Improving Soil Health to Suppress Soil Borne Diseases of Ginger

by Tony Pattison, Jenny Cobon, Zane Nicholls, Rob Abbas and Mike Smith
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Australia’s rural industries make a fundamental contribution to the Australian economy and way of life. In addition to the major industries, numerous new and smaller established rural industries bring opportunity, diversity and resilience to rural Australia. The Rural Industries Research and Development Corporation invests in these industries on behalf of government and stakeholders. These industries provide opportunities to be captured by rural producers and investors. They also contribute to community resilience, regional development and provide a distinctive regional character in rural Australia.

Industries, such as the ginger industry, face a number of challenges including threats posed by the three major soil borne diseases, Pythium Soft Rot, Fusarium Yellows and root-knot nematodes. Providing solutions to losses caused by these diseases is underpinned by directed research and development facilitated by RIRDC.

The importance of this report is that it provides the results from studies that have identified the soil health indicators that relate to disease suppression and has identified practices to improve soil health in a ginger farming system. Ultimately the goal of this research is to reduce production losses, improve product quality and provide more sustainable and profitable production practices for the Australian ginger industry.

This project was funded by ginger industry revenue which is matched by the Australian Government with support also provided by the Queensland Department of Agriculture and Fisheries.

This report, an addition to RIRDC’s diverse range of over 2000 research publications, forms part of our New Plant Products R&D program, which aims to facilitate the development of rural industries based on plants or plant products that have commercial potential for Australia.

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John Harvey
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Dr Tony Pattison is a Principal Nematologist with the Queensland Department of Agriculture and Fisheries (DAF) and has 22 years of experience in tropical horticulture production, focusing on the suppression of plant-parasitic nematodes and Fusarium wilt of bananas. He developed and leads the soil health framework within DAF which is currently being used in the banana and vegetable industries to help manage soil borne diseases.

Jenny Cobon is a Senior Experimentalist with DAF with 23 years of experience working with plant-parasitic nematodes of economic importance in horticultural crops. The focus of her work includes the suppression of these nematodes by improving soil health.

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Dr Mike Smith is a Senior Principal Scientist with DAF. He has led research into ginger farming systems and control of ginger pests and diseases since 1991.

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Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>DA</td>
<td>Discriminant Analysis</td>
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<tr>
<td>FDA</td>
<td>Fluorescein diacetate</td>
</tr>
<tr>
<td>Foz</td>
<td>Fusarium oxysporum f.sp. zingiberi</td>
</tr>
<tr>
<td>DAF</td>
<td>Queensland Department of Agriculture and Fisheries</td>
</tr>
<tr>
<td>RKN</td>
<td>Root-knot nematode</td>
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<tr>
<td>PSR</td>
<td>Pythium Soft Rot</td>
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</table>
Executive Summary

What the report is about

Declining soil fertility and biological soil health represent a major threat to sustainable agricultural development in Australia. To remain competitive, ginger growers have intensified crop production to supply growing markets, but have typically failed to replenish organic matter adequately. They have consequently experienced falling yields and increasing problems with soil borne diseases and nematodes that are symptomatic of declining soil health.

When this project commenced in 2013, ginger processors were not receiving an adequate supply of fresh ginger with approximately $2m lost at the farm gate due to Pythium Soft Rot (PSR) caused by Pythium myriotylum. The disease was not only a threat to individual growers, but also to processors that add value to the crop. Damage to the rhizome caused by root-knot nematodes (RKN), Meloidogyne javanica and M. incognita, as well as losses to Fusarium oxysporum f.sp. zingiberi (Foz) contribute to further declines in yield and profitability.

Current soil management recommendations for increased pathogen suppressiveness are mainly based on increasing organic inputs to the soil, reducing disturbances such as tillage, and diversifying crop rotation. To successfully enhance soil suppressiveness, it is necessary to understand how particular farming practices will influence key components of biodiversity and the soil ecosystem. The specific aims of the research were to find the indicators that related to ginger soil health and determine if the soil health indicators could be validated with suppression of the soil borne diseases of ginger. This research is important as it identifies practices to improve soil health in a ginger farming system which are designed to reduce losses and increase production of ginger following successful control of Pythium Soft Rot and other soil borne diseases such as Fusarium Yellows and root-knot nematodes.

Who is the report targeted at?

This report is targeted at commercial growers and agronomists involved in the Australian ginger industry.

Where are the relevant industries located in Australia?

Ginger production in Australia is based primarily in South East Queensland with farms stretching from Gatton to Bundaberg comprised of producers who supply both the fresh and processing markets.

The Australian ginger industry is valued at $34m per annum at the farm gate with a further $80m per annum added as first-order processing. The Australian processing sector is supplied with 40% of the 9000 tonnes harvested each year while the remainder is supplied to fresh markets mainly in the capital cities. There are approximately 45 growers with two major producers with over 50 ha under production, 7 medium size growers with around 5 ha and the remainder being small producers with less than 1 ha under production. It is estimated the industry employs 200 full time farmhands with approximately 385 casual staff helping out during peak harvesting periods.
Background

Previous RIRDC funded research (PRJ-005612; PRJ-008343) into the control of Pythium Soft Rot in ginger has indicated that some of the critical measures to limit losses are through the use of organic amendments and cultural practices that are thought to improve soil health. In other words, practices that stimulate the build-up of beneficial microorganisms that can suppress ginger pathogens, as well as improve soil structure and fertility, are needed and this project assessed a range of soil health indicators that were linked to disease suppression and improved ginger growth. This project analysed soils that were selected by the grower as ‘good blocks’ that were healthy and productive, as well as ‘poor blocks’ that had a history of crop losses due to disease. Glasshouse trials were established under controlled conditions to validate some of the practices associated with disease suppression by amending soils and challenging the established ginger with various combinations of soil borne pathogens.

Aims/objectives

The ultimate goal of these experiments was to understand how soil health can be improved to suppress soil borne diseases and lead to the development of more productive and sustainable ginger farming systems.

Methods used

Ginger fields in South East Queensland were sampled over three production seasons. Ginger producers were asked to nominate ‘good’ and ‘poor’ ginger producing fields, based on their observations and cropping history. A total of 51 ginger fields were sampled over the three years.

Soil samples from the top 0-25 cm soil profile were collected at different points within each ginger field. The samples were processed for physical, chemical and biological soil characteristics. A soil health score was determined based on eight key indicators from a stepwise discriminant analysis, with the addition of clay as an inherent indicator of soil conditions. The soil health score could signify if a soil would be ‘good’ or ‘poor’ for ginger production and was correlated with both the growth of ginger and the suppression of soil borne diseases.

Glasshouse experiments were established to validate whether the soil health score had an influence on plant growth and disease suppression. One experiment investigated differences in disease development in five selected ginger soils collected during the farm surveys. The soils were selected from sites having differences in soil health properties and representing distinct groups determined from the farm survey. Half of each soil was pasteurised by free-steaming at 90°C for 30 minutes before ginger seed pieces were planted into 150mm pots. After three weeks half of the pots had shoots, and were inoculated with the different pathogens, *Pythium myriotylum*, *Fusarium oxysporum* f.sp. *zingiberi* and *Meloidogyne javanica* plus uninoculated controls. Plants were monitored for disease symptoms and growth parameters over a growth period of 52 days. Soils from all pots were analysed for biochemical and soil nematode community analyses and a standard soil nutrients analysis was determined from bulked soil samples allowing the calculation of the soil health score determined from the farm survey.

A further two glasshouse experiments were used to determine the impact of management practices on soil properties and subsequently the soil health score. The first experiment was undertaken to determine if soil amendments; green waste woodchips, molasses and a microbial product could alter
soil biological characteristics and favour suppression of soil borne diseases that cause problems in ginger production. A clay-loam soil (45% sand, 22% silt and 33% clay), with moderate organic C (1.3%) and acid soil pH 5.4, which had not previously been used in ginger production was used in the experiment. The soil remained untreated (control), or had green waste woodchips incorporated at a rate equivalent to 400 m³/ha, or had molasses applied at a two weekly rate of 20 L/ha or a microbial product applied at 80 L/ha applied 6-weekly, or combinations of two of the treatments and one treatment with all three treatments combined, resulting in a total of eight treatments. Two months after planting, the ginger pots were inoculated with the three soil borne pathogens *Pythium myriotylum* 2 mL of colonised grain/pot, *Foz* 5 mL of colonised grain/pot and 10 000 *M. javanica* eggs/pot and compared to uninoculated soil. All treatments were replicated four times and randomised. External disease symptoms and plant heights were assessed weekly and isolations were performed from plants with disease symptoms to identify the pathogen responsible. The experiment was terminated two months after inoculation and the plants destructively harvested. The soil was characterised for changes in physical, chemical and biological properties.

The final glasshouse experiment investigated the use of woodchip, urea and lime individually or as a combined treatment compared to untreated soil. The five treatments were untreated, wood chip (14 mm at 400 m³/ha), lime (2.5 t/ha), urea (50 kg/ha), and a combination (urea, woodchip and lime). The treated soil was inoculated with five pathogen treatments, either untreated, *Pythium myriotylum*, *Foz*, RKN and combination of the three pathogens (*Pythium, Foz, RKN*) and replicated four times. The experiment was terminated after two months as previously described and the assessments done on soil and plants.

**Results/key findings**

The soil health scores were calculated for the 51 fields over the three growing seasons and the fields nominated as ‘good’ for ginger production tended to have a higher score than those nominated as ‘poor’, but with some overlap. The soil indicators were assigned functions, such as inherent soil properties (clay), nutrient availability (P and K), diseases suppression (abundance of plant-parasitic nematodes such as RKN and *Pratylenchus* species), organic matter (β-glucosidase and organic C), soil disturbance enrichment index and bacterivore nematode abundance.

The validation of soil health scores was conducted in a glasshouse experiment where three soils were classified as being ‘good’ for ginger production and two soils as ‘poor’. There was a significant difference in the growth of ginger in the different soils with one of the ‘good’ soils having a significantly higher stem height, stem number and stem index relative to the two soils classified as ‘poor’ for ginger production. The other two ‘good’ soils gave intermediate ginger growth. There was a significant negative relationship with increasing soil health score and decreasing disease rating, which indicated that as the soil health improved, disease incidence decreased.

The soil health score for the ginger grown with the different management treatments tended to increase with increasing number of management practices imposed. In the first glasshouse experiment, the lowest score was recorded in the untreated soil with no management and the highest soil health score was recorded in the green waste, microbial product and molasses treatment. A second glasshouse experiment used urea, lime and woodchip alone or in combination, to determine impacts on plant growth, soil borne diseases and soil health score. There was a significant difference in the ginger rhizome weight at the end of the experiment, with untreated soil having the lowest rhizome weight, which was significantly less than when a combination of woodchip, urea and lime were added to the soil.
Using the untreated soil as a reference, lime was found to decrease disease suppression, resulting in the lower overall soil health score. Additionally, urea decreased disease suppression through more plant-parasitic nematodes and also increased soil disturbance resulting in a lower score. Conversely, the combination treatment, which had the urea, lime and woodchip, increased the disease suppression score by reducing numbers of plant-parasitic nematodes. The combination of green waste, microbial inoculant and molasses, which had the highest soil health score relative to the untreated soil, had improved scores for soil disturbance, disease suppression and organic matter.

**Implications for relevant stakeholders**

Selection of soil health indicators and development of a Soil Health Score could discriminate between ‘good’ and ‘poor’, but had seasonal variations and high error when averaged across the growing seasons. The classification of fields as ‘good’ or ‘poor’ was based on the growers experience and knowledge and, therefore, had errors associated with it as it was a subjective question. Soil type variability of inherent soil properties contributed to some misclassification of sites as ‘good’ or ‘poor’ when developing the Soil Health Score, as not all fields were on the same soil type. The nine indicators developed could indicate important soil functions such as the inherent soil properties, nutrient availability, soil disturbance, disease suppression and organic matter status of ginger soils. However, the functions do not operate in isolation and changes to one function are likely to impact on other soil functions. Soil borne pathogens, *Pythium myriotylum*, *Fusarium oxysporum* f.sp. *zingiberi* and *Meloidogyne javanica* could be suppressed and ginger growth enhanced with improved soil health practices. Organic matter mediated soil health practices that incorporated a recalcitrant form of organic matter, such as woodchips, increased soil health, decreased the soil borne diseases and improved ginger production. Conversely, practices that simplified soil biological interactions such as the application of high analysis products like urea tended to reduce the health of the soil intended for ginger production.

Ultimately the development of a commercially available soil health diagnostic test would be important for the ginger industry. Elements are already available but the nematode community analyses as they exist today require specialist skills and knowledge which are not readily available. Work towards robust, quick and accurate biological tests require further development as they relate to soil health and disease suppression.

**Recommendations**

For soil health to be effective in the ginger industry, suppression of the three principal soil borne pathogens, namely *Pythium myriotylum*, *Fusarium oxysporum* f.sp. *zingiberi* and *Meloidogyne javanica* is required. PSR has become a major problem for the ginger industry in recent years. The disease is exacerbated under wet soil conditions, with the motile zoospores moving with soil water leading to disease epidemics. Inherent soil properties, such as clay content and internal soil drainage can influence the severity of PSR. Soils regarded as ‘good’ or ‘poor’ to ginger production were closely associated with the soils’ ability to suppress *Pythium myriotylum* in the validation glasshouse trial. The suppression observed with increasing soil health was largely due to the inherent properties of the soil, but could be influenced by management practices. Organic carbon content of the soil was an important contributor in the increased Soil Health Score and suppression of *Pythium*. Practices that improve soil drainage and reduce soil disturbance can also lead to improved suppression. However, the severity of losses from *Pythium* can be dictated by seasonal conditions, with years receiving above average rainfall more prone to losses from *Pythium*. 
Fusarium Yellows is a perennial problem in the ginger industry that is often seed transmitted. The re-introduction of the disease into ginger fields on infested planting material could override any biological suppression developed through improved soil health. Improvements in the production of clean planting material are currently a ginger industry priority with industry investing in tissue culture and clean planting materials. The greatest suppression of *Foz*, allowing good plant growth, occurred with the addition of green waste, molasses and a microbial product. It is feasible under these conditions there was greater microbial activity, which increased suppression of *Foz* through microbial degradation of recalcitrant organic material, like those containing lignin. The complex chemistry required to degrade lignin requires the development of specialised enzymes which often require mutualistic microbial relationships. The organisms, either fungi or bacteria, which produce the enzymes and are involved in the mutualistic relationship often produce substances or develop mechanisms to protect one another to discourage other soil organisms, such as pathogens, from interfering with these functions. It is this special relationship between organisms in the degradation of woodchips that may lead to the suppression of plant pathogenic fungi like *Foz* and *Pythium*.

The suppression of root-knot nematode was also influenced by increasing organic matter inputs which increase soil organic C. This adds to the findings from other studies which highlight that appropriate soil management practices including minimum tillage, use of organic amendments, mulching with crop residues, and appropriate crop rotation reduces plant pathogenic nematodes, and can be more productive and profitable than conventional strategies based on pesticides, synthetic fertilisers and extensive tillage.

Finally, while soil health is important, plant health is equally important as a healthy plant is more resilient and capable of combating pathogen attack. When choosing a block of land to grow ginger, soil type is a major selection criteria, as is access to good quality water. The Soil Health Indicators have indicated that clay content is important as the soils should neither be too sandy nor too heavy (33% clay was the optimal value). Meeting the nutritional requirements and water needs of the ginger crop are also important. The two indicators on the role nutrition has on soil health were phosphorus and potassium, which were considered of most importance for disease suppression with an optimal figure of 100 mg/kg P and an upper value of 1.7 meq/100 g K. Regular soil and leaf nutrient testing is critical in crop management.
Introduction

Ginger (Zingiber officinale) is a tropical rhizomatous crop, which is suited to well drained friable loamy soils rich in humus (Dinesh et al. 2012). Ginger production in Australia is based primarily in South East Queensland from Gatton to Bundaberg comprised of producers who supply both the fresh and processing markets worth AU$116 million annually. The majority of ginger is produced on red ferrosol soils, which traditionally are intensively managed in terms of agricultural inputs and tillage, with multiple annual production cycles before the land is rotated to fallow crops (Smith et al. 2011; Stirling et al. 2011). The ginger crop is commonly grown on raised beds, with supplementary irrigation and the underground rhizome mechanically harvested, disturbing the beds.

Intensive cultivation can lead to loss of soil quality and soil degradation in terms of reduced organic matter levels, subsoil acidification, poor water infiltration and nutrient depletion, which are being experienced within ginger production areas (Dinesh et al. 2012; Smith et al. 2011). Management of soil-borne pathogens is a significant challenge in agriculture. Furthermore, ginger production in the Sunshine Coast region is currently under threat due to soil borne diseases. The most significant diseases are Pythium Soft Rot (PSR) caused by Pythium myriotylum, Fusarium Yellows caused by Fusarium oxysporum f.sp. zingiberi (Foz) and root-knot nematodes (RKN) (Meloidogyne incognita and M. javanica) (Le et al. 2014; Le et al. 2016; Stirling et al. 2011; Stirling 1989; Stirling et al. 2009). Losses have been exacerbated by above average rainfall in summer months leading to inundation in some fields and periodic waterlogging. Pathogen management often requires toxic pesticides, which strongly affect soil ecosystems or complex combinations of management techniques (Löbmann et al. 2016). Management of the soil borne diseases has typically relied on soil fumigants and nematicides (Stirling et al. 2011). However, there was some suggestion that organic matter mediated suppression could be effective in the control against fungi, oomycetes and nematodes and would be useful against the suite of soil-borne pathogens that cause problems in ginger (Stirling et al. 2011).

Pythium spp. are some of the most important soil-borne pathogens causing diseases in forest and agricultural systems associated with root lesions, damping-off, and root rot (Weiland 2011; White 1986). Pythium species are opportunistic pathogens that can depend on soil properties, microbial community and field history. They are known to cause disease rapidly when general suppressiveness of soil is reduced (Postma et al. 2000). Pythium Soft Rot of ginger was first reported around a century ago in India and has since been problematic in most ginger growing regions worldwide (Dohroo et al. 2005). The disease caused by any one of a number of Pythium spp. is of most concern due to the destructiveness and aggressiveness of the pathogens on ginger (Dohroo et al. 2005). Losses generally vary from 5% to 30%, but in some cases they can be up to 100% in fields where conditions conducive for disease development, such as water logging and high temperatures, are reached (Le et al. 2016; Stirling et al. 2009). Once ginger fields have been infested with Pythium spp., the persistence of the pathogens leads to PSR in subsequent replanting of ginger in these fields, as reviewed in Le et al. (2014).

Improvements in soil quality by overcoming physical and chemical constraints are proposed to improve soil biological properties. It has been suggested that organisms capable of suppressing a wide range of soil borne diseases through a diversity of mechanisms exist in field soils (Stone et al. 2004). Therefore, developing a greater understanding of the soil constraints to ginger production with an emphasis on understanding changes in soil biological properties could identify soil properties which are suppressive or conducive to soil borne diseases.
Soil borne diseases are difficult to control due to the hidden status of the causal agents and historic availability of broad-spectrum soil fumigants and pesticides. However, there is renewed interest in developing farming methods that do not rely on chemical applications, but enhance soil biological processes to suppress diseases and enhance soil functions.

Soil suppressiveness to diseases is a characteristic of any given soil, ranging along a continuum from highly conducive to suppressive (Janvier et al. 2007). In this case suppressive soils should be considered as healthy soils, where disease outbreaks are limited (Janvier et al. 2007). Furthermore, Alabouvette et al., (2006) proposed the idea of soil receptivity, that every soil has some potential for disease suppression. Suppression of soil borne diseases should include both inoculum potential of naturally infested soils and its level of suppressiveness (Alabouvette et al. 2006). Therefore, to develop a better understanding of suppression it is necessary to separate the effects of inoculum levels in the soil and the organisms which suppress the development of the diseases. In natural ecosystems, soil organisms stabilise the soil with a multitude of physical, chemical and structural processes such that plant growth is enhanced and single opportunistic organisms are less likely to dominate, thus soil biodiversity may contribute to suppressiveness indirectly by creating a physical environment that favours the plant over the pathogen, or directly by supporting high trophic level organisms that consume pathogens (Löbmann et al. 2016).

To guide the development of improved management practices, indicators of soil health and soil degradation are required concentrating on a minimum data set (Andrews et al. 2004; Pattison et al. 2008). It was suggested that soil health indicators would be useful for risk prediction and technical advice and that these should be tested at a regional level in close association with end users (Janvier et al. 2007). Furthermore, Schut et al. (2014) warn against the use of mono-disciplinary, cause and effect research, suggesting the need for more participatory research which recognises farmers as sources, as well as end users of information. With the development of new technology, such as information systems that use an integrated approach to management of soil borne pest and diseases problems, communication and engagement of farmers from the onset of research is suggested as being fundamental to adoption of any new practices or modifications to production systems (Sherman and Gent 2014).

Inherent soil properties such as texture, mineralogy or depth are determined by parent material, climate or topography, giving soils their constraints and limitations, and are less sensitive to soil management practices. On the other hand, soil ‘dynamic’ parameters such as organic matter content, nutrient availability, biological activities and community structure, or total and available trace element concentrations, are strongly influenced by farm management practices (Obriot et al. 2016). As biological properties associated with disease suppression are influenced by physical and chemical soil properties it is important to understand the factors which are having the greatest impact on soil biology to enhance environmental conditions for disease development. Biochemical indicators that reflect the size and activity of microbial process are considered as sensitive and significant because biological mediated process are central to their ecological functions and play key roles in the mineralisation of organic C and nutrient cycling and are sensitive to environmental conditions, land use and management (Dinesh et al. 2012). Biochemical indicators are sensitive to environmental stress, play a major role in degradation and provide an accurate estimate of soil quality (Dinesh et al. 2012). Nematode community based indicators have been touted as well developed metrics for soil health, but lacking with their application to support agricultural management practices (Ugarte et al. 2013). Agronomic systems which lead to crop simplification, reliance on annual tillage and use of inorganic inputs tend to reduce the stability of soil organisms and soil food webs complexity,
increasing proportions of opportunistic organisms with a presumed reduction in soil function (Ugarte et al. 2013), which would include suppression of soil borne diseases.

Manipulating soil management through farm management has a great potential for increasing the ability of agricultural soils to suppress plant disease (Ghorbani et al. 2008). Current soil management recommendations for increased pathogen suppressiveness are mainly based on increasing organic inputs to the soil, reducing disturbances such as tillage, and diversifying crop rotation (Stirling et al. 2016). Recommendations are very general and have varying results (Alabouvette et al. 2006; Stone et al. 2004). To successfully enhance soil suppressiveness, it is necessary to understand how particular farming practices will influence key components of biodiversity and the soil ecosystem. Stirling et al. (2016) highlighted that appropriate soil management including minimum tillage, organic amendments, mulching with crop residues, and appropriate crop rotation reduces plant pathogenic nematodes, and can be more productive and profitable than conventional strategies based on pesticides, synthetic fertilisers and extensive tillage.

The hypothesis for this research is that the development of the three major soil borne pathogens of ginger, namely *Pythium myriotylum*, *Fusarium oxysporum* f.sp. *zingiberi* and *Meloidogyne javanica* exists along a continuum from conducive to suppressive within ginger production soils, which can be characterised through the use of indicators to develop a risk potential for soils for developing diseases for a consistent inoculum level. The specific aims of the research were to find the indicators that related to ginger soil health and determine if the soil health indicators could be validated with suppression of the soil borne diseases of ginger.

**Objectives**

To identify practices to improve soil health in a ginger farming system.

To reduce losses and increase production of ginger following successful control of Pythium Soft Rot and other soil borne diseases such as Fusarium Yellows and root-knot nematodes.

**Methodology**

**Survey Sites**

Ginger fields in South East Queensland were sampled over three production seasons. Ginger producers were asked to nominate ‘good’ and ‘poor’ ginger producing fields, based on their observations and cropping history. A total of 51 ginger fields were sampled over the three years (Table 1).

<table>
<thead>
<tr>
<th>Season</th>
<th>2013-14</th>
<th>2014-15</th>
<th>2015-16</th>
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<td><strong>Grower</strong></td>
<td>Good</td>
<td>Poor</td>
<td>Good</td>
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<td><strong>classification</strong></td>
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<tr>
<td><strong>Number of fields</strong></td>
<td>10</td>
<td>10</td>
<td>7</td>
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Soil Measurements

Soil samples from the top 0-25 cm soil profile were collected at different points within each ginger field. The samples were processed for physical, chemical and biological soil characteristics. Chemical analysis of soils was conducted by Incitec Pivot laboratories for standard nutrient analysis as well as soil particle size analysis (OC, pH, EC, NO₃-N, P, PBI, K, Ca, Mg, Na, Cu, Fe, Mn, Zn, SO₄, sand, silt and clay). Biochemical analysis of soil samples were conducted at the DAF Centre for Wet Tropics Agriculture, South Johnstone. Labile carbon contents were determined by measuring the amount of C oxidised by 33 mM KMnO₄ in duplicate 5 g sub-samples using the method described by Moody and Cong (2008). Similarly, fluorescein diacetate (FDA) hydrolysis rate was determined from duplicate 5 g sub-samples using a modified version of the method initially proposed by Schnürer and Rosswall (1982). β-glucosidase was determined with the procedure published by Eivazi and Tabatabai (1988), except the toluene was substituted with 0.1% Tween solution and the modified universal buffer was replaced with a McIlvaine buffer (pH 6.0) (Hayano 1973).

Soil nematode community analysis was determined at the DAF Ecosciences Precinct by extracting soil nematodes using a modified Baermann funnel technique (Whitehead and Hemming 1965). A 200 g sample of field soil, maintained at the soil moisture capacity at the time of sampling, was weighed onto a mesh sieve with a single ply of tissue and then placed into a tray with 250 mL of water and left for 48 hours. The nematodes were collected on a 25 µm sieve and backwashed into a vial. The total number of nematodes in the 200 g soil sample was determined on a counting slide and expressed as the number per 100 g of soil. From a 50 µL aliquot that was placed on a glass slide, a minimum of 100 individual nematodes were identified to genus level for plant-parasites and to the family level for free-living nematodes. Soil nematode community analysis was made on soil nematode trophic groups (parasites, fungivores (Fu), bacterivores (Ba), omnivores (Om), predators (Ca)) along a coloniser-persister scale (1-5) according to their life history characteristics, where lower scores on the c-p scale are indicative of fast reproducers in early stages of succession from disturbance and higher scores are indicative of slower reproducers, more abundant in later stages of succession (Bongers 1990; Ferris et al. 2001).

Indices of the nematode community composition were calculated from the number of nematode taxa extracted from each plot. Nematode diversity was determined using the Shannon-Weiner index (Yeates and Bongers 1999). The bacterivore to fungivore ratio was calculated from the total abundance of bacterivores (B) and fungivores (F) (B/(B+F)) (Yeates and Bongers 1999). Additionally, the weighted functional guilds concept was applied, without plant-parasites. Nematode families were assigned a colonizer-persister (c-p) score from 1–5. The score depended on the changes in the environment, with the index values representing life-history characteristics associated with r- and K-selection, respectively (Bongers and Bongers 1998). For example, bacterivores with a c-p score of 2 were classified in functional guild Ba2 and predators with a c-p score of 4 were classified in functional guild Ca4. The nematode functional guilds were used to calculate the basal, enrichment index (EI), structure index (SI) and channel index (CI) of the soil food web (Ferris et al. 2001). Plant-parasitic nematodes were identified to species level where possible and the abundance of each individual classification of plant-parasitic nematode was kept separate.

Glasshouse Experiments

A glasshouse experiment to investigate differences in disease development in five selected ginger soils was established at the DAF Ecosciences Precinct. The soils were selected from sites having differences in soil health properties and representing distinct groups determined from the farm survey.
Half of each soil was pasteurised by free-steaming at 90°C for 30 minutes before ginger seed pieces were planted into 150 mm pots. After three weeks half of the pots had shoots, and were inoculated with the different pathogens, *Pythium myriotylum, Fusarium oxysporum* f.sp. *zingiberi* and *Meloidogyne javanica* plus uninoculated controls. Plants were monitored for disease symptoms and growth parameters over a growth period of 52 days. Disease development was determined from leaf yellowing symptoms in pasteurised and field soil, with suppression determined by subtracting the rating for pasteurised soil from the rating of field soil. At the termination of the experiment plant height and stem number were recorded and used to calculate a stem index (Stem index = \( \sum \) (plant height of each stem)). All plants showing symptoms of leaf yellowing had isolates taken to determine the causal organisms. RKN eggs were extracted from the roots systems of inoculated plants as well as the control plants from pasteurised and unpasteurised soil and numbers of eggs determined. Furthermore, soils from all pots were analysed for biochemical and soil nematode community analyses and a standard soil nutrients analysis was determined from bulked soil samples allowing the calculation of the soil health score to be determined from the farm survey.

A further two glasshouse experiments were used to determine the impact of management practices on soil properties and subsequently the soil health score. The first experiment was undertaken to determine if soil amendments; green waste woodchips, molasses and a microbial product could alter soil biological characteristics and favour suppression of soil borne diseases that cause problems in ginger production. A clay-loam soil (45% sand, 22% silt and 33% clay), with moderate organic C (1.3%) and acid soil pH 5.4, which had not previously been used in ginger production was used in a glasshouse experiment. The soil remained untreated (control) or had green waste woodchips incorporated at a rate equivalent to 400 m\(^3\)/ha, or had molasses applied at a two weekly rate of 20 L/ha, or a microbial product applied at 80 L/ha applied six-weekly or combinations of two of the treatments and one treatment with all three treatments combined, resulting in a total of eight treatments. The soil and amendments were established in Styrofoam boxes 447 mm x 288 mm, with approximately 17.5 kg of soil in each box. The soils remained in the Styrofoam boxes in a glasshouse maintained at 20-30°C for nine months to simulate a fallow used in ginger production. The soil treatments were then placed into 150 mm pots and planted with ginger seed pieces and the molasses and microbial product treatments continued. Two months after planting the ginger they were inoculated with the three soil borne pathogens; *Pythium myriotylum* 2 mL of colonised grain/pot, *Foz* 5 mL of colonised grain/pot and 10 000 *M. javanica* eggs/pot and compared to uninoculated soil. All treatments were replicated four times and randomised. External disease symptoms and plant heights were assessed weekly and isolations were performed from plants with disease symptoms to identify the pathogen responsible. The experiment was terminated two months after inoculation and the plants destructively harvested. The soil was characterised for changes in physical, chemical and biological properties as previously described.

The final glasshouse experiment investigated the use of woodchip, urea and lime individually or as a combined treatment compared to untreated soil. The five treatments were untreated, wood chip (14 mm at 400 m\(^3\)/ha), lime (2.5 t/ha), urea (50 kg/ha), and a combination (urea, woodchip and lime). The treated soil was inoculated with five pathogen treatments, either untreated, *Pythium myriotylum, Foz, RKN* and combination of the three pathogens (*Pythium, Foz, RKN*) using rates of inoculum as described in the previous glasshouse experiment and replicated four times. The experiment was terminated after two months as previously described and the assessments performed on soil and plants.
Statistical Analyses

A correlation analysis was performed on the data to remove variables that were derived from one another and highly correlated ($r > 0.80$). In these circumstances the variable that was measured, rather than derived indices, remained in the analysis. The uncorrelated means were used in a forward step-wise Discriminant Analysis (DA) to determine the minimum number of variables required to separate soils determined to be good and poor. A cross validation of the DA model was made using the leave-one-out (jack knife error) method. The minimum data set determined from the DA was used in a cluster analysis to determine the similarity between sites. Box-and-whisker plots were constructed for the key soil indicators determined from the DA for the groups of similar sites identified from the cluster analysis.

Results

Soil Factors Contributing to Suppression of Ginger Diseases

A stepwise discriminant analysis, which used 41 different soil parameters, 22 biological, 16 chemical and three physical, of the 51 farm sites surveyed over three years could discriminate between good and poor ginger producing sites with a 27% error. The model used eight soil parameters; the abundance of bacterivore (Ba2), root-knot (*Meloidogyne* sp.) and *Pratylenchus* sp. nematodes, nematode enrichment index, $\beta$-glucosidase, organic C, potassium and phosphorus content of soils. There was some seasonal variation that affected the ability to predict between good and poor soil. The model chosen was the overall best prediction of good and poor soil, which comprised many of the soil parameters in the yearly surveys (Table 2). A ninth indicator, clay was added to the model as it was an indicator of good and poor soil for the 2014-15 season and gave some indication of the inherent soil conditions. When the model was applied across the three years, there was some overlap evident for good and poor ginger producing soils, with the greatest separation between soil groups in the 2015-16 season (Figure 1).

Table 2. Parameters used to separate ‘good’ and ‘poor’ ginger soils determined from a stepwise discriminant analysis from survey data collected over three cropping seasons.

<table>
<thead>
<tr>
<th>Overall</th>
<th>2013-14</th>
<th>2014-15</th>
<th>2015-16</th>
</tr>
</thead>
<tbody>
<tr>
<td>Organic C</td>
<td>Alum.</td>
<td>Ba1 bacterivore</td>
<td>Manganese</td>
</tr>
<tr>
<td>Root-knot nematode</td>
<td>Ba3 bacterivore</td>
<td>Ba2 bacterivore</td>
<td>Alum.</td>
</tr>
<tr>
<td>$\beta$-glucosidase</td>
<td>$\beta$-glucosidase</td>
<td>Clay</td>
<td></td>
</tr>
<tr>
<td>Ba2 bacterivore</td>
<td>Ca4 predators</td>
<td>Copper</td>
<td></td>
</tr>
<tr>
<td>Pratylenchus sp.</td>
<td>Iron</td>
<td>Enrichment index</td>
<td></td>
</tr>
<tr>
<td>Enrichment index</td>
<td>Fu2 fungivores</td>
<td>Sulphur</td>
<td></td>
</tr>
<tr>
<td>Potassium</td>
<td>NO$_3$-N nitrate</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Phosphorus</td>
<td>Sulphur</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Cross-validation error calculation

<table>
<thead>
<tr>
<th>2013-14</th>
<th>2014-15</th>
<th>2015-16</th>
</tr>
</thead>
<tbody>
<tr>
<td>27%</td>
<td>10%</td>
<td>7%</td>
</tr>
</tbody>
</table>
Figure 1. Biplot of ginger soils grouped as either ‘good’ or ‘poor’ for the different production seasons using an overall discriminant analysis function from Table 1.

To overcome seasonal differences, a scoring function was constructed using five scenarios; more is better, less is better, optimum, threshold value or presence or absence (Figure 2). The different indicators were allocated to scenarios, depending on the most appropriate option. Ba2, EI, P and clay were assigned as having an optimum value, whereas \( \beta \)-gluc, K and OC, were designated as more is better (Table 3). The two plant-parasitic nematodes were assigned different functions. Root-knot nematodes were assigned a threshold value, where 0 nematodes received a score of 1.0, above 150 nematodes per 100 g soil a score of 0.5 was allocated, but above this threshold a zero score was given (Table 3). Due to the infrequency of *Pratylenchus* spp. found in the samples a presence and absence scenario was given, with *Pratylenchus* spp. detected in any samples receiving a score of zero (Table 3). The conditions to develop a score for each indicator was given in Table 3 and used the criteria established by Obriot et al. (2016) to give an answer between zero and one (Table 3). Organic carbon received a greater weighting than the other eight indicators due to the high latent vector score from the
discriminant analysis (data not shown) and its central importance to soil functions. This enabled a maximum soil health score of 10.

Figure 2. Hypothetical types of scoring functions for soil health indicators from zero to one.

Table 3. Scoring functions and criteria used to develop a Soil Health Score for ginger producing soils based on nine soil indicators determined from a stepwise discriminant analysis.

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Type</th>
<th>Critical value</th>
<th>Conditions</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ba2</td>
<td>Optimum</td>
<td>150 nems/100g soil</td>
<td>Score = Ba2/150 or Score = 150/Ba2</td>
<td>1</td>
</tr>
<tr>
<td>RKN</td>
<td>Threshold</td>
<td>150 nems/100g soil</td>
<td>Score = 1.0 if RKN=0 or Score = 0.5 if RKN &gt; 0, &lt;150 or Score = 0.0 if RKN &gt; 151</td>
<td>1</td>
</tr>
<tr>
<td>Prat</td>
<td>Presence or Absence</td>
<td>1 nems/100g soil</td>
<td>Score = 1.0 if Prat = 0 or Score = 0.0 if Prat &gt;1</td>
<td>1</td>
</tr>
<tr>
<td>EI</td>
<td>Optimum</td>
<td>70 (0-100)</td>
<td>Score = EI/70 or Score = 70/EI</td>
<td>1</td>
</tr>
<tr>
<td>β-gluc</td>
<td>More</td>
<td>75 µg/g soil/hr</td>
<td>Score = β-gluc/75 or Score = 1 if β-gluc&gt;75</td>
<td>1</td>
</tr>
<tr>
<td>P</td>
<td>Optimum</td>
<td>100 mg/kg</td>
<td>Score = P/100 or Score =100/P</td>
<td>1</td>
</tr>
<tr>
<td>K</td>
<td>More</td>
<td>1.70 meq 100 g soil</td>
<td>Score = K/1.70 or Score = 1.0 if K&gt;1.70</td>
<td>1</td>
</tr>
<tr>
<td>OC</td>
<td>More</td>
<td>3.00 %</td>
<td>Score = OC/3.00 or Score = 1 if OC&gt;3.00</td>
<td>2</td>
</tr>
<tr>
<td>Clay</td>
<td>Optimum</td>
<td>33%</td>
<td>Score = Clay/33 or Score = 33/Clay</td>
<td>1</td>
</tr>
</tbody>
</table>

Soil Health Score = Σ (Ba2, + RKN, + Prat, + EI, + B-gluc, + P, + K, + (OC, *2) + Clay)

Where: Ba2 = abundance of Ba2 type bacterivores (150 nems/100g soil), RKN = abundance of Meloidogyne spp. (150 nems/100g soil), Prat = abundance of Pratylenchus spp. (150 nems/100g soil), EI = nematode Enrichment index (0-100), β-gluc = β-glucosidase (µg/g soil/hr), P = Phosphorus Colwell (mg/kg), K = Potassium (meq 100 g soil), OC = Organic carbon and (%), Clay = Clay (%).

The soil health scores were calculated for the 51 farms over the three growing seasons and the fields nominated as ‘good’ for ginger production tended to have a higher score than those nominated as ‘poor’, but with some overlap (Figure 3). Overall, the soil health score for fields nominated as ‘good’ for ginger production had a higher average score 6.11 ± 0.25 compared to fields nominated as ‘poor’ for ginger production 5.33 ± 0.19. Good soils in the 2015-16 growing season had the highest average
soil health score 6.25 ± 0.43, whereas the poor fields had an average soil health score of 5.34 ± 0.22 (Figure 3). The lowest soil health score were in the poor fields in 2014-15, which had a soil health score of 4.85 ± 0.35, compared to the good fields which had a soil health score of 6.03 ± 0.48. (Figure 3).

Figure 3. Box and whisker plots of soil health scores based on nine soil health indicators average over the three years (A) or over each growing season (B).

Ginger Growth and Disease Validation Experiment

The validation of soil health scores was conducted in a glasshouse experiment with five soils collected in the 2013-14 growing season. Three soils were classified as being good for ginger production and two soils as poor. There was a significant difference in the growth of ginger in the different soils with a good soil (RaG) having a significantly higher (p<0.05) stem height, stem number and stem index relative to the two soils classified as poor for ginger production (Table 4). The other two ‘good’ soils gave intermediate ginger growth compared to RaG and the two ‘poor’ ginger producing soils. There was no significant difference (p>0.05) in the overall disease rating or the recovery of the fungal pathogen Pythium and Foz from the different fields. However, there was a significant increase in the recovery of the pathogens when the treatments which had been inoculated with each pathogen (Table 4). There was some recovery of Foz from all treatments, which was due to contaminated seed material used in the glasshouse experiment. Root-knot nematodes were recovered in greater abundance in the ReG soil and also in the root-knot nematode inoculated treatments (Table 4).
Table 4. Growth parameters and disease quantification of ginger in five selected ginger producing soils either pasteurised or field and inoculated with three soil borne disease pathogen relative to uninoculated soil.

<table>
<thead>
<tr>
<th>Farm</th>
<th>Stem height (cm)</th>
<th>No. stems</th>
<th>Stem index</th>
<th>Disease rating</th>
<th>Pythium</th>
<th>Foz</th>
<th>RKN</th>
<th>SHS</th>
</tr>
</thead>
<tbody>
<tr>
<td>ReG</td>
<td>36.7 bc</td>
<td>2.3 b</td>
<td>124 bc</td>
<td>1.5</td>
<td>0.22</td>
<td>0.44</td>
<td>1421 c</td>
<td>6.4</td>
</tr>
<tr>
<td>ReP</td>
<td>27.1 ab</td>
<td>1.3 a</td>
<td>77 ab</td>
<td>2.0</td>
<td>0.22</td>
<td>0.59</td>
<td>79 ab</td>
<td>5.8</td>
</tr>
<tr>
<td>RaG</td>
<td>41.9 c</td>
<td>2.3 b</td>
<td>136 c</td>
<td>1.6</td>
<td>0.19</td>
<td>0.44</td>
<td>93 ab</td>
<td>6.8</td>
</tr>
<tr>
<td>MeG</td>
<td>18.8 a</td>
<td>1.0 a</td>
<td>48 a</td>
<td>2.1</td>
<td>0.22</td>
<td>0.56</td>
<td>14 a</td>
<td>5.5</td>
</tr>
<tr>
<td>CaG</td>
<td>33.2 bc</td>
<td>1.6 ab</td>
<td>86 ab</td>
<td>1.9</td>
<td>0.25</td>
<td>0.47</td>
<td>316 bc</td>
<td>5.5</td>
</tr>
<tr>
<td>Control</td>
<td>44.1 b</td>
<td>2.4 b</td>
<td>147 b</td>
<td>1.3</td>
<td>0.00</td>
<td>0.40</td>
<td>8 a</td>
<td>-</td>
</tr>
<tr>
<td>Foz</td>
<td>22.1 a</td>
<td>1.2 a</td>
<td>51 a</td>
<td>2.3</td>
<td>0.00</td>
<td>0.88</td>
<td>na</td>
<td>-</td>
</tr>
<tr>
<td>Pythium</td>
<td>17.1 a</td>
<td>1.0 a</td>
<td>45 a</td>
<td>2.3</td>
<td>0.87</td>
<td>0.38</td>
<td>na</td>
<td>-</td>
</tr>
<tr>
<td>RKN</td>
<td>43.0 b</td>
<td>2.3 b</td>
<td>136 b</td>
<td>1.4</td>
<td>0.00</td>
<td>0.35</td>
<td>2100 b</td>
<td>-</td>
</tr>
</tbody>
</table>

Stem index = stem height x no. of stems. Ratings based on leaf yellowing; 0 = Healthy Plant, 1 = Mild Yellowing, 2 = Severe Yellowing &/or Dying Stems, 3 = Dead Plant. Pythium = Pythium myriotylum 0 not present, 1 present; Foz = Fusarium oxysporum f.sp. zingiberi 0 not present, 1 present; RKN = root-knot nematode eggs per root system. na = data not available, SHS = Soil Health Score (0-10)

A regression analysis of the soil health score and the stem index revealed a significant (p<0.05, $r^2 = 0.77$) positive linear relationship, with increasing ginger stem index with increasing soil health score (Figure 4A). Similarly, there was a significant (p<0.05, $r^2 = 0.71$) negative relationship with increasing soil health score and decreasing disease rating (Figure 4B). There was no significant linear relationship with the individual pathogens; however, Pythium myriotylum gave the strongest relationship of the three soil borne pathogens with soil health scores (p=0.10, $r^2 = 0.53$) (Figure 4C).
Figure 4. Linear regression of soil health score with ginger stem index (A) and ginger disease rating (B) and for three soil borne diseases *Pythium myriotylum* (C), *Fusarium oxysporum f.sp. zingiberi* (D) and *M. javanica* (E) for five ginger producing soils from 2013-14, ReG, ReP, RaG, MeP and CaG.

**Ginger Management Practices**

When ginger was planted and inoculated with *Pythium myriotylum*, disease symptoms appeared quickly, while those inoculated with *Foz* and RKN were slower to produce disease symptoms. There was a significant interaction in the height of the ginger plants at the end of the glasshouse experiment and the soil borne pathogen used as inoculum. The shortest ginger plants were in the uninoculated treatment with no management (Table 5), whereas the tallest plants were recorded in plants with all management treatments and soil inoculated with *Foz*. No significant differences (p>0.05) were recorded in the disease ratings of plants due to high disease in soils.
Table 5. Height of ginger plants after 50 days inoculated with *Pythium myriotylum*, *Fusarium oxysporum* f.sp. *zingiberi* or *M. javanica* compared to uninoculated plants.

<table>
<thead>
<tr>
<th>Management treatment</th>
<th>Uninoculated</th>
<th>Foz</th>
<th>Pyth</th>
<th>RKN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nil</td>
<td>19.2</td>
<td>37.3</td>
<td>27.5</td>
<td>28.5</td>
</tr>
<tr>
<td>Green Waste</td>
<td>42.3</td>
<td>42.0</td>
<td>45.3</td>
<td>41.8</td>
</tr>
<tr>
<td>Microbial Product</td>
<td>40.0</td>
<td>29.5</td>
<td>46.8</td>
<td>52.5</td>
</tr>
<tr>
<td>Molasses</td>
<td>29.5</td>
<td>41.3</td>
<td>30.3</td>
<td>32.0</td>
</tr>
<tr>
<td>Green Waste + Microbial Product</td>
<td>41.8</td>
<td>37.9</td>
<td>48.3</td>
<td>49.3</td>
</tr>
<tr>
<td>Green Waste + Molasses</td>
<td>32.6</td>
<td>50.6</td>
<td>30.8</td>
<td>25.3</td>
</tr>
<tr>
<td>Microbial Product + Molasses</td>
<td>23.1</td>
<td>40.5</td>
<td>38.8</td>
<td>40.0</td>
</tr>
<tr>
<td>Green Waste + Microbial Product + Molasses</td>
<td>35.5</td>
<td>56.5</td>
<td>33.8</td>
<td>49.0</td>
</tr>
<tr>
<td>LSD</td>
<td></td>
<td></td>
<td></td>
<td>11.7</td>
</tr>
</tbody>
</table>

The soil health score for the ginger grown with the different management treatments tended to increase with increasing number of management practices imposed. That is the lowest score, 4.67 ± 0.22 was recorded in the untreated soil with no management and the highest soil health score was recorded in the Green Waste + Microbial Product + Molasses treatment 5.51 ± 0.10 (Figure 5A).

A regression analysis of the soil health scores for the different management treatments revealed a significant (p<0.05 r² = 0.80) positive linear relationship with the height of ginger plants inoculated with *Foz* (Figure 5). However, there was no significant linear relationship with plant height for the other soil borne pathogens with the soil health score.
Figure 5. Soil health scores for soil used in a glasshouse experiment with different management treatments (A) and a linear regression of the soil health scores and the height of stems when plants were inoculated with *Foz* (B).

A second glasshouse experiment used urea, lime and woodchip alone or in combination, to determine impacts on plant growth, soil borne diseases and soil health score. There was a significant difference in the ginger rhizome weight at the end of the experiment, with untreated soil having the lowest rhizome weight, which was significantly less than when a combination of woodchip, urea and lime were added to the soil (Figure 6A). There were no significant differences in other disease and ginger growth parameters in this experiment (data not shown). The soil health score following the experiment relative to the untreated soil decreased when lime and urea were added to the soil (Figure

![Graph A](image1)

![Graph B](image2)
However, when woodchips or a combination of urea, lime and woodchips were added to the soil there was an increase in the soil health score (Figure 6B). There was a non-significant ($p=0.09$ $r^2 = 0.53$) linear relationship between the soil health scores and ginger rhizome weight.

Figure 6. Ginger rhizome weight (A) and soil health scores (B) when lime, urea, woodchips or a combination of lime, urea and woodchips were added to soil.

As the management glasshouse experiments were conducted at different times it was more relevant to compare changes in the soil health score with the unamended soil (Figure 7). The relative comparison reveals a decrease in soil health score when non-organic treatments either urea or lime were added to the soil (Figure 7). The greatest increase in soil health scores occurred when a combination of treatments with woodchips or green waste was used as a basis. The addition of the microbial product alone increased the soil health score, but the increase was small compared to the addition of recalcitrant carbon sources such as woodchips and green waste (Figure 7).
Figure 7. Relative changes in soil health scores of management practices to improve soil health relative to untreated soil from two glasshouse experiments.

To develop a clearer understanding of where soil health improvements were made, radar charts were constructed using the soil health scores from nine parameters (Figure 8). The soil indicators were assigned functions, such as inherent soil properties, clay, nutrient availability, P and K, soil disturbance enrichment index and Ba2 bacterivore abundance, diseases suppression, abundance of root-knot nematode and Pratylenchus species and organic matter β-glucosidase and organic C (Figure 8). Using the untreated soil as a reference, lime was found to decrease disease suppression, resulting in the lower overall soil health score (Figure 8A). Additionally, urea decreased disease suppression through more plant-parasitic nematodes and also increased soil disturbance resulting in the lower score (Figure 8B). Conversely the combination treatment, which had the urea, lime and woodchip increased the disease suppression score by reducing numbers of plant-parasitic nematodes (Figure 8C). The combination of green waste, microbial inoculant and molasses, which had the highest soil health score relative to the untreated soil (Figure 7) had improved scores for soil disturbance, disease suppression and organic matter (Figure 8D).
Figure 8. Radar diagrams of scores for management impacts with lime (A), urea (B), combination (Combo) of lime, urea and woodchip (C) and combination of greenwaste (GW), microbial inoculant (MP) and molasses (Mol) (D) on soil health indicators relative to the untreated soil.

Discussion

The selection of specific soil health indicators could distinguish between ‘good’ and ‘poor’ ginger producing soils in Queensland. However, there were large seasonal variations over the three years of crop production that altered importance of parameters and increased the error in being able to predict if soils were ‘good’ or ‘poor’ for ginger production. Notwithstanding the seasonal variations, the selection of eight indicators from a stepwise discriminant analysis, with the addition of clay as an inherent indicator of soil conditions, could signify if a soil would be good or poor for ginger production. The soil health scores were correlated with both the growth of ginger and the suppression of soil borne diseases. Furthermore, the soil health score was sensitive to management impacts which could reduce or increase the soil health score. In most cases the management impacts were small incremental changes in the overall soil health score, but could indicate which practices were having a positive benefit and which practices were unlikely to improve soil health. Furthermore, by individually analysing the score for each indicator deficiencies in the management practices or inherent soil properties could be determined.

Overlap of indicators due to inherent soil conditions of fields producing ginger was observed. As there was a large range in the variability of soil types included in the three year survey, this resulted in an overlap of what growers perceived to be a ‘good’ and a ‘poor’ ginger producing soil. The classification of ‘good’ and ‘poor’ was subjective based on ginger grower’s perceptions. In most cases the soil health score agreed with grower’s perceptions, particularly in regard to their own farm where
multiple samples were taken over years. However, between farms the classifications were not as robust. What one grower classed as a ‘good’ soil another grower could class as a ‘poor’ soil, or vice versa what one grower classed as a ‘poor’ soil another could regard as a ‘good’ soil, based on the experience from their own farming experience. The development of a soil health score was meant to add some quantification to what is perceived as a ‘good’ and ‘poor’ soil. However, the seasonal variabilities between the years included in the survey made this task more difficult. Therefore, the development of a ‘universal’ set of soil health indicators was problematic when it was based on grower’s opinions across multiple years on different soil types. However, the soil health indicators selected should be able to discriminate between the extremes, that is, a ‘very good’ and a ‘very poor’ ginger producing soil, but will have problems separating fields when the differences are not as great.

Management practices that increased organic matter inputs and contained a recalcitrant form of organic material such as woodchip gave the greatest improvements in soil health scores and improved the growth of ginger. Organic mediated suppression of soil borne diseases has been observed in many agricultural industries (Stirling et al. 2016). The decomposition of recalcitrant forms of organic matter requires interaction between soil organisms. The recalcitrant, carbon rich organic matter requires increased enzymatic activity to decompose and typically requires additional nutrients, which can be acquired from other soil organisms, such as plant pathogens. As numerous organisms are involved in the decomposition of recalcitrant organic matter, they act collectively resulting in general biocontrol of plant pathogens through a range of mechanisms, such as parasitism, predation, competition and antibiosis (Stirling et al. 2016). The result is conservation biocontrol, where endemic soil organisms are encouraged to overcome restrictions and limitations to their activities. Conversely, non-organic treatments such as urea and lime, tended to reduce the soil health, through application of high analysis forms of nutrients, either nitrogen or calcium carbonate. The high analysis forms of nutrients tended to disturb soil organism and change the soil microbial interactions. Changes in microbial soil interactions tend to suppress antagonistic organisms and allow pathogens an opportunity to colonise plants resulting in increased disease and long term poor plant growth.

The soil health indicators that were selected could be grouped into different soil functions, disease suppression, inherent soil conditions, nutrient availability, soil disturbance and organic matter, which help to support plant growth. However, the soil functions do not act independently as changes in organic matter indicators can also change disease suppression, nutrient availability and soil disturbance. Likewise, changes in other soil functions will also impact on the organic matter indicators. The growth of the ginger plants in the glasshouse experiments was evident that multiple soil processes were occurring, which allowed the plant to respond with increased growth when more favourable soil health conditions prevailed.

For soil health to be effective in the ginger industry suppression the three principal soil borne pathogens, namely *Pythium myriotylum*, *Fusarium oxysporum* f.sp. *zingiberi* and *Meloidogyne javanica* is required. PSR has become a major problem recently for the ginger industry (Le et al. 2014; Le et al. 2016). The disease is exacerbated under wet soil conditions, with the motile zoospores moving with soil water. Inherent soil properties, such as clay content and internal soil drainage can influence the severity of PSR. Soils regarded as ‘good’ or ‘poor’ to ginger production were closely associated with the soil’s ability to suppress *Pythium* in the validation glasshouse trial of the 2013-14 soil survey (Figure 4C). The suppression observed with increasing soil health was largely due to the inherent soil properties, with smaller contributions from management practices. Organic carbon content of the soil was also an important contributor in the increased soil health score and suppression of *Pythium*. Practices that improve soil drainage and reduce soil disturbance can lead to further
improvements in disease suppression. However, the severity of losses from PSR can be dictated by seasonal conditions, with years receiving above average rainfall more prone to losses from Pythium.

Foz is a perennial problem that was often seed transmitted. The re-introduction of the disease into ginger fields on infested planting material could override any biological suppression developed through improved soil health. Improvements in clean planting material for ginger is currently a ginger industry priority, with investment in tissue culture and clean planting material schemes. The greatest suppression of Foz, allowing plant growth, occurred with the addition of green waste, molasses and a microbial product (Table 5). It is feasible under these conditions there was greater microbial activity, which increased suppression of Foz. The microbial degradation of recalcitrant organic material, like those containing lignin with complex chemistry, require development of specialised enzymes and often requires mutualistic microbial relationships. The organisms, either fungi or bacteria, which produce the enzymes and are involved in the mutualistic relationship often produce mechanisms to protect one another to discourage other soil organisms. It is this special relationship between organisms in the degradation of woodchips that may lead to the suppression of plant pathogenic fungi like Foz and Pythium.

The suppression of root-knot nematode was determined by quantifying the abundance of the nematode in soil samples. The abundance of RKN was one of the nine indicators selected for soil health of ginger. Therefore, it should be easier to determine if a field was likely to suppress RKN by quantifying the abundance of the nematodes. Some fields were found to have high RKN populations in the soil and, therefore, received a lower soil health score. If no RKN were found in soil samples the soil received a maximum score of 1.0. If RKN abundance was greater than zero but less than 150 RKN per 100 g soil, it received a score of 0.5, whereas if the abundance was greater than 150 RKN per 100 g soil it received a score of 0.0. However, the abundance of RKN is strongly dependent on the presence of plants roots. If other pathogens like Pythium and Foz are infecting ginger, the lack of plant roots may also reduce the abundance of RKN, and therefore confound the suppression of RKN. In the validation glasshouse experiment RKN had the poorest correlation with the soil health score, and demonstrated a positive relationship (e.g. as the soil health score increased so did the abundance of RKN). This observation confirms that where there is greater root mass it is more likely to have greater RKN if it is present in the soil. The inorganic practices of the addition of lime and urea, both decreased the soil health score by having greater abundance of RKN. It is hypothesised that the microbial population in soil have some suppressive potential of RKN, but this is easily overcome by soil disturbance induced by farm management practices in the growth of ginger. The practices that increase organic matter inputs and increase soil organic C tend to suppress plant-parasitic nematodes, like RKN (Smith et al. 2011; Stirling 1989).

Pratylenchus spp. are not considered pathogenic to ginger in Australia. The presence of Pratylenchus sp. in ginger producing soils is due to their ability to parasitise other crops grown in rotation with ginger. Therefore, their inclusion as an indicator can be viewed as the soil microbial community’s ability to suppress pathogens remaining from previous crops. If Pratylenchus sp. remain in the soil when ginger is grown, there is a high potential that the soil microbial community does not have the capacity to suppress plant pathogens. Therefore, the scoring function assigned to Pratylenchus sp. was either presence or absence. A soil health score was a maximum 1.0 if no Pratylenchus sp. were present, but if any were detected in the soil samples the soil health score was 0. Pratylenchus sp. were found in only 11 of the 51 ginger soils included in the three year survey, with an average of 33 nematodes per 100 g soil on the fields where it was detected, and a maximum population of 81 Pratylenchus sp. per 100 g soil.
The inherent soil conditions or soil types are known to strongly influence soil properties including soil microorganisms (Stirling et al. 2016). The suppression of soil borne pathogens like Fusarium sp. and Pythium sp. can be linked to clay content in the soil (Löbmann et al. 2016; Peng et al. 1999). This usually occurs in soils with a low clay content, such as sandy soils, where a small increase in clay content can have a large impact on a number of different chemical and biological soil properties (Stirling et al. 2016). However, if clay is not a limiting factor in the soil it is less likely to become an indicator of soil health or disease suppression. In the ginger soil survey soils with low and high clay contents were perceived by ginger growers as being poor. It appeared there was an optimum which was around 33% clay content, above or below and soil health began to decline. High clay content becomes more problematic in wet years, particularly increasing the likelihood of losses due to PSR. The 33% clay content was somewhat confirmed in the validation glasshouse experiment with the soil giving the greatest ginger growth and least effected by Pythium had a clay content of 33%.

Nutrients are required for optimal crop growth. Insufficient fertiliser inputs leads to poor yields, but over fertilisation leads to environmental problems, and can increase the risk of soil borne diseases by reducing competition for nutrients among soil organisms (Dordas 2008; Löbmann et al. 2016; Yan et al. 2013). Furthermore, nutrient depletion makes plants more susceptible to pathogens (Graham 1983). Hence, nutrient balance plays an important role in biological suppressiveness (Dordas 2008; Ghorbani et al. 2008). The two indicators of the role nutrition has on soil health were phosphorus and potassium. The overuse of phosphorus in intensive horticultural production is a widespread problem (Yan et al. 2013). Phosphorus is the second most widely applied nutrient in agriculture and is essential for the cellular functions and metabolism of plants. Its role in disease suppression is not clear with applications being able to suppress some plant diseases, while encouraging other plant diseases (Dordas 2008). The greatest impact of phosphorus is in the developing plant, but over application of phosphorus can suppress beneficial microbial associations such as mycorrhiza and phosphorus solubilising bacteria. Therefore, an optimum soil health score was given for phosphorus at 100 mg/kg, above which soil health declined. The average soil P for the 51 fields surveyed was 157 mg/kg but levels up to 640 mg/kg were found in some ginger fields.

Potassium was the other nutrient that was linked as a soil health indicator. Potassium does not have the same environmental concerns of the farms as nitrogen and phosphorus and therefore, over application of K is not seen as environmentally problematic. Similarly, with resistance towards plant diseases, there is an optimum up to which disease resistance of the plant is increased, and beyond which there is no further improvement (Dordas 2008). Potassium is an important nutrient in the synthesis of proteins, cell wall strength and water regulation within the plant. Therefore, a deficiency in K can make the plant more susceptible to plant’s disease as it is unable to produce compounds which enhances it resistance to parasitism (Dordas 2008). Potassium as a soil health indicator was regarded that ‘more is better’, with a maximum score 1.0, equivalent to an upper value of 1.70 meq/100 g soil. Beyond this there was no improvement in soil health.

The role of organic matter in soil health is well documented, having multiple effects on soil properties (Weil and Magdoff 2004). Furthermore, there are numerous examples of organic matter mediated suppression of plant diseases (Stirling et al. 2016; Stone et al. 2004; van Bruggen et al. 2015). Therefore, organic carbon as a measure of organic matter in the soil is an important soil health indicator and is widely used as an indicator of soil health in agricultural systems (Andrews et al. 2004; Gugino et al. 2007; Pattison et al. 2008). Similar to potassium as a nutrient indicator of soil health, it is likely that with low organic C levels there is a vast improvement in soil health with increasing organic C levels in the soil, up to a point when organic C is no longer limiting. Therefore, organic C was made as an indicator where ‘more is better’ up to 3% soil organic C. An average organic C for the
51 fields included in the survey was 1.88%, with some ginger fields less than 1% organic C and only one found to have organic C greater than 3.0%.

As well as having the organic C present in the soil, it is the soil microbial community’s ability to utilise the carbon to support microbial functions which make it an important soil health indicator. The utilisation of organic C in the soil by the microbial community is indicated by the enzymatic activity of β-glucosidase. The β-glucosidase enzyme plays a major role in the degradation of soil organic matter and plant residues as it catalyses the hydrolysis of β-d-glucopyranosides in the final, rate-limiting step in the degradation of cellulose, into simple sugars like glucose for the soil microbial population and has been used as an indicator for soil health (Stott et al. 2010). Similar to organic carbon, ‘more is better’, as greater β-glucosidase activity is an indicator of greater microbial function in utilising organic C in the soil. There are fewer studies that use β-glucosidase as a soil health indicator and there is some variation in the techniques used to measure its activity in the soil, making studies difficult to compare. For the ginger industry and the method used in this study, an upper maximum of 75 μg PNG released/kg soil/hour was set. The average β-glucosidase activity as 24 μg PNG released/kg soil/hour, with one site exceeding the upper limit, but values as low as 6 μg PNG released/kg soil/hour were also observed.

The nematode community assessment has been suggested as a valuable method of indicating the function of the greater soil food web, due to the trophic differences and life strategies used by nematodes (Ferris et al. 2001; Neher 2001; Yeates and Bongers 1999). The functional guilds proposed by Ferris et al. (2001) allows nematodes to be formed into groups more closely aligned to the function in the soil. The Ba2 type nematodes are described as basal bacterivores, that exist in most soils no matter how depleted, disturbed or enriched it may be (Ferris et al. 2001). Therefore, it is suggested that the abundance of Ba2 nematodes can act as a surrogate indicator of soil disturbance. High numbers of Ba2 nematodes can indicate that the soil is highly disturbed, but they can still exist in ‘good’ agricultural soil, and therefore low abundance of the nematodes can indicate soil conditions that are detrimental to soil microbial activity. Therefore, an optimum abundance of Ba2 nematodes is suggested as an indicator or soil health. An optimum of 150 Ba2 nematode per 100 g soil was suggested for ginger soil health scores, above and below which received reduced scores. The greatest abundance of Ba2 nematodes in ginger soils was 1947 and lowest number was 17, with an average of 223 Ba2 nematodes per 100 g soil. This indicated that some ginger soil were highly disturbed, but the majority were only slightly disturbed.

The enrichment index (Ferris et al. 2001) was also used as a soil health indicator as it could be integrated with farm management practices that led to nutrient enrichment in the soil (Ferris and Bongers 2006; Zhong et al. 2016). The enrichment index is based on fast growing bacterivore nematodes that can multiply quickly under favourable conditions, but are unable to persist when conditions are not. Soil disturbance either through tillage or inorganic nutrient application tend to create more favourable conditions for the proliferation of copiotrophic organisms that lead to an increase in the nematode enrichment index. However, as disturbance leading to soil enrichment is common for agricultural production, particularly in annual crops, some enrichment is inherent. Ginger soils that have a reduced nematode enrichment index may have poor plant growth and soil health as nutrients are not available for plant production. Therefore, an optimum enrichment index of 70 was suggested. Below 70 and nutrients may be less available for microbial soil function and ginger production. Above 70 and there is excessive nutrients that can lead to reduced soil health, as soil organisms do not have to compete for nutrients, and suppressive organisms are swamped by copiotrophic organisms, unable to suppress plant-pathogens.
The use of the nematode community structure can provide much information on soil functions in agriculture; however, it is problematic as a commercial indicator for agricultural producers due to the availability of laboratories and personnel with the specialised skills for nematode identification. Furthermore, the time taken to perform the nematode identification makes it use expensive and slows the turn-around time when growers received the information back. The development of high throughput assays, like Community Level Physiological Profiles such as MicroResp™ (Campbell et al. 2003) and soil enzyme analysis (Popova and Deng 2010) may provide more useful commercial diagnostic tests. However, there needs to be more work to ensure a strong correlation between high throughput assays and the information provided by the assessment of the nematode community.

**Implications**

Selection of soil health indicators and development of a Soil Health Score could discriminate between ‘good’ and ‘poor’, but had seasonal variations and high error when averaged across the growing seasons. The classification of fields as ‘good’ or ‘poor’ was based on the growers’ experience and knowledge and therefore had errors associated with it as it was a subjective question. Soil type variability of inherent soil properties contributed to some misclassification of sites as ‘good’ or ‘poor’ when developing the Soil Health Score, as not all fields were on the same soil type. The nine indicators developed could indicate important soil functions such as the inherent soil properties, nutrient availability, soil disturbance, disease suppression and organic matter status of ginger soils. However, the functions do not operate in isolation and changes to one function are likely to impact on other soil functions. Soil borne pathogens, *Pythium myriotylum*, *Fusarium oxysporum* f.sp. *zingiberi* and *Meloidogyne javanica* could be suppressed and ginger growth enhanced with improved soil health practices. Organic matter mediated soil health practices that incorporated a recalcitrant form of organic matter, such as woodchips, increased soil health, decreased the soil borne diseases and improved ginger production. Conversely, practices that simplified soil biological interactions such as the application of high analysis products like urea tended to reduce the health of the soil intended for ginger production.

Ultimately the development of a commercially available soil health diagnostic test would be important for the ginger industry. Elements are already available but the nematode community analyses as they exist today require specialist skills and knowledge which are not readily available. Work towards robust, quick and accurate biological tests require further development as they relate to soil health and disease suppression.

**Recommendations**

For soil health to be effective in the ginger industry suppression of the three principal soil borne pathogens, namely *Pythium myriotylum*, *Fusarium oxysporum* f.sp. *zingiberi* and *Meloidogyne javanica* is required. PSR has become a major problem for the ginger industry in recent years. The disease is exacerbated under wet soil conditions, with the motile zoospores moving with soil water leading to disease epidemics. Inherent soil properties, such as clay content and internal soil drainage can influence the severity of PSR. Soils regarded as ‘good’ or ‘poor’ to ginger production were closely associated with the soils’ ability to suppress *Pythium myriotylum* in the validation glasshouse trial. The suppression observed with increasing soil health was largely due to the inherent properties of the soil but could be influenced by management practices. Organic carbon content of the soil was an important contributor in the increased Soil Health Score and suppression of *Pythium*. Practices that
improve soil drainage and reduce soil disturbance can also lead to improved suppression. However, the severity of losses from Pythium can be dictated by seasonal conditions, with years receiving above average rainfall more prone to losses from Pythium.

Fusarium Yellows is a perennial problem in the ginger industry that is often seed transmitted. The re-introduction of the disease into ginger fields on infested planting material could override any biological suppression developed through improved soil health. Improvements in the production of clean planting material are currently a ginger industry priority with industry investing in tissue culture and clean planting material schemes. The greatest suppression of Foz, allowing good plant growth, occurred with the addition of green waste, molasses and a microbial product. It is feasible under these conditions there was greater microbial activity, which increased suppression of Foz through microbial degradation of recalcitrant organic material, like those containing lignin. The complex chemistry required to degrade lignin requires the development of specialised enzymes which often requires mutualistic microbial relationships. The organisms, either fungi or bacteria, which produce the enzymes and are involved in the mutualistic relationship often produce substances or develop mechanisms to protect one another to discourage other soil organisms, such as pathogens, from interfering with these functions. It is this special relationship between organisms in the degradation of woodchips that may lead to the suppression of plant pathogenic fungi like Foz and Pythium.

The suppression of root-knot nematode was also influenced by increasing organic matter inputs which increase soil organic C. This adds to the findings from other studies highlighting that appropriate soil management practices including minimum tillage, use of organic amendments, mulching with crop residues, and appropriate crop rotation reduces plant pathogenic nematodes, and can be more productive and profitable than conventional strategies based on pesticides, synthetic fertilisers and extensive tillage.

Finally, while soil health is important, plant health is equally important as a healthy plant is more resilient and capable of combating pathogen attack. When choosing a block of land to grow ginger soil type is a major selection criteria, as is access to good quality water. The Soil Health Indicators have indicated that clay content is important as the soils should neither be too sandy or too heavy (33% clay was the optimal value). Meeting the nutritional requirements and water needs of the ginger crop are also important. The two indicators of the role of nutrition has on soil health were phosphorus and potassium which were considered of most importance for disease suppression with an optimal figure of 100 mg/kg P and an upper value of 1.7 meq/100 g K. Regular soil and leaf nutrient testing is critical in crop management.

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Improving Soil Health to Suppress Soil Borne Diseases of Ginger

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