articles are good and keep me informed.* *I certainly saw things across all platforms. Personally, I am a short & sharp person- so videos are good. IJ if good will click on it. Like the AFG articles that get to the point.* *The roadshow was certainly very important. Got the researchers out. Crucial. The researchers benefit and that's what needs to happen.* *Excellent content & volume. We [service provider organisation] need to better coordinate what we pick-up and disseminate locally through our socials.* *The PIPS is doing all they can, the issue is more about grower time pressures to read and engage.*
EFFICIENCY: *What efforts did the PIPS3 Program partners make to improve efficiency?*		
• To what extent did collaboration across the PIPS3 Program improve efficiency of pest, natural enemy and soil/tree health measurements?	**AP19006 efficiency rating achieved:** 4.1 (n=22) **Overall program efficiency:** 4.1 (n=39)	***Researcher*** *We needed to get our house in order, then bring them in [referring to AP19002]- it was confusing for the region. Comes*

	The AP19006 respondents rated the PIPS3 Program as strong on its performance to deliver an efficient approach to research, and communication and extension of the research. Issues were raised that need to be addressed for PIPS4. These are the development of standard protocols and processes for demonstration sites in trial design and the collection and management of data. Regional coordinators suggest that standard templates and a schedule of delivery expectations is needed at commencement to ensure that the integrated requirements across projects (in PIPS3 this was AP19006 & AP19002) are clear, and they know what has to be done and when it needs to be done.	*back to project start-up- if we felt organised, we could have better coped with their input.* ***Grower*** *I'm a real fan. When they all come together, they are really powerful. It has got better- some are not good communicators though [example provided]. Someone like Nigel is great. It is good that there is an exchange of researchers between projects too.* *It's good to talk about all system issues together- The roadshow day showed that the researchers are working together to consider the impacts across the whole system.* *A good example is you can't look at root stocks without considering IPDM and irrigation. Systems approach needs to happen and works more effectively in PIPS now.* *I get the impression that they are collaborating pretty intensely now. Much better way to be conducting this style of holistic soil- nutrition approach.* *Makes a difference for the information to come out as whole.* *With both my hats on [Grower & Fertiliser reseller], the program allows you to see across different projects and data and allows you to extract this for your property. The Roadshow definitely stimulated a lot of discussion, very interesting.* ***Service Provider*** *With you [coordinator] coming onboard it has been a godsend. This project has forced researchers to be more aligned and work together. Cross fertilisation of ideas is a must and has worked.* *I like the whole program approach as you gain lots of insight across the system. FO is pigeonholing into business. In*

<table>
<tr><td></td><td></td><td>PIPS, growers can look at what is relevant to them. Its great because you get to see the outcomes of trials and the information is good.

It's important that there is a focus on fruit quality etc., not just soils. For what it does, it's an extremely good program at this.</td></tr>
<tr><td colspan="3">LEGACY: Are there signs that the PIPS3 Program will influence apple and pear growers in the future?</td></tr>
<tr><td>• To what extent has the project resulted in greater confidence, intention to adopt, or adoption of practices in sustainable orchard management practices?

PROGRAM

• Is there evidence that outcomes and outputs of the PIPS3 Program will continue to be adopted by growers and front-line advisors?
• To what extent do stakeholders believe that outcomes/ outputs of the PIPS3 Program are likely to become “usual grower practice” within the next ten years?</td><td>AP19006 legacy rating achieved: 3.8 (n=23)

(Improved knowledge & understanding of the concepts= 3.9 & Likelihood of adoption <10 yrs.= 3.7)

Overall program legacy: 4.0 (n=43)

(Improved knowledge & understanding of the concepts= 4.1 & Likelihood of adoption <10 yrs= 3.8)

AP19006 has raised awareness on the concepts of soil health and its relationship with nutrient availability and water management, however, it has not necessarily provided confidence to growers that making orchard floor management changes will be beneficial to their business (yield, quality, or profitability). Most respondents are waiting for data-driven evidence and economic analysis of the value proposition of the trialed interrow and tree line managements in their farming system. There is agreement across the board that soil health takes time to respond to changes in management and therefore evaluate, but commencing the conversation and having focal points in the regional demonstration sites has facilitated this foundational process.

Improvements in grower and advisor consultation to inform trial design were suggested by a</td><td>Researcher

As the project has progressed, as we have discussed implementation of the soil health treatments, we have changed the way we have advised growers about the practicalities and what works. Have a look locally as how it can be done and getting the conversation happening- a major aim was to really raise the awareness of soil health and the way growers manage the orchard floor.

Growers seem to have more awareness of the soil biology and its role in the system.

I think now that we have done this roadshow, understanding has increased significantly. The final report will have region-by-region specific approach for soil health orchard management, and SINATA, and deliver out to growers, so that will hopefully put some of the engagement into more initial steps other than just awareness. Clearly articulating application to their businesses is important.

Short duration project but we have learned we need to do more. The extension needs to be more- but the appetite is there. There is a big gap and PIPS often fills that as there is a need, but it's not what we are contracted to do.

Grower

The site helps us have the discussion amongst each. A focus provides an opportunity to talk about our approaches to</td></tr>
</table>

	number of respondents. They believed this would provide a more practical and realistic element to the treatments applied, and also increase confidence in the concept of orchard floor management longer-term. Both are seeking more information on long-term management of the treatments, especially to better evaluate the labour, water, and nutrient input implications, both positive and negative. SINATA trial farmers see the value proposition of the tool, however, there is concern amongst some respondents that growers may not be willing to pay a subscription to SWAN Systems to access the tool. The benefits and economic value need to be clearly articulated and promoted. All growers are looking forward to trialing the tool again over the next season to evaluate the benefits of varying seasonal conditions. All are enthusiastic about being local ambassadors for the tool. The idea of extending more of the 'known' research and experiences from other industries was raised by respondents who saw a gap in industry extension. While they know the research has been undertaken, they believe there is a gap in apple and pear extension of the outcomes of R&D over the past 5-10 years but acknowledge this is not the ongoing role of PIPS as an R&D program.	*managing soil health.* *If we go to legume then we are not spraying, but we need to better understand how this changes our management and what the benefits are of various approaches. e.g., if I can reduce nutrient by 50%, then it's really important- needs the economics though. Fertiliser is a good driver some of this change.* *Yes & no on the soil health- I don't know if that's the track I'll go down as I have grown-up with clean under tree- big mind change.* *Soil Health- may be achievable for new blocks but difficult to implement on existing blocks- all comes down to practicalities and establishment. Native blocks- need to be careful about pests such as dimpling bug.* *Understory clovers are something I think I can work on- and it has made me look more closely at what I already have. I am exploring how I can diversify the floor. The time and energy are about the long-term. It's not an automatic economic winner. When you have people there who have the expertise, it's an opportunity to talk these things over.* *Practice change will come as we address the big SA constraints such as water quality and how floor management can help.* *Basically, the confirmation- keep doing what I am doing. At this stage has given me faith. [SINATA]* *I have actually adopted something and happy to implement anything that makes life easier. Cost of SWAN V Benefits= takes out the headaches, saves in water costs, labour benefits (decisions through my PC/ phone). I do this at any time of the day and wherever I am, the platform is clear and*

		good to makes printouts, ready to go at your fingertips. [SINATA] ***Service Provider*** *Definitely leaving interrow and not mowing every row, every time. Mulch & mow/throw are things they think they can do. Need the data to underpin & communicate this to support what they are seeing.* *Essentially, I haven't seen much data, it's been mainly from a discussion point with growers. That's not a bad thing- we can have conversations now that we couldn't have in the past. I have been reading a lot more and acting upon this.* *Perhaps we can look at this idea of "champion" advisors. Could use company annual meetings to get these agronomists involved. Some agronomists just don't want to engage, and I don't know what to do- make it more data driven? Even just exposing the agronomists is a step in the right direction.*

Recommendations for continuous improvement

Comments from interviewees were grouped into the following areas for future research and communication of the results:

- Target audience events for growers and advisors
  - *Very important to get out in the right format. Some information can be too technical for young staff. In some ways that's why it's good to have the advisors on farm to provide the foundational knowledge and then build on that. We employ people who don't necessarily have formal education in this space- but are good to practical side. So different approaches for different audiences.*
  - *Research needs to go to the technical people, then they can take it to their managers.*
  - *At Nutrien (other companies likely also) have quarterly technical days- link with these to get R&D out. Especially in the soil health and nutrient space. Flip it around so run things for advisors.*
  - *Need to be making sure we get to the advisors. The trouble is that advisors need to get sales, but the good ones will gravitate towards it as they are interested. They need to know that our research will influence their businesses- what's in trend.*
  - *Personally believe the best way to get this idea out there is to get champions who are in front of growers day to day, not researchers who only have one small opportunity to get the message across.*
- Utilise regional organisation networks and resources more for improved penetration:
  - *Use the regions as they are well ahead of the game.*
  - *We need to make sure people know what we have for them and always want to improve. Really onboard to do more targeted WA sign-posting.*
  - *Integrating more of the research outcomes into the NSW Orchard Management Guide.*
  - *User friendly to my region and the data is relevant to our region. We are all different growing environments so need it to be done here.*
  - *Would be good to have things go out through Fruit Producers SA & Muirs have a newsletter too.*
  - *Better branding so we know it's PIPS and not APAL material. Keep local trials going as we need to see how things work here.*
- Economic evaluation to demonstrate value proposition as well as soil health benefits:
  - *Communication using an economic approach at the same time as the other benefits. We need to respond to growers as they tell us what they want to learn about, profitability being part of this.*
  - *I am seeing some changes in the district, but they want to see this work and see the economic data.*
  - *We need the data combined into how healthy some existing orchard soils are at the moment (good baseline), and then compare to long-term good soil health management- also some economic around this.*
  - *It could be better, but lack of grower funds on farm can be an issue when cashflow is an issue.*
- Improved project planning, especially in relation to the development and implementation of standard protocols and processes across regional experiment and demonstration site:
  - *Needs much more engagement with the local agronomists [in treatments imposed].*
  - *Improved inter-team coordination. We needed to have more involvement with the soils project- we provided samples and have heard nothing back.*
  - *Initial stages were very high, but I think towards the end there was specific collaboration on Mastrus & SINATA, but the demonstration sites were let down.*
  - *More room for improvement- cross-project communications and protocols that are actually followed.*
  - *The team needs to have bi-monthly all team webinars. Updates and informal. Questions & discussion. TIA needs to better plan team meetings.*

A guide to managing the orchard floor.

Minimising the environmental impact of apple & pear production

Sally Bound & Michele Buntain

Published by Tasmanian Institute of Agriculture, 2023

This project output from the PIPS3 Program's *Improved Australian apple and pear orchards soil health and plant nutrition* (AP19006) project has been funded by Hort Innovation, using the apple and pear research and development levy, contributions from the Australian Government and co-investment from the Tasmanian Institute of Agriculture. Hort Innovation is the grower-owned, not-for-profit research and development corporation for Australian horticulture.

Contents

Introduction

Current perennial fruit production systems can be highly productive but often contain practices that are unsustainable in the long term. The orchard floor comprises a series of interconnected systems and relationships that have a deep influence on tree health, nutrition, water availability and orchard resilience, and hence on the production of high-quality fruit. It also has a physical role in supporting orchard operations involving the movement of tractors, mobile labour/harvest assist platforms and other mechanised equipment through the orchard.

Many growers already implement practices that encourage good soil health such as compost application prior to orchard establishment, planting of inter-row swards, and use of soil amendments and/or mulches in the tree-line. Yet the benefits (above and below ground) of these various approaches are not well understood. There is also a substantial knowledge gap on how orchard floor management practices promote (or inhibit) the presence and function of beneficial organisms and how these organisms interact with trees to increase tree water and nutrient-uptake.

This publication provides information relating to the orchard floor and summarises the findings from the three-year Hort Innovation funded project *AP19006 Improved Australian apple and pear orchards soil health & plant nutrition*.

About the project

This project set out to test key principles of a sustainable production system with different orchard floor management strategies aimed at promoting long term orchard resilience. We examined and demonstrated a range of orchard floor management strategies in the Huon Valley (Tasmania), Adelaide Hills (SA), Manjimup (WA) and Orange (NSW).

Our key question

How does orchard floor management using cover crops (living mulches) and other locally sourced composts influence soil health and apple fruit yield and quality?

Over its short timeline of 3 years, the research demonstrated positive trends for incorporating living mulches, composts or organic mulches into the orchard design, and the results have provided a framework for further studies.

Both inter-row and tree-line treatments were examined (Table 1), and plant species used in each region reflected regional priorities.

Table 1*: Orchard floor treatments imposed in the inter-row and tree-line.*

Inter-row	Tree-line
Ryegrass & clover mix	Herbicide bare earth
Mixed flowering meadow plants	Compost
Native plant mix	Grass/clover mix
Fescue species & clover mix	Mow & throw

Species lists for the different cover crops / living mulches in each region are provided in Appendix 1.

Multiple assessments were undertaken to determine the impact of treatments on soil physics, chemistry and biology and on the crop (Table 2).

***Table 2**: Assessments undertaken during the project.*

Soil	Biology	Crop (years 2 & 3)
- compaction	Soil: - arthropods	- growth
- moisture content	- microbial biomass	- yield
- water infiltration	- microbial diversity	- fruit quality
- aggregate stability	-mycorrhizal fungi	- tree physiology
- organic carbon	Crop & groundcover:	- pest/disease damage
- nutrient status	- pest arthropods	
	- beneficial arthropods	

Functions of the orchard floor

The traditional orchard floor has a grassy inter-row sward and herbicide treated band along the tree line to maintain a weed free strip. This enables simplicity of management, traction and stability for tractors and machinery during wetter periods and reduces soil erosion and runoff.

Figure 1*. The orchard floor consists of the inter-row and the tree-line, with management varying between orchards.*

The orchard floor is the gateway to the tree's life support system of roots, soil, water and nutrients, and home to a myriad of life forms from micro to macro, both above and below the surface. Orchardists are becoming increasingly aware that an ecologically balanced system is essential for maintaining healthy crops and optimising fruit quality.

The orchard floor can make an important contribution to plant and animal diversity which in turn influences soil health, pest and disease management and sanitation of the orchard floor.

There is a growing appreciation of the integral importance of soil life and plant-symbiotic interactions in orchard sustainability and healthy soils. At the microscopic scale, the way that the orchard floor is managed strongly influences important soil functions such as nutrient availability, water holding capacity and microbial presence and diversity.

Sustainable orchard floor management

Sustainable agriculture has been defined in many ways and the meaning is still evolving. The following definition provides a reasonable description: *Sustainable agriculture is managing the land so that it can continue to produce food for future generations whilst preserving the natural resources of soil, water, flora and fauna.* However, being sustainable is not just about preservation of the land, it must also be economically viable for the orchardist.

There is real scope to achieve highly sustainable production in orchard systems due to the perennial nature of the crop and low soil disturbance.

The orchard floor is a place we can really influence key sustainability principles to reduce pesticide, herbicide and synthetic fertiliser use, and at the same time improve soil structure and productivity.

What makes an orchard system sustainable?

Fruit trees have been productively grown in the same ground for hundreds of years, demonstrating that orcharding can be a long-term sustainable system. Sustainable systems tend to be highly diverse with many different species of living organisms (flora and fauna). This diversity gives the system resilience and balance both above and below ground and means that the system rebounds quickly from disturbances or even the impact of climatic events such as high rainfall or drought. These living organisms provide both direct and broader services to the productivity and health of the orchard (Table 3).

***Table 3**: Services provided by living organisms in an agricultural system.*

Direct services	Broader services
– Pollination – Biological pest & disease regulation – Weed suppression – Nutrient cycling – Maintenance of soil physical structure & chemical fertility	– Carbon storage – Regulation of soil & water quality – Regulated nutrient & water availability across seasons – Breakdown of wastes and toxins – Maintenance of genetic diversity

Is being sustainable just letting nature take over?

Although relying on nature, sustainable agricultural systems are still highly influenced by human intervention, and for good reason. They are artificially created systems that need our intervention to create the best balance of components to support fruit production. This might be planting the right species to improve soil function, encouraging beneficial organisms and deterring pests and disease, managing the inter-row to reduce frost risk and allow efficient harvest, or applying synthetic inputs more strategically to optimise benefit.

The aim is to enhance the natural ecosystem using multiple tools.

How is it different to other systems?

Conventional (sometimes termed high input) agriculture has a high reliance on synthetic fertilisers and pesticides. Conventional systems tend to be less diverse than balanced agroecosystems and usually have more bare ground. There is a wide spectrum of production systems, both conventional and alternate, with a range of labels given to alternative practices, including *organic*, *low input*, *biological*, and more recently *regenerative*. However not all alternative systems are truly sustainable. For instance, organic production is widely perceived as sustainable, but this is not always the case: e.g., a grower may not be using synthetic pesticides or fertiliser, but they have created a very simple ecosystem with low diversity by repeatedly using a steam weeder or solarisation leaving the soil bare and exposed to damage and loss, thus the system is not sustainable. Regenerative agriculture is based on principles closely aligned to achieving sustainable agriculture, and regenerative practices strive to do more good than harm by actively giving back, renewing, restoring, and achieving net benefit to the system.

The soil environment

The terms quality and health are often used interchangeably in relation to soils. Orchard soil health is related to factors such as physical structure, aggregate size, water retention and infiltration, soil chemistry and nutrient availability, and biodiversity including microbe and invertebrate (arthropod) populations.

According to soil scientist Dr Bill Cotching, the health of a soil can be identified by how the soil performs all its functions. **Management strategies that optimise multiple soil functions have the greatest potential for improving soil health**.

Physical properties

Soil physical properties include soil texture, structure, porosity, water holding capacity and bulk density. As physical properties influence air-water relations in the soil they can have a strong impact on plant growth and microbial activity.

Soil texture refers to the inorganic solid material of the soil mass. There are three separate components that make soil texture: sand (0.02-2mm diameter), silt (0.002-0.02mm), and clay (≤0.002mm).

Soil structure is the result of aggregation of soil particles. Aggregates are naturally formed assemblages of sand, silt, clay, organic matter, root hairs, microorganisms and their mucilaginous secretions, extracellular polysaccharides, and fungal hyphae. Aggregates create the pores necessary for air exchange and water infiltration, which are essential for root growth. Strong stable aggregates resist breaking down and are vital for maintaining good conditions for root growth. When aggregates are unstable, soil pores can clog and the soil surface can crust and become impenetrable. Aggregate stability is affected by soil texture, the type and amount of organic matter present, and the nature and size of the microbial population. For example, the long strands of fungal mycelia bind soil particles together more effectively than smaller organisms such as bacteria.

Soil porosity refers to the space between soil particles, which consists of various amounts of water and air. Porosity depends on both soil texture and structure. For example, a fine soil has smaller but more numerous pores than a coarse soil. Water can be held tighter in small pores than in large ones, so fine soils can hold more water than coarse soils.

Water holding capacity of soil is the ability to hold water against the force of gravity. Available water is the difference between field capacity, which is the maximum amount of water the soil can hold, and wilting point where the plant can no longer extract water from the soil. Soil texture and structure greatly influence water infiltration, permeability, and water-holding capacity. Soils with smaller particles (silt and clay) have a larger surface area than those with larger sand particles, and a large surface area allows a soil to hold more water. In other words, a soil with a high percentage of silt and clay particles, which describes fine soil, has a higher water-holding capacity. Organic matter percentage also influences water-holding capacity.

Soil bulk density provides an indication of soil compaction. It is significantly influenced by soil organic matter, with higher organic matter resulting in lower bulk density. It has been shown to influence nutrient uptake through its effect on physical, chemical and biological properties of soil-plant systems.

Basic soil chemistry

Most growers will be familiar with soil chemistry from annual soil nutrient tests. Chemical elements (nutrients) required for healthy plant growth are divided into non-mineral and mineral. The non-mineral nutrients are carbon (C), hydrogen (H) and oxygen (O) and these are obtained from the atmosphere and water. The mineral nutrients obtained from the soil are divided into macro [nitrogen (N), potassium (K), calcium (Ca), phosphorous (P), magnesium (Mg), and sulphur (S)] and micro [iron (Fe), chlorine (Cl), manganese (Mn), boron (B), zinc (Zn), copper (Cu), molybdenum (Mo), nickel (Ni), and silicon (Si)] nutrients. Macronutrients form the structural components of proteins, cell walls, membranes, nucleotides and chlorophyll, and have roles in energy and water maintenance. Micronutrients are required for the functioning of plant enzyme systems and play important roles in photosynthesis and reactions such as N fixation and protein synthesis.

For uptake by plants, nutrients need to be in an available form. Nutrients are taken up in an ionic, or charged, form, so to become available to plants, nutrients need to be solubilised or released from mineral sources and mineralised from organic sources. Mineralisation occurs when soil microorganisms convert organically bound elements such as N, P, and S into plant available inorganic mineral forms (in the case of N into NH_4^+ and NO_3^-). Nutrients vary in their mobility, both in the plant and in the soil, and this mobility can be influenced by pH, temperature, moisture, and proportion of organic matter, layer silicates and metal hydroxides.

Soil fertility is a measure of the amount of available nutrients and is determined by the combination and volume of microbial populations that digest and transform these minerals to compounds readily available for plant uptake (mineralisation).

Soil biota

The soil biota consists of a diverse array of organisms and can be divided into flora (plants) and fauna (animals).

- Plant roots and macro-algae comprise the macroflora, while soil microflora (< 5µm in size) consist of bacteria, actinomycetes, fungi and algae.
- Soil fauna is classified according to size. Macrofauna is generally defined as being larger than 2 mm (e.g. earthworms, slaters, millipedes, centipedes, beetles, spiders, ants, snails, slugs); mesofauna are 0.1 to 2mm (e.g. springtails, mites), and microfauna less than 0.1 mm in size (protozoa, nematodes).

Soil biota play a key role in cycling of organic nutrients for plant growth and some beneficial soil microbes can compete with disease causing agents, thus reducing the incidence of disease in plants.

Bacteria take part in some of the most important transformations in soils including weathering of rocks and minerals, breakdown of organic matter, and many aspects of nutrient cycling. Fungi are important in stabilising soil aggregates and in the decomposition of organic matter. Arbuscular mycorrhizal fungi form a symbiotic relationship with the roots of most plant species, playing a major role in enhancing soil structure and fostering the microbial community within the mycorrhizosphere, thus increasing nutrient mineralisation, and enabling increased nutrient uptake. Soil microbial biomass has been described as the "eye of the needle" through which all decomposing organic matter must pass before being transformed into plant available nutrients and soil humus (Sparrow, pers. communication); microbial activity has been suggested to mimic slow release fertiliser with minimal leaching of the plant available nutrients into the groundwater.

Earthworms transport and mix organic, mineral, and microbial soil components to deeper soil horizons, and their activities can alter the physical and chemical conditions in the soil, increasing mineral nutrient availability to plants. Other macro- and meso-fauna play a role in nutrient cycling by shredding materials into smaller pieces with higher surface area, thus providing greater access for microorganisms. Several studies have found a positive correlation between soil invertebrate biomass and diversity (particularly mites) and soil health and crop performance, demonstrating that invertebrate biomass and diversity can be used as indicators of soil health.

Microbiological indicators are now recognised as the most sensitive indicators of soil health. Soil microorganisms are incredibly dynamic as their populations respond rapidly to changes in conditions, whether man-made, or environmental such as temperature and rainfall.

There are many tests now available for testing the size, activity and identity of the microbial population in the soil. The Australian Soil CRC is developing practical soil tests specifically to help growers make decisions based on soil health indicators (https://soilcrc.com.au/spotlight-on-emerging-soil-technologies/).

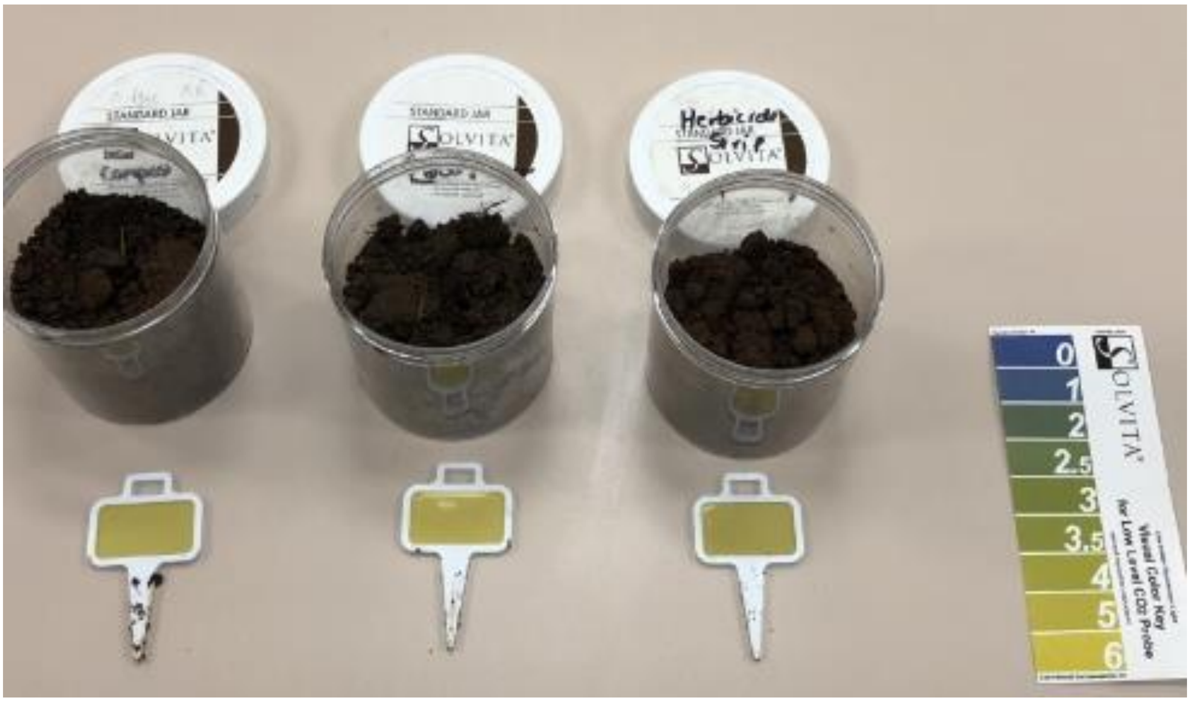


***Figure 2**. Field measurement of microbial respiration (Photo credit: Jessica Fearnley, NSW DPI)*

Soil organic matter

Soil organic matter (SOM) is a heterogenous mixture of plant and animal litter in various stages of decomposition, living microbial biomass and its detritus, and humus which is the final product of decomposition. It is a major source of nutrients such as phosphorus, sulphur and nitrogen and the main food that supplies carbon and energy to soil organisms. SOM has physical, chemical and biological functions (Table 4), and dynamic interactions occur between these three major functions.

***Table 4**. Functions of soil organic matter*

Physical functions	Chemical functions	Biological functions
- bind soil particles together in stable aggregates - influence water holding capacity & aeration - greater porosity - reduced bulk density - improved water infiltration	- major source of cation exchange capacity (CEC) - source of pH buffering - binding site for heavy metals and pesticides	- food source for microbes, meso-and macrofauna - major reservoir of plant nutrients - contributes to resilience of the soil/plant system

The speed of decomposition of SOM is determined by the soil organisms present, the physical environment, and the quality of the organic matter. Different products are released in the decomposition process: carbon dioxide (CO_2), energy, water, plant nutrients and resynthesised organic carbon compounds. The simpler organic molecules such as sugars, amino acids, and cellulose are valuable food sources for many organisms and are readily consumed, hence do not remain in the soil for long.

The importance of plant roots

According to soil scientist Dr Bill Cotching, soil structure is as much about growing roots as the physical structure - actively growing plant roots exert a pressure of 2,000 kilopascals, helping to break up clods and improve structure. Clods indicate a lack of biology and/or root material in the soil.

***Figure 3**. Good soil structure showing roots and macropores (left) and 'dreadlock' roots with adhering soil particles held together by the biotic glue produced by bacteria and fungi (right).*

Root exudates provide a food source for microorganisms, particularly those that form symbiotic relationships such as mycorrhizal fungi and nitrogen fixing bacteria. Protozoa and nematodes that graze on bacteria are also more abundant in the rhizosphere. The rhizosphere is the soil zone immediately surrounding the roots, i.e. the plant-root interface. It is the most dynamic environment in the soil and is directly influenced by root secretions, exudates and associated soil microorganisms. Much of the nutrient cycling and disease suppression needed by plants occurs within the rhizosphere. Rhizosphere microbes also produce polysaccharides that bind soil particles, increasing the stability of soil aggregates.

What we found

The key question for this research was: *How do different orchard floor management practices influence soil health, yield and fruit quality*?

Impact on soil properties and biology

The inter-row treatments revealed very little change in the soil parameters measured, suggesting that any fit for purpose ground cover will provide benefits in the inter-row. Despite the relatively short time frame that treatments were implemented in this project, we did observe some positive differences between treatments in the tree-line compared to the herbicide control plots (Table 5).

Table 5: *Effect of orchard floor treatments on key soil health indicators*

Soil Health Indicator		**Effect of tree-line treatments compared to herbicide plots**
Soil microbiology	Soil microbial carbon	Increased in compost plots
	Bacterial species diversity	Increased in grass/clover plots
	Microbial respiration	Highest in living grass/clover at NSW site
Soil Macro fauna	Earthworm numbers	440% increase in grass/clover plots
Soil Physical Characteristics	Aggregate stability	Trend for improved aggregate stability in all tree-line cover treatments (compost, living grass/clover, mulch) meaning better soil structure
	Soil bulk density	Trend for reduced soil bulk density in all tree-line cover (compost, living grass/clover, mulch) meaning less compaction
	Hydraulic conductivity	Trending for improved hydraulic conductivity in all tree-line cover treatments (compost, living grass/clover, mulch)
	Infiltration rate	Improved infiltration rate in compost plots
Soil Chemistry	pH	Grass clover plots less acidic
	Nitrate nitrogen	3 times higher in compost plots
	Ammonium nitrogen	2.2 times higher in grass/clover plots
	Phosphorus	2.2 times higher in compost plots
	Potassium	over 3 times higher in compost plots

One conclusion we can draw is that keeping the soil bare through regular herbicide application exposes organisms to temperature fluctuations and soil erosion - ground cover in the tree-line is important to protect the soil microbes.

However more time is needed to quantify these changes, as building up good soil health is a gradual process.

Impact on tree growth, crop load and fruit quality

Tree-line treatments had no effect on tree growth, measured as increase in trunk circumference, blossom density or crop load.

There were small differences in fruit soluble solids and dry matter content, although these differences were not consistent across the two seasons. Fruit firmness was higher in the grass/clover plots compared with the herbicide plots in both seasons. Fruit from the grass/clover plots showed slightly more redness than the other plots, while fruit from the compost plots had the least redness. Starch pattern index (SPI) showed a slower rate of conversion of starch to sugar in the grass/clover plots across both seasons.

There was no difference in mean fruit weight between the tree-line treatments in 2022, but in the 2023 season fruit in the grass/clover tree-line plots was 11g lighter on average than in the herbicide plots. One explanation for this difference is that the grass in this season was well established and growing vigorously and hence was competing with the trees for water and nutrients – potentially if these plots had been mown regularly there may have been no effect. This is worth exploring in future studies.

A visual difference was observed in autumn 2023 between mulched treatment rows and non-treatment rows where the tree-line had become overgrown. Trees in the mulched plots retained their leaves longer than those in the overgrown non-treatment rows (Figure 4). Later leaf fall has also been observed in trees planted on fertile soils such as river flats, so this suggests improved nutrient availability in the mulched treatment plots.

Figure 4*. Delayed leaf fall in third leaf trees in mulched plots (left) compared with overgrown tree-line (right).*

Competition

Many orchardists are concerned about competition for water and nutrients from ground cover plants on the orchard floor, particularly in the tree-line, reducing yield and fruit quality. However, the results from both the intensive research site and the regional demonstration sites suggest that the impact of living mulches in the tree-line is not necessarily detrimental to fruit quality. Further studies examining tree-line living mulch mixes and their vigour will alleviate this concern. Another option is the use of summer dormant species, however in an irrigated orchard these species do not always become dormant.

There is also concern that a vegetated tree-line provides habitat for pest species and tall vegetation growing up into the lower branches of the trees can create a humid microclimate, thus increasing disease pressure. Managing the tree-line vegetation by mowing, or even an occasional herbicide application, can ameliorate these problems.

Managing pests

The research sites were monitored as part of a collaboration with project AP19002 S*trengthening cultural and biological management of pests and diseases in apple & pear orchards*. Several lessons arose from this collaboration in relation to management of pests within the orchard and the benefits of groundcovers:

- arthropod species change with orchard floor plant species, so arthropod abundance and diversity can be manipulated by altering ground cover composition;
- within the tree line predators such as earwigs in tree canopies and spiders on the orchard floor were encouraged by living mulches;
- movement of beneficial fauna from the inter-row towards the vegetated (living mulch) tree-lines was observed, providing potential to have a greater impact on economically important pest species;
- non-pest ground dwelling mite populations increased in the tree-line where compost was applied;
- costs and benefits for pest management can be quantified but may be site specific;
- pesticide applications can undo any improvements in numbers of beneficial insects;
- the treatments applied within this project did not trigger any changes in fruit damage.

Conclusions from this study in relation to pest management include:

- use of groundcovers in the inter-row and tree-line can potentially aid in suppressing ground dwelling pest species (i.e., LBAM during winter) and canopy borne pests such as woolly apple aphid during the production season;
- promoting biodiversity of orchard natural enemies can be achieved through adoption of inter-row vegetation management practices such as adapting mowing schedules or use of no-mow flowering strips;
- application of compost or mulch within the tree-line is recommended to provide harbour for ground-dwelling predators and detritivores.

Improving the orchard floor

The way that the orchard floor is managed has a strong influence on soil structure and functions such as nutrient availability, water holding capacity and microbial presence and diversity. Practices such as reducing herbicide use and adding organic matter to the soil will assist in increasing soil life. Non-living organic materials such as compost, and/or mulches such as straw or mower clippings can contribute to orchard soil health. However, living mulches such as grass/clover swards with actively growing plants is critical to healthy microbial communities that support nutrient cycling.

For a truly sustainable orchard we need to put in place practices that enable a return to complex systems with strong food webs and beneficial trophic interactions. The starting point is to increase biodiversity within the orchard, and simple methods for achieving this include:

- ☑ increasing soil organic matter
- ☑ incorporation of compost into soil prior to planting new blocks
- ☑ diversifying orchard floor vegetation for a range of root architectures
- ☑ minimising herbicide use
- ☑ use of cover crops / living mulches
- ☑ applying organic mulches in the tree row
- ☑ mow and blow (throw) inter-row vegetation into the tree row
- ☑ reducing frequency of mowing
- ☑ planting of flowering hedgerows around the orchard and/or between blocks
- ☑ planting of multiple tree species
- ☑ use of biocontrol strategies for pest control rather than pesticides

Selecting species for the orchard floor

The plants growing on the orchard floor have a large influence on what happens both in the soil and above ground - ideally there should be a mix of species with a range of root architecture and each species should fulfil a range of functions. Deep-rooted species will bring leached nutrients to the surface and assist with breaking up compaction layers. Above ground, the plants of the orchard floor provide a home and/or a food source for pollinators, predators and other beneficial insects.

Figure 5*. Different orchard inter-row plantings.*

Plant species selected need to be robust and resilient to traffic, but not invasive and competitive, and provide shelter without creating a negative environment for pest and disease. A myriad of invertebrates (insects, millipedes, spiders, and earth worms) and microbes live at the soil boundary and below, and these organisms are strongly influenced by the plant species on the orchard floor. They are an essential part of the cycling system for leaf litter and prunings that contribute to soil and tree health. These in turn are influenced by other orchard management practices including irrigation and nutrient applications.

As root exudates from actively growing plants provide a food source for soil microbes, the abundance and diversity of the soil microbial community is likely to be increased by ensuring full ground cover with a range of plant species. There is normally a decline in carbon availability with increasing soil depth, and this has been attributed to the vertical soil distribution of microbial communities. The dominant factor influencing microbial biomass and activity at different depths appears to be plant root distribution, with the presence of deeper rooting species resulting in higher microbial populations and diversity deeper in the soil profile.

Any ground cover, even weeds, as a living mulch is preferable to bare soil, but the more diverse the plant species on the orchard floor, the greater the diversity of root architecture (fibrous, spreading and tap roots). There is evidence that the more diverse the plant species, the greater the diversity in soil organisms.

A useful tool developed for vineyards can be found here: https://www.covercropfinder.com.au/tool.php?id=1

A living mulch dominated by perennials is logical in an orchard situation, as it enables the inter-row sward to be maintained without the need for reseeding each year. Use of annual species requires either reseeding every season, adding to the costs of maintaining the orchard floor, or allowing the annuals to flower and seed. Although one benefit of this will be reducing mowing costs, it will require a change in mind set and acceptance of an 'untidy' orchard.

There are multiple criteria to be considered when selecting species for planting in the orchard inter-row and/or tree-line, and these are listed in Table 6.

Table 6*: Considerations when selecting plant species for living mulches in the orchard.*

Inter-row	Tree-line
- easy and fast to implement	- easy and fast to implement
- rapid establishment of sward	- established rapidly
- ease of maintenance after establishment	- longevity and maintenance
- longevity	- productive organic matter source
- range of root architecture	- food source/habitat for beneficial insects/mites
- traffic resilience and provide sufficient grip for tractors/equipment	- avoid tall growth habits that can reduce air flow and promote disease unless willing to manage
- aids in reducing soil compaction	- improved soil structure & water infiltration
- improves water infiltration	- improved water retention
- nutrient recycling	- nutrient recycling and availability
- habitat for beneficial insects and mites	- increased soil biology
- floral diversity to provide food sources for a diverse range of natural enemies / pollinators	- maintain/improve fruit quality
	- sustainability

Pros and cons of different orchard floor management options

Any management option applied to the orchard floor will have both positive and negative impacts, so the question to ask when deciding on options for managing the orchard floor is:

> Do the benefits outweigh any negative impacts?

The experience and results from the research trials and regional demonstration sites are summarised in Table 7.

Table 7: *Pros and cons of different orchard floor management options*

Orchard floor treatment	Pros	Cons
Bare earth Strip	- Easy to maintain	- Does not contribute to soil health - Herbicide can be a health risk to workers - Expense of regular application of herbicide – labour and chemical costs - Potential for erosion of bare soil
Native plants	- Encourage native fauna - Can be drought resilient	- Difficult to establish - Less competitive particularly if a large weed seed bank is present - Slow growth rate - Can be expensive
Living Mulches	- Contribute to soil health - May encourage beneficial insects, mites and pollinators - Establishment easiest in Autumn	- Mowing of vigorous species can be costly - Tall species can create easy access into the tree canopy for pests and/or encourage disease by creating a more humid environment - Can pose a significant risk of damage to the orchard from bushfires
Non-Living Compost/Mulch/ Mow & Throw	- Add organic matter and contribute to soil carbon - Suppress weeds if applied thickly with good coverage - Use locally sourced with low transport costs to reduce cost or grow your own (mow & throw)	- Fine compost breaks down quickly and acts as a seed bed for weeds - High cost of regular replacement of imported materials - Can potentially act as a wick in bushfires

Monitoring your orchard soil health

There are many simple ways of keeping track of the condition of your soil, from commercially available soil test kits to simple tests using everyday equipment. Although depending on what you find it may still be useful to send some samples to a commercial laboratory for a full analysis.

Indicators of good soil health

Healthy soil attributes to work towards include:

- ☑ good levels of organic matter;
- ☑ abundant populations of earthworms (10-12 per spadeful), macro- and meso-arthropods;
- ☑ thriving populations of micro-organisms - bacteria, fungi, protozoa, and nematodes;
- ☑ nutrient cycling to provide plant available nutrients;
- ☑ 100% ground cover with a diverse mix of species;
- ☑ small & large pore spaces for air & water;
- ☑ good soil aggregation;
- ☑ good water infiltration rates (>100 mm/hr);
- ☑ absence of a compaction or crusting layer.

Change for the better

With soil health indicators, it is important to recognise that there is a difference between changed and improved soil properties due to a treatment. Soil health testing is not so much about absolute values but showing how a soil is responding to change, whether that change is time or a new management practice. So, watch for changes over time but make sure you are consistent in the time of year you take a sample, the way you take a soil sample, and the lab you use if you are sending samples for laboratory analysis.

Remember that if you change the way you manage your orchard floor, results won't be seen immediately – so to know whether the change was beneficial you need to monitor what is happening over time.

Principles for assessing your soil health

Assessing your own soil health can be a simple process - there are multiple tests that you can do yourself, or you can send samples to a commercial laboratory.

Determine what you want to monitor for change over time and stick to the following:

1. Monitor at the same time each year from the same place (GPS on your phone or a flag in the ground);
2. Use the same laboratory for analysis each season;
3. Take several samples from across the orchard block;
4. Record your results and compare to results from previous seasons;
5. Collect and store a sample of soil in an icecream container each year for a physical comparison of your soil condition across seasons.

A simple toolkit for measuring orchard soil health

Essentials

- Record sheet
- Phone or camera
- Spade
- Large plastic sheet or tray
- Clean ziplock bags for collecting soil for laboratory analysis
- Clean ice cream container with lid for storing soil
- Cotton undies or calico strips

More specialised (see Table 8 for further details)

- Infiltration rate: PVC pipe (30 mm diameter X 150 mm long) marked at 100 mm and 125 mm
stopwatch or your phone with timer
plastic cling wrap
mallet and block of wood
ruler
- Compaction: soil penetrometer, or
a 4-6 mm steel rod, or
length of heavy fencing wire (3 mm diameter and approx. 50 cm long)
- Aggregate stability: baking tray,
bottle of distilled or rain water,
shallow glass or dish
- Soil Biology: Solvita respiration kit & screw top glass jar

***Figure 6**: Measuring soil health parameters in the orchard.*

Table 8: Monitoring and interpreting soil health measures

Soil Health Indicator	How to measure	Interpreting the results
Soil Organic Matter (SOM)	Laboratory soil test.	Local agronomist or Industry Development Officer. Compare to a typical soil in your region: https://www.applesoils.com/ Monitor changes from season to season.
Nutrient levels	Laboratory soil test of major nutrients, micronutrients, pH and EC.	Local agronomist or Industry Development Officer. Compare to a typical soil in your region: https://www.applesoils.com/ Monitor changes from season to season.
Earthworms and other soil arthropods	The best time to count earthworm populations is early in the spring, or after the soil has wetted up in the autumn. Count earthworms when it is warm and after rain to provide the best population estimates. Avoid taking samples when the soil is very dry. Soil should have been wet for a few days prior to sampling. Dig a soil pit of around 20 cm (spade width) deep and wide onto a mat. Sort what you find in your soil into juvenile and adult earthworms; other arthropods. Record the numbers.	Typically, 10-12 per spade full is considered a healthy population. Monitor numbers from different parts of your orchard over several seasons. More information: How to count earthworms (pdf 321 KB).
Soil Structure	**Visual soil assessment (VSA)** Watch this YouTube video on visual soil assessment from NSW DPI https://www.youtube.com/watch?v=Rv2BYMjnW-g Use a score card such as the FAO VSA Field Guide for orchards https://www.fao.org/3/i0007e/i0007e03.pdf	**Visual soil assessment:** The FAO guide will help you interpret soil texture, soil structure, soil porosity, soil colour (mottles) earthworms, rooting depth, crusting, ponding and erosion.
	Collect and store Collect an intact sample of orchard soil with your spade and store in an ice cream container until next season.	**Collect and store** Compare soil collected each season to visually see if the structure is changing.

Soil Health Indicator	How to measure	Interpreting the results
Soil Aggregate stability	Collect a few handfuls of soil from the orchard, usually from the top 10 cm. Allow the soil to air dry completely – usually takes around 3 days. Place three pea sized aggregates (4 – 6 mm diameter) into 20 – 40 mm of rain or distilled water. Watch carefully for the first few minutes, then observe in an hour and again in 24 hours.	How much the soil 'disperses' and makes the water cloudy will indicate how stable your soil aggregates are. Watch a video: https://www.youtube.com/watch?v=xuXFQDzXNQU Read more here: https://vro.agriculture.vic.gov.au/dpi/vro/vrosite.nsf/pages/soilhealth_bonding_aggregation_qrg
Soil compaction / soil 'strength'	A penetrometer is tool for measuring soil compaction. Simple tools for measuring soil compaction include your spade, a steel rod (8-10 mm diameter) or heavy gauge fencing wire (3 mm) about 50 cm long. A laboratory test of soil bulk density usually carried out for research purposes.	Visually observe the soil in the pit you have dug. Examine the rooting pattern. Take a photo. This will be a reference point as to whether soil compaction is restricting root growth. Using a tool: The readings from a penetrometer can be compared from year to year. Readings greater than 1.5 MPa indicate root growth is restricted. How much force do you need to push a spade, steel rod or wire into the soil? Do you reach a point where it is hard to push through? Is it easier to push in once you have passed this point (compaction layer) or does it get progressively harder (increasing compaction with depth)? *Compare your results with a spot in the orchard where compaction is not a problem – such as under a hedgerow or fence line.*
Water Infiltration	A PVC pipe is hammered into soil to a depth of 100 mm. The pipe is then gently filled to 25 mm depth. The time it takes for the water to soak into the soil will be a measure of the soils water infiltration rate.	Read more here: https://www.hort360.com.au/wordpress/wp-content/uploads/2020/11/Measuring-Soil-Water-Infiltration.pdf Watch a video: https://www.youtube.com/watch?v=awvoKMQCSbY https://www.youtube.com/watch?v=xuXFQDzXNQU

Soil Health Indicator	How to measure	Interpreting the results
Soil Biology	Calico strips or cotton undies are buried for 6 – 8 weeks (see below for a description of the method). Respiration test using a commercial kit for example from Solvita: https://solvita.com/	Visual comparisons of undies or calico strips: 1. Compare results from different orchard blocks. Faster or more breakdown means a more active fungal population in your soil; 2. Take photos each year and compare results. Compare respiration results from different orchard blocks and each season.
Ground Cover	Take photos of ground cover in both tree-line and interrow. Easiest if you use a set measure of the area you photograph such as a square frame (quadrat).	Visual comparison of species and ground cover present.

Cotton degradation test of soil microbial activity

Bury calico strips (or cotton undies) for 6-8 weeks to provide an indication of microbial activity – predominantly fungal as they feed on cellulose (Figures 7&8).

Make sure that you mark the burial site!

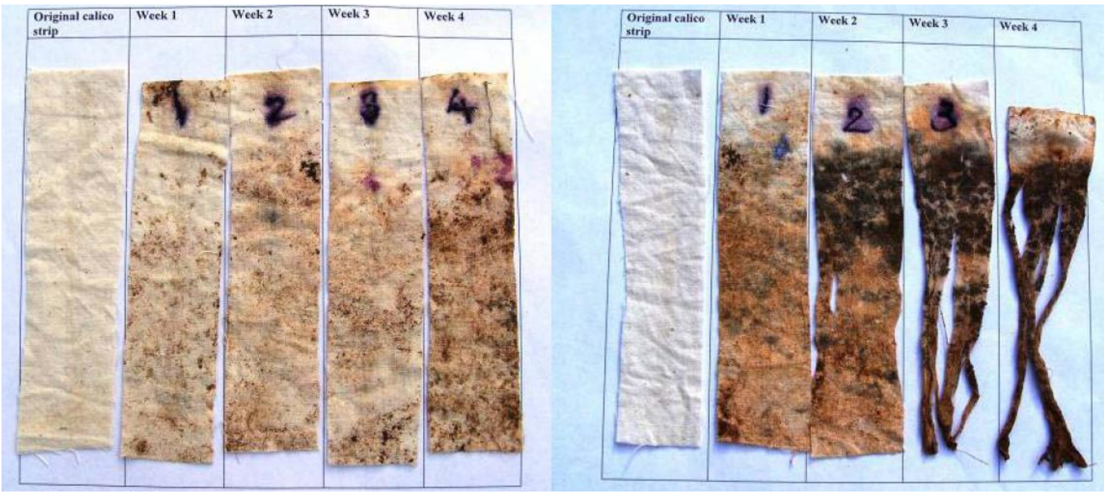


Figure 7: *Calico strips showing low biological activity (left and high biological activity (right).*

Figure 8: *Cotton undies for checking soil biological activity. Note lack of degradation of synthetic elastic and thread in photo on right.*

Other resources to help you monitor orchard soil health

Sampling your soil for laboratory testing (Washington State University)
https://treefruit.wsu.edu/soil-sampling-for-tree-fruit-orchards/

5 Soil testing techniques every farmer should know (AHDB – Soil Association UK):
https://www.youtube.com/watch?v=TMXghhKStvE

A spade is your best friend!

One of the most valuable tools to see what is happening in your soil is a spade!

Dig a hole so you can see the subsoil

- Moss on the surface is a sign that soil is not very active.
- Do plant roots penetrate through to the subsoil?
- Are old inactive roots decomposing (evidence of bacteria and fungi)?
- Does the soil smell earthy (actinomycetes- soil bacteria that decompose organic matter)?
- Is the soil dark in colour (soil organic carbon)?
  - Grey and yellow soil colour indicate anaerobic soils.
- Smell - hydrogen sulphide is an indication of lack of air (anaerobic conditions).
- Is the soil well structured (soil aggregation)? – test by putting aggregates in water, if they hold together the soil structure is stable.

Look for evidence of organisms

- Bury calico strips (or cotton undies) – the rate of decomposition gives an indication of fungal activity as fungi break down the cellulose in the cotton. Wooden stakes can also be used.
- Set pitfall traps for macrofauna (2-20 mm size including woodlice, earthworms, beetles, beetle larvae, centipedes, millipedes, slugs, snails, ants, and harvestmen) & mesofauna (0.1 to 2 mm size including nematodes, mites, springtails, earthworms, small spiders, pseudoscorpions).
- Look for tunnels and faecal piles (bioturbation) - indicates presence of earthworms and/or beetles.
- Count earthworms – 10-12 per spadeful is good!
- Examine nodules on clovers and other legumes - a bright pink/red internal colour indicates active nitrogen fixing bacteria.

Appendix 1 – Living mulch species

***Table A1.1**: Species in each mix and planting rates in Tasmanian trial sites.*

	Common name	Rate
Ryegrass/clover sward		
Victorian ryegrass }		8 kg/ha
Kingston ryegrass } Huon #2 mix from		12 kg/ha
USA red clover } Nutrien Ag		5 kg/ha
USA white clover }		2 kg/ha
'Apex' white clover		1 kg/ha
Clover/grass mix		
Festuca rubra	Creeping red fescue	5 kg/ha
Festuca ovina	Sheeps fescue	5 kg/ha
Festuca rubra ssp Commutata	Chewings fescue	5 kg/ha
Dactylis glomerata cv. Summadorm	Cocksfoot	5 kg/ha
Trifolium fragiferum cv. Palestine	Strawberry clover	3 kg/ha
Trifolium repens cv. Apex	White clover	3 kg/ha
Flowering meadow mix		
Phacelia tanacetifolia	Lacy phacelia / Blue tansy	4 kg/ka
Fagopyrum esculentum	Buckwheat	5 kg/ka
Coriandrum sativum cv. Santo	Coriander	3 kg/ka
Plantago lanceolata cv. Tonic	Plantain	4 kg/ka
Trifolium michelianum	Balansa clover	2 kg/ka
Brassica sp.	BQ mix	2 kg/ka
Raphinus sativus acanthiformis	Daikon radish	3 kg/ka
Cichorium intybus cv. Commander	Chicory	2 kg/ka
Native flowering mix		
Microleana stipoide	Weeping grass	2 kg/ha
Viola hederacea	Native violet	0.5 /m
Einardia nutans	Climbing saltbush	0.3 /m
Geranium solanderia	Native geranium	0.3 /m
Goodenia elongata	Lanky goodenia	0.3 /m
Arthropodium milleflorum	Vanilla lily	0.3 /m
Calocephalus lacteus	Milky beauty-head	0.3 /m

***Table A1.2**. NSW regional site flowering meadow mix.*

Bee Friendly Mix	Beneficial Insect Mix
Blanketflower (*Gaillardia pulchella*)	Blanket Flower (*Gaillardia aristata)*
Blue Flax (*Linum perenne*)	California Poppy (*Eschscholzia californica*)
Blue-thimble-flower (*Gilia capitate*)	Candytuft (*Iberis umbalatta*)
California Poppy (*Eschscholzia californica*)	Common Dill (*Anethum graveolens*)
China aster (*Callistephus chinensis*)	Coriander *(Coreopsis sativum*)
Chinese hound's tongue (*Cynoglossum amabile*)	Dense Blazing star *(Liatris spicata)*
Common Poppy (*Papaver Rhoeas*)	Garden/Dwarf Cosmos *(Cosmos bipinnatus)*
Garden Tickseed (*Coreopsis tinctoria*)	Mayfield Giants (*Coreopsis lanceolate)*
Korean Mint (*Agastache rugose*)	Menzies' baby blue eyes (*Nemophila menziesii*)
Lance-leaved coreopsis (*Coreopsis lanceolate*)	Queen Anne's Lace *(Ammi majus)*
Menzies' baby blue eyes (*Nemophila menziesii*)	Rock Cress (*Aubrieta hybrid)*
Moroccan Toadflax (*Linaria maroccana*)	Shasta Daisy (*Chrysanthemum maximum)*
Purple coneflower (*Echinacea purpurea*)	Sweet alyssum *(Alyssum benthamii)*
Sweet alyssum (*Lobularia maritima*)	Wallflower *(Cheirianthus Chieri)*
Tidy tips (*Layia platyglossa*)	Wild bergamot (*Monarda fistulosa*)
Wallflower (*Cheiranthus allionii*)	
Wild bergamot (*Monarda fistulosa*)	

Table A1.3. *NSW regional site native herbaceous mix, sourced from* Native Seeds Australia*.*

Common name	Species name
Burra Weeping grass	*Microlaena Stipoides var. Burra*
Common Tussock grass	*Poa labillardieri*
Curly Mitchell grass	*Astrebla lappacea*
Evans Wallaby grass	*Rytidosperma caespitosa*
Griffin Weeping grass	*Microlaena Stipoides var. Griffin*
Kangaroo grass	*Themeda triandra*
Native Wheat grass	*Anthosachne scabra*
Oxley Wallaby grass	*Rytidosperma bigeniculata*
Purple Wire Grass	*Aristida personata*
Scent Top grass	*Capillipedium spicigerum*
Silky Bluegrass	*Dichanthium sericeum*
Silky top Lemon Scented grass	*Cymbopogon obtectus*

Table A1.4. *SA regional site flowering meadow mix.*

Common name	Species name
Sweet alyssum	*Alyssum benthamii*
Queen Anne's Lace	*Ammi majus*
Common Dill	*Anethum graveolens*
Rock Cress	*Aubrieta hybrida*
Wallflower	*Cheirianthus chieri*
Shasta Daisy	*Chrysanthemum maximum*
Mayfield Giants	*Coreopsis lanceolate*
Coriander	*Coreopsis sativum*
Garden/Dwarf Cosmos	*Cosmos bipinnatus*
California Poppy	*Eschscholzia*
Blanket Flower	*Gaillardia aristate*
Candytuft	*Iberis umbalatta*
Dense Blazing Star	*Liatris spicata*
Wild Bergamot	*Monarda fistulosa*
Menzies' Baby Blue Eyes	*Nemophila menziesii*

Table A1.5. *SA regional site native species mix.*

Common name	Species name
Kneed wallaby grass	*Rytidosperma geniculatum*
Wallaby grass	*Rytidosperma caespitosum*
Weeping grass	*Microlaena stipoides*
Windmill grass	*Chloris truncata*
Red-leg grass	*Bothriochloa macra*
Woolly New Holland daisy	*Vittadinia Gracilis*
Lemon Beauty Heads	*Calocephalus citreus*
Yellow buttons	*Chrysocephalum apiculatum*

Table A1.6. *WA regional site flowering meadow mix.*

Phacelia scorpion weed
Coriander
Marigold
Equine mix sourced from Bells Pasture Seeds and sown at 12kg/600m^2 consisting of:
- Ryecorn cereal
- Everlast ryegrass
- Fescue
- Cocksfoot
- Balansa clover
- Arrowleaf crimson clover
- Cadiz serradella
- Chicory
- Phalaris

Table A1.7. *WA regional site native species mix.*

Common name	Species name
Wallaby grass	*Austrodanthonia caespitosa*
Weeping grass	*Microlaena stipoides*
Spear grass	*Austrostipa sp*
Running postman	*Kennedia prostrata*
Pink everlastings	*Rhodanthe chlorocephala*
Fan flower	*Scaevola crassifolia*
Slender Lobelia	*Lobelia tenuior*
Native Bluebell Creeper	*Billardiara fusiformis*