Vegetable Plant and Soil Health

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Purpose:

Soil health or quality can be defined as *a soil that has the continued capacity to function as a vital living system that sustains plants, animals, and humans*. A decline in soil health has resulted from agricultural activities since European settlement revealing itself as soil structural decline, increased surface run off and erosion, and the need for increased agricultural inputs to sustain plant productivity. Much of this decline can be linked to an intensification of farming operations with little regard to the sustainability of the operations.

There is a need to develop soil health indicators (physical, chemical and biological) and soil assessment tools that can be linked to the health of vegetable crops, to develop an improved understanding of how farm management practices impact on soil health for a more sustainable vegetable production industry.

This project aims to understand soil health limitations, identify improved soil health management practices, determine the most appropriate indicators to monitor changes in soil health and to determine what information vegetable growers need to implement and progress plant and soil health strategies.

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Media summary

Healthy soils can mean more than just an absence of pests and diseases. Soils are complex ecosystems that rely on the interaction of physical, chemical and biological properties to function and sustain agricultural production. To understand soil health, we need to understand the soil's inherent properties, as well as how soil management practices change soil properties. Inherent soil properties determine the soil's behaviour and limitations and are associated with soil types. Soils also have dynamic properties that change readily and are influenced by farm management practices. This makes the dynamic soil properties useful indicators in assessing impacts of cropping systems on soil health.

Soil health indicators have been developed to help vegetable growers better understand soil functions and to manage soil health. These indicators measure the soil's physical, chemical and biological properties. Some indicators form part of standard nutrient tests, such as organic carbon, nitrate nitrogen, extractable phosphorus, phosphorus buffering index (PBI), cation exchange capacity (CEC) and sodium saturation. Other indicators require additional measurements, such as bulk density, aggregate stability, penetrometer resistance, a soil drop test and a dispersion test. While a final group of indicators are still under development, like labile carbon and nematode diversity, but can give useful information about soil health.

The project VG06100 identified two areas of soil health of national importance for the Australian vegetable industry; nutrient management and soil carbon management. These two issues were important to vegetable growers regardless of soil type and farm location. Further, issues for soil health management for the vegetable industry were related to soil type. For example, in clay soils, the need to maintain good soil structure by managing compaction and sodicity risks and in sandy soils, the need to increase nutrient and water holding capacity. Other issues, such as pest and disease suppression, salinity and sodicity were considered more site specific.

Soil health on vegetable farms can be managed by implementing strategic tillage, using green manures and cover crops, crop rotation, organic amendments and controlled traffic. The development of systems that minimise soil disturbance and maximise organic matter inputs tend to increase the health of the soil by improving soil physical, chemical and biological properties. However, soil health improvements should not be assumed to happen because practice changes have been put in place. Monitoring changes in soil properties is important to ensure progress toward healthier soils, soil limitations are being overcome and sustainable vegetable production systems are being developed. To help vegetable growers improve their soil health management, a manual has been produced to capture the current knowledge generated from the project. The manual titled "Soil Health for Vegetable Production: A soil management manual for the Australian vegetable industry", will be made available from the QPIF web site and the Australian Vegetable Industry Soil and Land Management Knowledge Exchange.

To advance soil health for the Australian vegetable industry, further work is needed to; develop more efficient fertiliser practices, increase knowledge of the benefits from improved soil organic matter management, increase knowledge of the soil limitations that induce pests and disease problems, develop strategies to overcome a decline in

soil structure on clay soils and develop strategies to increase the nutrient and water holding capacity of sandy soils. The concepts of understanding soil limitations identified from this work will be taken to a proposed new project, linking the soils physical, chemical and biological limitations with the risk of developing soil borne diseases in vegetable crops. It is hoped by developing a greater understanding of how soil properties interact with beneficial organisms, pathogens and plants, the severity of soil borne diseases can be reduced without the need for pesticides. The soil health manual developed in VG06100 will form a foundation for understanding soil health limitations, which will assist in following projects. A coordination of soil health projects associated with the vegetable industry would provide greater benefit for vegetable producers in Australia ensuring that outcomes from research can result in healthy vegetable soils.

Technical summary

Soil health or quality can be defined as *a soil that has the continued capacity to function as a vital living system that sustains plants, animals and humans*. A decline in soil health has resulted from agricultural activities since European settlement revealing itself as soil structural decline, increased surface run off and erosion, and the need for increased agricultural inputs to sustain plant productivity. To determine the changes that have occurred in the soil and the sensitivity of indicators of physical, chemical and biological soil properties, 14 paired sites across Queensland, New South Wales and Western Australia were measured. The paired sites compared a "conventional" vegetable production system with a nearby site where the land manager had implemented a soil management practice that they believed would improve soil health. Practices that land managers had implemented included minimum tillage / mulch systems, organic production, compost application and controlled traffic. Paired sites, had varying soil types from heavy clays to sands. Furthermore, there was a range of vegetable crops grown on the different sites. At each site soil samples were collected from four representative areas and physical, chemical and biological properties determined. Data were analysed using multivariate techniques and using the leaving-one-out method to determine the minimum set of indicators that could explain changes due to management practices and production systems.

Soil texture was determined to be an important factor in determining the soil health properties. The sites could be discriminated into three groups; clay, loam and sand based on resistance penetration, bulk density, organic carbon, pH, phosphorus buffering index (PBI), Na%, EC, nematode diversity, FDA and B/(B+F). Sites where additional organic matter had been incorporated could be discriminated from sites with no additional organic matter based on penetration resistance, bulk density, pH, nitrate nitrogen, Mg, CEC, Na%, organic C, FDA, microbial biomass C and the nematode channel index. Sites that had adopted controlled traffic could be distinguished from sites where the traffic was not controlled by measuring soil penetration resistance, bulk density, nitrate nitrogen, Ca, Mg, CEC, organic C, β-glucosidase and a bean bioassay. Nutrient content of soils was variable across the sites, but the sites could be classified into three groups. The three groups could be discriminated from one another based on nitrate nitrogen, $P_{Colwell}$, CEC and Na%. One group of sites had high nitrate nitrogen and two groups of sites had high $P_{Colwell}$. A discriminate analysis of the different vegetable production systems; conventional, organic, compost minimum tillage-mulch systems and interrows could be discriminated based on 16 different indicators. However, validation of the groupings using the leave-one-out method failed to correctly assign 66% of compost sites, 46% of conventional sites, all of the interrows, 25% of the minimum tillage with mulch sites and 20% of the organic sites. This suggested that soil health indicators were good at predicting practice changes, but were poor at determining the differences between the farming systems. The more complex the system, the more subtle the changes in management or the less time between changes in soil management practices, the greater the number of indicators that were required to detect differences in soil properties. Further work is required in vegetable production systems to develop more efficient fertiliser practices, increase knowledge of soil organic matter management, increase knowledge of the soil limitations that induce pest and disease problems, develop strategies to overcome decline in soil structure of clay soils and to

develop strategies to increase the nutrient and water holding capacity of sandy soils. A coordination of project activities in soil research associated with the vegetable industry would provide greater benefit for vegetable producers in Australia ensuring that outcomes from research can result in healthy soils.

Part A: A snapshot of soil health in the Australian vegetable industry

Introduction

The Australian vegetable industry is valued at over $2.3 billion, produced from approximately 6,500 farms (Price *et al.* 2005). Vegetable production centres tend to be located close to major capital cities, except for commodities where the climate and scale of operations may give a marketing advantage. However, the industry is constantly facing a cost-price squeeze and must address issues of economic and environmental sustainability, while retaining consumer confidence in the quality of produce (Price *et al.* 2005). A diverse variety of crops are grown on a range of soil types in various climatic zones using different production systems. Kelly and Anderson (2006) describe nine different soil type classes which range in texture from heavy clays to sands. A number of issues that are regional, soil type and crop specific need to be addressed.

In vegetable production systems, the soils maintain essential functions by providing support for the plant, supplying water and nutrients, helping to suppress pests and diseases and degrading xenobiotics preventing them from entering the food chain. However, intensive vegetable production has largely ignored the ecosystem functions of the soils that support agriculture using an industrialised production model, which utilises external inputs (irrigation, fertilisers, chemical pest control) to achieve production goals (Hendrickson *et al.* 2008). Soil management practices in vegetable production usually aim to overcome the most limiting soil constraints, such as poor nutrient supply, compaction or pest and disease problems (Moody and Cong 2008; Sanchez *et al.* 2003). Regardless of soil type, crop or region, these practices focus on management of traffic and tillage, nutrients and organic matter. The combination of management practices incorporated into vegetable production systems depends on the intensity of the farming operation (Dogliotti *et al.* 2004; Wells *et al.* 2000). The amount and type of tillage is known to impact on physical, chemical and biological soil properties (Bandick and Dick 1999; Hoyte *et al.* 1994; Stirling and Eden 2008). However, recent work has investigated the use of minimum tillage in integrated vegetable production (Stirling 2008; Wells *et al.* 2000).

There has been past work determining fertiliser application rates to optimise production. However, the focus of current research is to maximise production without impacting on the off farm environment (Chan *et al.* 2007; Dogliotti *et al.* 2004). Management of the organic carbon component in the soil can include crop rotations, green manures and applications of organic amendments (Chan *et al.* 2008; Chaves *et al.* 2005; Rotenberg *et al.* 2005; Schutter *et al.* 2001; Srivastava *et al.* 2007). The addition of extra organic matter is typically aimed at maintaining or enhancing the organic carbon content of soils or attempting to develop pest and disease suppressive soils (Stirling 2008; Stirling and Pattison 2008).

The integration of the different management practices used in vegetable production form a system of production. For example, studies have compared organic or best management practice systems with conventional production systems where multiple soil management practices have changed (Andrews *et al.* 2002; Srivastava *et al.* 2007;

Wells *et al.* 2000). However, the systems of production used on farms reflect soil managers socio-economic status, goals and aspirations, as well as their knowledge of alternative practices and systems (Brodt *et al.* 2006; Lobry de Bruyn and Abbey 2003; Vanclay 2004). Responses to future challenges in developing agricultural systems should include the development of systems that are productive, minimise their impact on the environment, use renewable resources and are sympathetic with the goals of the land managers (Hendrickson *et al.* 2008).

Indicators related to soil properties can be used by farm managers to determine if they are achieving their soil management goals. Monitoring soil conditions uses indicators that represent particular constituents, processes and conditions (Burns *et al.* 2006; Idowu *et al.* 2008). Soil health cannot be summarised by a single measurement, therefore, its assessment must include information from several indicators. Criteria for indicators of soil health relate mainly to the ability to define ecosystem processes, their ability to integrate physical, chemical and biological properties and their sensitivity to management (Benedetti and Dilly 2006; Idowu *et al.* 2008; Shukla *et al.* 2006). The development of soil health indicators have been used in other agricultural production systems to determine the best set of practices to improve soil management in commercial agricultural production (Andrews *et al.* 2002; de Lima *et al.* 2008; Lilburne *et al.* 2004; Pattison *et al.* 2008; Shukla *et al.* 2006; Stamatiadis *et al.* 1999)

The overall focus of our research was to survey vegetables farms in Australia to determine the main issues related to soil health management and to measure the effects of divergent vegetable production systems on soil properties. The specific research objective was to determine a set of useful indicators for the vegetable industry that could indicate and discriminate between soil management practices and systems under vegetable production.

Materials and methods

Experimental sites

Sites were located in six major vegetable production regions within Australia, representing significant differences in soils and climates (Table 1). Soil types ranged from sands in the Perth region to heavy clays in the Lockyer Valley in Queensland. At least two survey sites were chosen in each region where vegetable producers had implemented a practice change or farming system that they thought would affect soil health. A range of vegetable crops and practices were surveyed. At paired sites, one site used a standard ‘conventional’ practice and the other site involved practice change, such as compost addition, organic production and minimum tillage with mulch or crop interrows.

Table 1: Background information for the sites surveyed for vegetable soil health.

Region	Latitude (°S)	Longitude (°E)	Site	Crop	Soil texture	Practice
Bowen/Burdekin	20.02	148.25	BC	Beans	Clay	Conventional
			BCom	Beans	Clay	Compost
Bowen/Burdekin	19.58	147.41	L1	Zucchini	Loam	Min till/Mulch
			L5	Zucchini	Loam	Min till/Mulch
Bowen/Burdekin	20.02	148.25	WC	Zucchini	Loam	Conventional
			WM	Zucchini	Loam	Min till/Mulch
Bundaberg/Gympie	24.89	152.32	DeC	Chilli	Loam	Conventional
			DeOr	Chilli	Loam	Organic
Bundaberg/Gympie	24.89	152.32	DeOl	Chilli	Loam	Conventional
			DeN	Chilli	Loam	Conventional/New
Bundaberg/Gympie	26.18	152.64	GyC	Beans	Clay	Conventional
			GyM	Beans	Clay	Min till/Mulch
Cowra	33.57	148.66	KoR	Chilli	Loam	Organic
			KoW	Chilli	Loam	Organic
Cowra	33.85	148.65	PaN	Corn	Clay	Conventional
			PaP	Corn	Clay	Conventional/Till
Lockyer Valley	27.55	152.33	LMC	Broccoli	Clay	Conventional
			LMO	Broccoli	Clay	Organic
Lockyer Valley	27.55	152.33	ViI	Broccoli	Clay	Interrow
			ViW	Broccoli	Clay	Interrow
Perth	31.92	115.87	BaC	Potatoes	Sand	Conventional
			BaCom	Potatoes	Sand	Compost
Perth	31.92	115.87	DoC	Leafy vegetable	Sand	Conventional
			DoO	Leafy vegetable	Sand	Organic
Sydney	33.62	150.75	SyC	Corn	Loam	Conventional
			SyO	Corn	Loam	Organic
Sydney	34.04	150.69	SyCon	Cabbage	Clay	Conventional
			SyCom	Cabbage	Clay	Compost

Sample collection

At each site a uniform block of 1 ha was chosen and divided into 4 sampling areas, each approximately 0.25 ha. From each sampling area 20 soil cores were randomly collected using a 5 cm diameter auger to a depth of 10 cm. The soil cores were used to form a composite sample for chemical and biological measurements. Samples for biochemical measurements were immediately placed in a foam box with ice. Samples for nematode analysis were kept out of the sun and cooled, but not refrigerated. Samples for chemical analysis were refrigerated overnight before being sent to a commercial laboratory.

Physical soil properties

Physical soil properties measured included soil penetration resistance, bulk density and aggregate stability. Soil resistance was measured using a drop penetrometer, with a cone 3 cm^2 and a 1.0 kg weight dropped over a distance of 1.0 m. The number of drops to force the cone through 10 cm of soil was calculated as the resistance using the formula in equation 1. Resistance readings were determined for 0-10, 10-20 and

20-30 cm intervals. In each 0.25 ha sampling area, 10 recordings to 30 cm depth were made, totalling 40 readings per site.

Equation 1: Calculation of soil resistance using a drop penetrometer

$$\text{Resistance (kg cm}^2\text{)} = \frac{M^2 h n}{2(M + m) S z}$$

Where M = weight of hammer (1.0 kg)
m = weight of penetrometer (2.0 kg)
h = height of hammer drop (1.0 m)
n = number of hammer drops
S = area of hammer tip (cm^2)
z = depth of penetration (10 cm)

Soil bulk density was determined using the procedure described by Arshad *et al.* (1996). Aluminium tubes 7.5 cm d x 10 cm and of known weight were driven into the soil until the ends were level with the soil surface. The wet weight of the soil and tubes was determined before being placed in an oven for three days at 105° C and then reweighed. Three tubes were used per 0.25 ha sampling area totalling 12 readings per site.

Aggregate stability was determined using the method described by Arshad *et al.* (1996). Soil particles were passed through a 2 mm sieve and then 10 g of sieved soil was placed on a 0.25 mm sieve and repeatedly submerged in deionised water at a rate of 30 oscillations per minute for 3 minutes. The soil and sieve were dried at 60° C for 24 hours and reweighed. The soil sample on the screen was submerged in a Calgon® solution (5 g per 3 L of deionised water) using the procedure described above for 3 minutes to determine the sand content of the soil. Again, the soil remaining on the screen was dried and weighed as described previously.

Chemical soil properties

All samples for chemical analyses were sent to a commercial laboratory (IncitecPivot Ltd, Melbourne, Australia) and analysed using the horticulture standard topsoil test. This included analysis for nitrate, phosphorus (Colwell), phosphorus buffer index (PBI), exchangeable cations (CEC), pH (water), chloride, electrical conductivity (EC), electrical conductivity in a saturated extract (ECSE), organic carbon (OC), colour and texture. The methods are described in more detail at http://www.incitecpivot.com.au/laboratory_methods.cfm (accessed 27 November 2008).

Biochemcial soil properties

Labile C was determined as the amount of carbon readily oxidised by $KMnO_4$, using the method described by Weil *et al.* (2003). A 5 g sample of air dried soil was added to a tube containing 2.0 mL of a 0.2 M $KMnO_4$ solution in 1 M $CaCl_2$ (pH 7.2) and made up to 20 mL with distilled water. This was shaken for 2 minutes and then allowed to stand for 10 minutes. A 0.5 mL aliquot, taken from the upper 1 cm of the suspension, was transferred to 45 mL of distilled water and made up to 50 mL and mixed thoroughly. The absorbance of the solution was then determined on a spectrophotometer (Hach) at 550 nm and compared to a standard curve to determine the amount of Labile C in the soil.

The hydrolysis of fluorescein diacetate (FDA) and β-glucosidase activity were determined using the method described by Dick *et al.* (1996). Soil was air dried prior to each analysis and the test performed on 5 g of air dried soil. From each site, 12 soil samples were tested for FDA and β-glucosidase activity.

Microbial biomass C was determined using the chloroform fumigation extraction method (Vance *et al.* 1987). Soil samples were extracted using potassium sulphate (K_2SO_4). The extracts were then analysed using a Carbon Analyser to measure the organic C in the aqueous solution (Wu *et al.* 1990).

Soil nematodes

Nematodes were extracted from soil by placing 200 g of field moist soil on a single layer of tissue contained within a mesh basket (Whitehead and Hemming 1965). The basket was placed in 200 mL of water within a tray and maintained at 25° C. After 48 hours, nematodes contained within the water of the tray were collected on a 25 µm sieve. The nematodes were backwashed from the sieve and collected in a 30 mL vial. The total number of nematodes extracted from 200 g of soil was determined. Using a compound microscope, nematodes were identified to genera for plant-parasitic nematodes or to family for non-parasitic nematodes and assigned to trophic groups according to Yeates *et al.* (1993).

Indices of the nematode community composition were calculated from nematodes extracted from the soil. Nematode diversity was determined using the Shannon-Wiener index, $H' = -\Sigma\, p_i \log_e p_i$, where p_i is the proportion of individuals in the *ith* taxon (Yeates and Bongers 1999). The bacterial-fungal ratio was determined using B/F ratio = B/(B+F) where B and F are, respectively, the relative contributions of bacterivorous and fungivorous nematodes to total nematode abundance, which is constrained to values between 1 (totally bacterivore dominated) and 0 (totally fungivore dominated) (Yeates 2003).

Additionally, the weighted faunal analysis concept was applied, without plant-feeders, to determine the basal, structure and enrichment conditions of the soil food web, as well as the decomposition channel of nutrients (Ferris *et al.* 2001). The enrichment index (EI) assesses the resources available to the soil food web and response by primary decomposers to those resources. The structure index (SI) is a measure of the number of trophic layers in the soil food web and the potential for regulation by predators. The channel index (CI) is an indication of the decomposition channel of nutrients, where a low value suggests a bacterial decomposer community and a high value indicates a fungal-dominated decomposer nematode community (Ferris *et al.* 2001; Hohberg 2003).

Bean bioassay

A bean (*Phaseolus* sp.) seedling bioassay was used to determine the presence of pathogens in the soil. The method was modified from one described by Gugino *et al.*(2007) and involved the visual rating of roots for discolouration. From each sampling site, 16 identical assays were performed on 250 g of soil. The 250 g soil samples were placed in pots with 5 bean seeds placed in each pot 10 mm below the soil surface. The pots were maintained in glasshouse conditions (14 – 28° C) for 5-weeks, after which bean plants were removed and all soil washed from the root systems. Root colour was assessed on a rating scale, 0 for a healthy white root system and 10 for a blackened necrotic root system.

Statistical analysis

The main idea behind the principal component analysis is to use a set of uncorrelated variables, derived from the original data set, to describe or explain the total variation in a multivariate data set. The hope is that the first few uncorrelated variables will describe most, if not all, of the variation in the original data set. This would result in the data dimensions being reduced from the original number of variables with little information held in the original data set being lost. These new independent variables may then be used in further analysis, such as multiple regression and help promote an understanding of the data (Collins and Seeney 1999).

The principle component analysis works by taking a linear combination of the variables and transforming them so that they are uncorrelated. The linear combinations are formed so that the first transformed variable explains more of the variation in the original response variable than any of the other transformed variables. The second transformed variable then explains more of the remaining variability than the remaining transformed variables and so on. These transformed variables or linear combinations are called principal components. If the principle component analysis has been successful then the majority of the variability in the response variable can be explained in the first few principal components and therefore, the original data set has been successfully reduced to two or three dimensions. It should also be possible to 'label' the principle component with an identifier linking it to one or more of the original variables (Collins and Seeney 1999). Ideally the number of principles components used should explain at least 90% of the total variation in the data.

Discriminant analysis is used to determine which variables discriminate between two or more groups. There are known groups of observations and these groups differ with respect to values from a set of independent variables. The variables can be used to produce a linear discrimination that can identify where groups of individuals belong, based on the values of the observed variables for that individual. This is done by forming a linear combination of the independent variables that discriminates between the groups. This linear combination is called the discriminate function. A score can be calculated from the linear combination for each individual that is to be classified into one of the groups and the value of the score will determine to which groups the individual is allocated (Collins and Seeney 1999).

There is a possibility of misclassifying individuals using discriminant analysis. The misclassification rates can be used to indicate the success or the performance of a discrimination rule, or to compare the merits of the different rules that are developed (Collins and Seeney 1999). In our case, we have used the leaving-one-out method (Lachenbruch et al. 1968) by holding out a site from the data set and seeing if the discriminate rule can correctly classify the individual based on the data of the remaining sites.

The aim of the cluster analysis is to determine if there is any inherent grouping amongst individuals or objects in a data set, and to gain an understanding of the data structure. There is no prior knowledge of distinct groups contrasting with the discriminant analysis. Classifying the data into a set of groups with similar individuals or objects can be a means of simplifying the data without a dramatic loss of information (Collins and Seeney 1999). A hierarchical cluster analysis was used where clusters were formed based on group averages and weighted by cluster size.

Results

Site characteristics

Fourteen paired sites, giving a total of 28 individual sites were sampled in the survey. Three-paired sites were sampled in each of the Bowen/Burdekin and Bundaberg/Gympie regions and 2 paired sites in each of the Lockyer Valley, Cowra, Sydney and Perth regions (Table 1). There were a range of crops grown on the sampling sites including beans, zucchini, chilli, sweet-corn, broccoli, potatoes, leafy vegetables and cabbages (Table 1). There were specific regional differences amongst sites. For example, only sites sampled in the Perth region were on sandy soils, while soils in other regions were a mixture of clays and loams (Table 1).

A total of 31 indicators, 6 physical, 10 chemical, 5 biochemical and 10 biological, were measured at each site (Table 2). Variation in soil properties between sampling sites was high for most indicators, but generally the sampled sites had a neutral pH. There was a large range in the physical properties of soil resistance, bulk density and stability of soil aggregates (Table 2). Aggregate stability tests could not be performed accurately on the sandy soils and was, therefore, excluded from the analysis.

Soil nutrient status varied widely, particularly nitrogen, which ranged from 1 to 290 mg kg^{-1} (Table 2). There tended to be high levels of P measured in soil tests with an average of 150 mg kg^{-1}, but levels ranged from 5 to 460 mg kg^{-1} (Table 2). Similarly, soil cation exchange capacity varied from 1.9 to 55.5 with an average 17.9 Meq 100 g^{-1} (Table 2).

All soils tended to have low organic carbon averaging 1.18 %, but ranged from 0.40 to 2.50 % (Table 2). However, microbial biomass carbon levels varied from 11 to 582 µg g^{-1}, with an average of 151 µg g^{-1} (Table 2).

Bacterivores tended to dominate the trophic composition of nematodes in the soil (Table 2). On average, over half the nematodes identified were bacterial feeding with as many as 100% bacterivores on some sites (Table 2). Plant-parasitic nematodes did not make up a large proportion of the nematodes in the soil except at one site, where they were as high as 84% of the nematode population. The diversity of nematode taxa tended to be low with a mean of 1.48, but was as high as 2.11 (Table 2). The enrichment index tended to be high, while the structure index tended to be low, that is, below 50 (Table 2). Both the channel index and the B/(B+F) suggested bacterial dominance of the soil food web in the vegetable soils sampled (Table 2).

The bean bioassay ratings were low which suggested that most soils tended to have low numbers of pathogens that would discolour bean root systems.

Table 2: Means, standard errors and the range of soil indicators, physical, chemical and biological, measured at 14 paired sites under vegetable production.

Indicator	(units)	Mean	(±SE)	Range
Physical				
Resistance (0-10 cm)	(kg cm^{-2})	2.8	(± 0.33)	(18.5 - 0.1)
Resistance (10-20 cm)	(kg cm^{-2})	3.8	(± 0.33)	(16.8 - 0.2)
Resistance (20-30 cm)	(kg cm^{-2})	5.1	(± 0.32)	(16.8 - 1.4)
Bulk density	(g cm^{-3})	1.31	(± 0.02)	(1.89 - 0.98)
Aggregate stability	(%)	40	(± 2.83)	(92 - 3)
Chemical				
pH		7.0	(± 0.07)	(8.1 - 5.1)
Electrical conductivity	(dS m^{-1})	0.32	(± 0.03)	(1.50 - 0.04)
Nitrate nitrogen	(mg kg^{-1})	45	(± 6.24)	(290 - 1)
$P_{Colwell}$	(mg kg^{-1})	209	(± 11.2)	(460 - 5)
PBI*		90	(± 4.26)	(190 - 14)
K	(Meq $100g^{-1}$)	0.7	(± 0.05)	(2.3 - 0.1)
Ca	(Meq $100g^{-1}$)	12	(± 0.82)	(32 - 1)
Mg	(Meq $100g^{-1}$)	5.8	(± 0.92)	(91.0 - 0.2)
CEC#	(Meq $100g^{-1}$)	17.9	(± 1.37)	(55.5 - 1.9)
Na % of cations	(%)	2.4	(± 0.16)	(7.6 - 0.0)
Biochemical				
Organic carbon	(%)	1.18	(± 0.05)	(2.50 - 0.40)
Labile carbon	(mg kg^{-1})	558	(± 12.5)	(789 - 327)
Fluorescein diacetate	(mg fluorescein kg^{-1})	1.15	(± 0.09)	(3.79 - 0.08)
β-glucosidase	(mg P-nitrophenol kg^{-1} soil h^{-1})	77	(± 11.8)	(690 - 0)
Microbial biomass C	(μg g^{-1})	151	(± 11.7)	(582 - 11)
Biological				
Plant-parasitic	(%)	6	(± 1.21)	(84 - 0)
Bacterivores	(%)	54	(± 1.99)	(100 - 10)
Fungivores	(%)	27	(± 1.59)	(73 - 0)
Predators	(%)	13	(± 0.92)	(57 - 0)
Diversity		1.48	(± 0.04)	(2.11 - 0.06)
B/(B+F)		0.66	(± 0.02)	(1.00 - 0.00)
Enrichment	(%)	72	(± 1.28)	(100 - 33)
Structure	(%)	46	(± 2.07)	(100 - 0)
Channel	(%)	26	(± 1.53)	(86 - 0)
Bean bioassay rating		2.3	(± 0.18)	(8.5 - 0.0)

*PBI = phosphorus buffering index, #CEC = cation exchange capacity.

Principal components analysis

To determine the number of principal components that could explain the variability between the sites, the eigenvalues were plotted against the roots (Figure 1). It was determined that 5 principal components were sufficient for analysis (Figure 1). The first five principal components were able to explain 75% of the variation in the data. The principal components could not be easily factorised, but were placed into logical groups according to soil functions with respect to the five indicators with the highest latent vector loading contributing to each principal component. The first principal component was able to explain 29.8 % of the variance and was labelled '*organic matter*' because the important indicators with the highest vector loadings were soil properties associated with additional organic matter, PBI (0.28), microbial biomass C (0.27), β-glucosidase (0.27), organic C (0.26) and CEC (0.26). The second principal component was identified as '*biological decomposition*' because the main contributing indicators were channel index (0.39), fungivore % (0.37), B/(B+F) (-0.35), bacterivores (-0.32) and enrichment index (-0.32) explaining 15.7% of the variation. The third principal component explained 12.8 % of the variation and was labelled '*soil structure*' because the indicators with the highest latent vector loadings were penetration resistance 20-30 cm (-0.37), penetration resistance 10-20 cm (-0.33), Ca (0.31), CEC (0.30) and Mg (0.29). The fourth principal component was labelled '*disease suppression'* and was able to explain 10.1 % of the variation with the contributing indicators being structure index (0.44), Na% (0.43), predator % (0.42), pH (0.38) and bean bioassay rating (-0.25). The fifth principal component was labelled '*soil surface condition*' and was made up of a mix of indicators with the highest vector loadings and consisted of penetration resistance 0-10 cm (-0.40), P (0.39), penetration resistance 10-20 cm (-0.29) labile C (0.22) and organic C (0.22) and was able to explain 7.1 % of the variation.

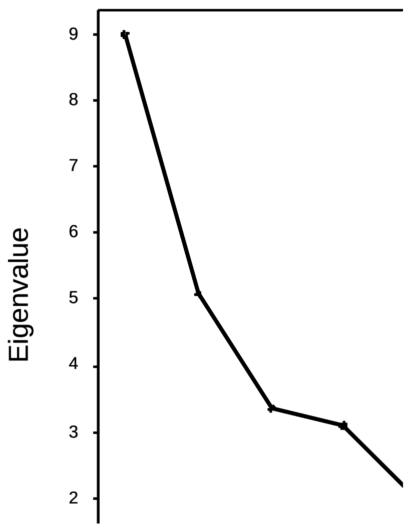

Figure 1: Scree plot of roots and eigenvalues to determine the minimum number of principal components that contribute to the explanation of the variability in the data.

Soil texture

A discriminant analysis function was derived to determine if it was possible to discriminate sites based on soil texture. Three broad soil textural classes were determined from soil test results; clay, loam and sand. Using an initial subset of variables selected from the heavily weighted variables in the first five principal components, indicators with low weightings in the discriminate analysis were sequentially removed until a site was classified in the incorrect textural class. This made it possible to determine a minimum data set that was able to discriminate between soil textural classes.

Eleven indicators (penetrometer resistance 0-10 and 10-20 cm, bulk density, nematode diversity, FDA, pH, PBI, Na%, organic C, ratio of nematode bacterivores to fungivores (B/(B+F)), and electrical conductivity) were needed to discriminate sites based on texture (Figure 2). The first discriminate function was able to explain 85 % of the variation, whereas, the second function described the remaining 15%.

Clay soils tended to have greater soil resistance, nematode diversity, organic C and PBI relative to sandy soils (Table 3). However, the sandy soils tended to be more bacterially dominated and had a greater soil bulk density relative to clay soils (Table 3). The loam soils tended to be intermediate in their soil properties, but had soil resistance, diversity, FDA and B/(B+F) similar to clay soils and bulk density and organic C similar to sandy soils (Table 3). Bulk density, nematode diversity, organic carbon and B/(B+F) were all indicators with weightings greater than 1 in the first and second discriminant functions (Table 3). Additionally, FDA had a weighting greater than 1 in the second discriminant function (Table 3).

Using the 11 indicators for texture, the leave-one-out analysis was able to correctly assign each site in the training set when the classification was known. However, when the classification was unknown, it failed to correctly assign two sites that were assigned as clay texture PaP and ViI, classifying them as loam texture soils.

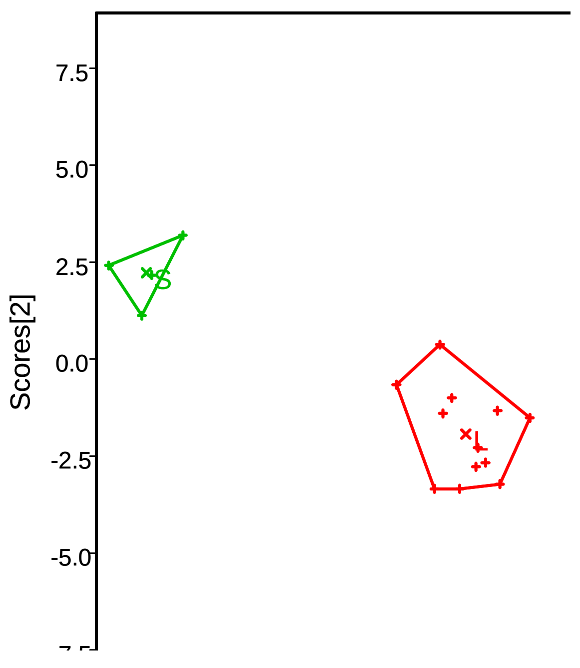

Figure 2: Scores on the two significant discriminate functions based on R10, R20, bulk density, diversity, FDA, pH, PBI, Na%, organic carbon, B/(B+F) and EC in three soil textural classes (C = clay, L = loam and S = sand).

Table 3: Means, standard errors and weightings of indicators used to discriminate between soil textural classes (clay, loam and sand) in vegetable production systems.

Indicator	Soil texture			Discriminate function weightings	
	Clay	Loam	Sand	1	2
Resistance (0-10 cm)	3.5 ±1.1	2.7 ±1.1	1.2 ±0.1	0.42	0.45
Resistance (10-20 cm)	4.4 ±1.0	3.9 ±1.0	1.5 ±0.2	-0.34	-0.51
Bulk density	1.15 ±0.03	1.46 ±0.06	1.31 ±0.07	-1.55	-2.53
pH	7.4 ±0.2	6.7 ±0.2	6.6 ±0.5	-0.08	0.37
Electrical conductivity	0.51 ±0.11	0.19 ±0.04	0.12 ±0.03	0.30	0.47
Phosphorus buffering	129 ±7	67 ±8	39 ±16	0.10	0.05
Na%	2.7 ±0.6	2.3 ±0.4	1.4 ±0.5	0.68	-0.15
Organic C	1.40 ±0.14	1.03 ±0.11	0.95 ±0.34	-4.71	-2.29
Fluorescein diacetate	1.15 ±0.24	1.42 ±0.30	0.35 ±0.08	0.87	1.15
Nematode diversity	1.65 ±0.05	1.62 ±0. 0.06	0.55 ±0.14	3.33	-3.63
B/(B+F)	0.63 ±0.03	0.59 ±0.05	0.92 ±0.06	-3.20	5.21
Variation (%)	-	-	-	85	15

Organic matter additions

A discriminant analysis function was used to determine if sites could be correctly separated based on organic matter application, followed by validation using the leaving-one-out method to develop a minimum data set. As there were only two categories, with and without additional organic matter, only one discriminate function was calculated. Eleven indicators were needed to be able to discriminate sites based on organic matter additions to the soil.

The sites with additional organic matter tended to have greater organic C and penetration resistance relative to sites without additional organic matter (Table 4). Conversely, sites not receiving any additional organic matter tended to have greater bulk density, Na% and channel index, indicating greater fungal decomposition of organic material. Three indicators; bulk density, organic C and FDA all had weightings greater than 1 in the discriminant function (Table 4).

Using the 11 indicators for organic matter addition, the leaving-one-out method was able to correctly assign 90% of the sites which had additional organic matter and 94% of the sites in the training set when the classification was known. However, when the classification was unknown it failed to correctly assign 1 out of the 9 sites with additional organic matter, incorrectly classifying the site BaCom, and 2 out of the 17 sites with no additional organic matter, incorrectly classifying the sites DoC and SyCon.

Table 4: Means, standard errors and weightings of indicators used to discriminate between additional and no-additional organic matter incorporated in vegetable production systems.

Indicator	Organic matter		Discriminant function weightings
	Additional	No-additional	
Resistance (10-20 cm)	4.3 ±1.3	2.1 ±0.7	0.15
Bulk density	1.22 ±0.04	1.34 ±0.06	-3.78
pH	7.2 ±0.2	6.9 ±0.2	0.48
Nitrate nitrogen	25 ±7	36 ±14	-0.03
Mg	5.4 ±1.9	5.9 ±1.8	-0.17
CEC	20.7 ±4.9	16.5 ±3.4	0.15
Na%	1.9 ±0.3	2.5 ±04	-0.37
Organic C	1.42 ±0.18	1.06 ±0.10	4.65
FDA	1.12 ±0.28	1.17 ±0.22	1.67
Microbial biomass C	182 ±49	134 ±20	-0.02
Channel index	19 ±3	30 ±3	-0.08

Traffic management

A discriminant analysis function was used to determine if the sites could be correctly separated based on the type of traffic operation they employed on the farm, either controlled traffic or normal traffic. As there were only two categories, a single function was calculated which required 9 indicators to discriminate the sites based on the traffic management adopted (Table 5).

The sites where traffic was controlled tended to have greater resistance, β-glucosidase, Ca, Mg, CEC and organic C relative to normal traffic management (Table 5). Conversely the normal traffic sites tended to have greater soil bulk density. Bulk density had the highest weighting of the indicators, but no indicator had a weighting greater than 1 (Table 5).

Using the 9 indicators for traffic management, the leaving-one-out method was able to correctly assign 91% of the sites which had controlled traffic and all of the sites with normal traffic in the training set when the classification was known. However, when the classification was unknown it failed to correctly classify 2 out of the 8 sites with controlled traffic, incorrectly classifying the sites Le5 and WiM and 1 out of the 17 sites with normal traffic, incorrectly classifying the site KoW.

Table 5: Means, standard errors and weightings of indicators used to discriminate between types of traffic, controlled or normal traffic, used on sites.

Indicator	Traffic management		Discriminate function weightings
	Controlled	**Normal**	
Resistance (0-10 cm)	4.7 ±1.1	1.8 ±0.7	0.15
Bulk density	1.16 ±0.03	1.39 ±0.05	-0.56
Nitrate nitrogen	26 ±7	36 ±15	-0.02
Ca	19.9 ±2.4	6.9 ±1.2	0.27
Mg	10.2 ±1.8	3.3 ±1.6	-0.23
CEC	32 ±4	10 ±2	0.05
Organic C	1.48 ±0.14	1.00 ±0.11	0.21
β-glucosidase	186 ±47	16 ±10	0.01
Bean bioassay	2.7 ±0.7	2.0 ±0.3	0.16

Nutrient management

There was a wide range of variability in the nutrient contents in the soil (Table 2). A cluster analysis was able to group sites into three groups with similar soil nutrient contents regardless of the soil textural group (Figure 3). The data used to determine the cluster analysis was based on the results of the standard nutrient test supplied by the commercial laboratory, which included all of the chemical results, as well as organic carbon from Table 1.

Group 1 included 10 sites; DeC, DeOr, DeOl, DoC, DeN, BaC, BaCom, KoW, KoR and WC. These sites had a similarity in soil nutrient analysis of greater than 95%. Group 2 included 9 sites; DoO, SyC, SyO, WM, SyCon, SyCom, L1, L5 and GyM. These sites had a similarity in nutrient content of the soil greater than 90%, but their similarity was less than 90% with the first group (Figure 3). The third group of sites consisted of all remaining sites and included 9 sites; BC, BCom, ViI, LMC, LMO, GyC, ViW, PaN and PaP. The third group of sites had a similarity greater than 80%, but were less than 80% similar to the other two groups (Figure 3).

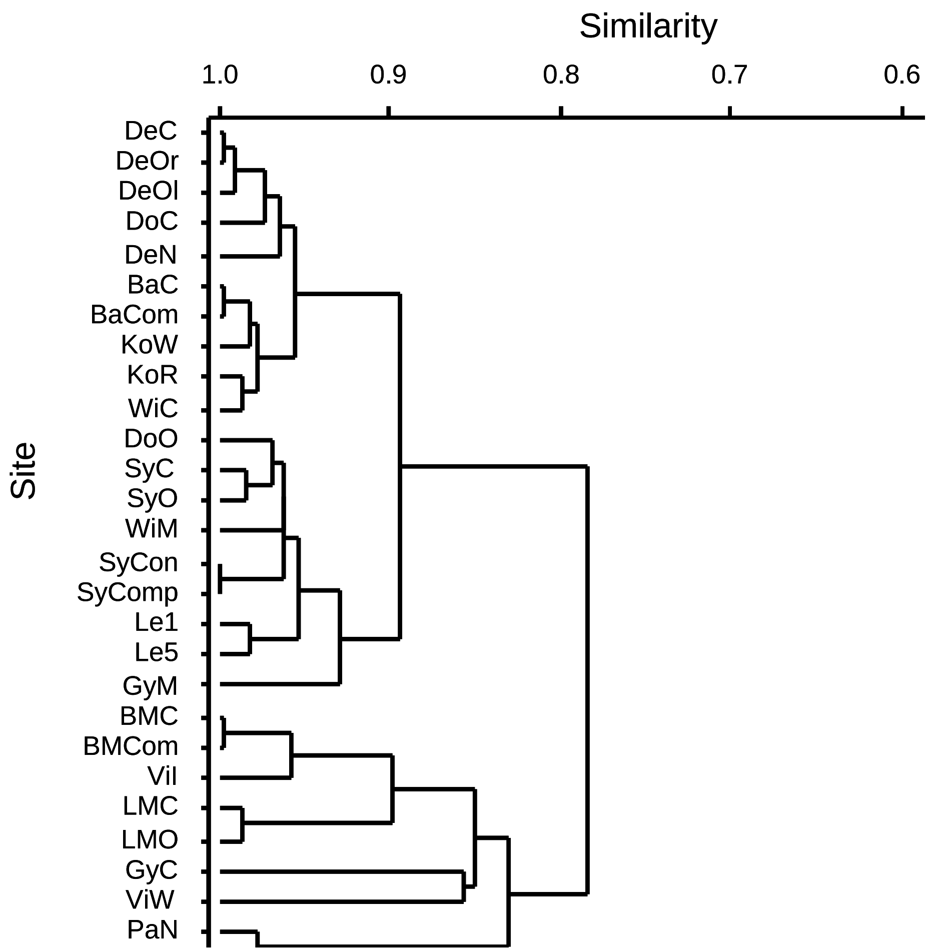

Figure 3: Cluster analysis of sites surveyed based on soil nutrient content of sites

A discriminant analysis function was used to determine if it was possible to separate sites based on the nutrient groups. The three nutrient groups 1, 2 and 3 assigned from the cluster analysis were retained in the discriminant analysis.

As there were three groups it was possible to separate the nutrient groups using two discriminate functions (Figure 4). The first discriminate function was able to explain 86% of the variation and the second function the remaining 14% of the variation between the sites. Four indicators, nitrate nitrogen, $P_{Colwell}$, CEC and Na% were able to discriminate between the nutrient groups (Figure 4). Sites belonging to nutrient group 3 tended to have greater nitrate nitrogen, CEC and Na% relative to the other nutrient groups (Table 6). Sites belonging to nutrient group 2 tended to have greater $P_{Colwell}$ relative to sites belonging to nutrient groups 1 and 3 (Table 6).

Using these 4 indicators the leaving-one-out method was able to correctly assign each site in the cross classification training set when the classification was known and unknown for each of the nutrient groups.

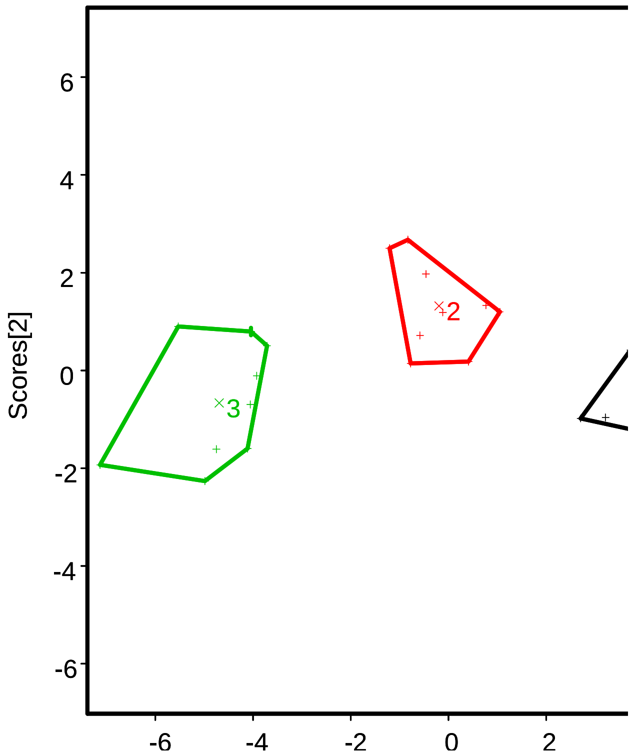

Figure 4: Scores on the two significant discriminate functions based on nitrate-nitrogen, $P_{Colwell}$, CEC and Na% in three soil nutrient groups (1, 2 and 3) based on cluster analysis groupings.

Table 6: Indicators, weightings, means and standard error of nutrient groups 1, 2, and 3 based on cluster analysis groupings.

Indicator	**Nutrient group**			**Discriminate function weightings**	
	1	**2**	**3**	**1**	**2**
Nitrate nitrogen	11 ±3	21 ±3	68 ±26	0.01	0.01
$P_{Colwell}$	106 ±27	309 ±3	222 ±30	0.01	0.01
CEC	4.9 ±0.7	14.1	36.0 ±3.4	0.21	0.03
Na%	1.8 ±0.4	2.3 ±0.4	3.0 ±0.7	0.65	0.17
Variation (%)				86	14

Vegetable production systems

A discriminate function was constructed to determine if indicators were able to separate sites based on farming systems. Five different farming systems were recognised from the 28 individual sites; conventional (13 sites), additional compost (3 sites), minimum tillage - mulch (4 sites), organic (6 sites) and crop interrow (2 sites). The first 2 discriminate functions combined were able to explain 90% of the variation between the sites (Figure 5). Sixteen indicators were needed to be able to discriminate the sites based on the type of production system the sites had adopted (Table 7).

The interrow system tended to have high soil resistance 0-10 cm, nematode diversity, CEC, Ca and bean bioassay mean values relative to other vegetable systems (Table 7). Conversely, the interrow systems tended to have a low B/(B+F) relative to other systems. The conventional system tended to have lower pH, but greater nitrate nitrogen and bulk density mean values relative to other systems (Table 7). The organic systems tended to have lower soil resistance, nitrate nitrogen, Ca, β-glucosidase and enrichment index, but greater Na% mean values than other systems (Table 7). The minimum tillage/mulch systems had the greatest $P_{Colwell}$ and organic C, but lower structure index mean values. The compost system had the lowest organic C, nematode diversity and bean bioassay, but the greatest B/(B+F) and enrichment index mean values relative to all other systems. Resistance (0-10), nitrate nitrogen, $P_{Colwell}$, PBI, Ca, Na%, enrichment index and structure index all had weightings greater than 1 in the first discriminate function, whereas CEC, Na% and B/(B+F) had weightings greater than 1 for the second discriminate function (Table 7).

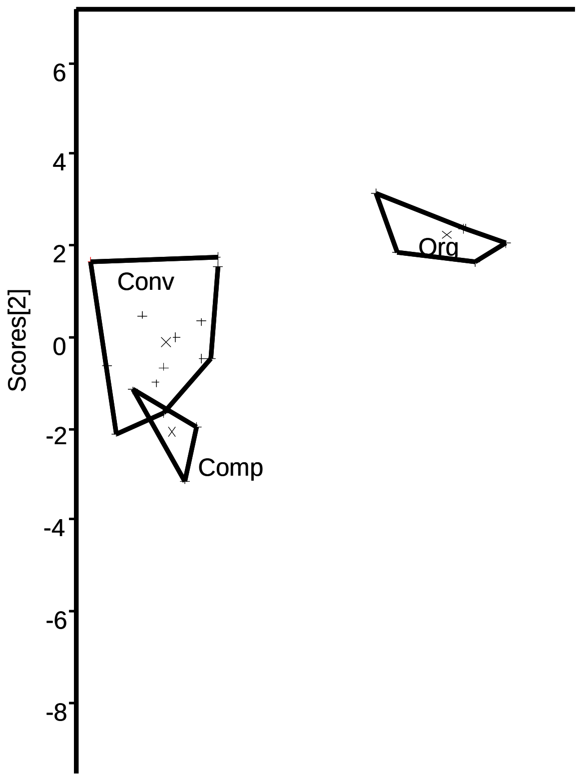

Figure 5: Scores on the two significant discriminate functions based on systems used by vegetable growers (where Conv = conventional, Comp = compost addition, Org = organic production, Min till/mulch = minimum tillage mulch and Interrow = crop interrow).

Table 7: Means, standard errors and weightings of indicators used to discriminate between vegetable production systems.

Indicator	Vegetable production system					Discriminate function weightings	
	Compost	Convent.	Interrow	Min- till	Organic	1	2
Resistance (0-10 cm)	1.5 ±0.4	1.3 ±0.2	9.8 ±2.4	5.7 ±2.0	1.1 ±0.2	1.60	0.05
Bulk density	1.31 ±0.02	1.35 ±0.07	1.23 ±0.20	1.22 ±0.05	1.29 ±0.08	-0.04	0.01
pH	7.4 ±0.3	6.8 ±0.2	7.2 ±0.3	7.1 ±0.4	7.2 ±0.2	-0.17	0.07
Nitrate nitrogen	16 ±10	47 ±20	20 ±8	33 ±13	13 ±5	4.04	0.14
$P_{Colwell}$	153 ±68	191 ±30	135 ±57	280 ±33	274 ±69	-2.08	-0.10
PBI	81 ±31	87 ±13	108 ±38	102 ±13	79 ±18	1.61	-0.92
Ca	12.7 ±6.4	10.3 ±2.4	19.8 ±8.2	12.0 ±2.2	8.7 ±3.0	2.92	2.08
CEC	19 ±11	16 ±4	33 ±14	17 ±2	13 ±5	0.02	-0.01
Na%	2.1 ±0.4	2.5 ±0.6	1.9 ±0.3	1.9 ±0.6	2.7 ±0.6	-10.42	7.65
Organic C	0.81 ±0.04	1.06 ±0.13	1.49 ±0.51	1.52 ±0.07	1.24 ±0.23	0.09	0.12
β-glucosidase	32 ±29	38 ±18	259 ±171	155 ±33	31 ±23	-0.09	0.02
B/(B+F)	0.78 ±0.09	0.66 ±0.05	0.49 ±0.06	0.61 ±0.09	0.67 ±0.08	-0.67	3.49
Enrichment index	81 ±7	72 ±4	70 ±5	74 ±2	68 ±6	1.51	-0.21
Structure index	48 ±13	44 ±5	51 ±9	42 ±1	47 ±8	1.60	0.05
Nematode diversity	1.41 ±0.29	1.44 ±0.14	1.63 ±0.09	1.60 ±0.15	1.44 ±0.21	0.03	-0.04
Bean bioassay rating	1.0 ±0.4	2.0 ±0.3	3.8 ±1.9	2.5 ±1.2	2.5 ±1.2	-0.17	0.07
Variation (%)						79	15

Using the 16 indicators for farming systems, when the classification was known, the leaving-one-out method was able to correctly assign 100% of the sites with compost added, 100% of the interrow sites, 100% of the minimum tillage/mulch sites and 100% of the organic sites, but only 89% of the conventional sites, placing 11% of the conventional sites into sites with additional compost. However, when the classification was unknown it failed to correctly classify two out of three of the compost sites, classifying them as conventional sites (Table 8). Furthermore, the leaving-one-out method only correctly classified 7 of the conventional sites, incorrectly classifying 4 conventional sites as having compost added and 2 conventional sites as being organic (Table 8). The leaving-one-out method also incorrectly placed the interrow sites as minimum tillage/mulch and an organic system (Table 8). Additionally, only 3 of the minimum tillage/mulch systems were correctly classified, with 1 site incorrectly classified as an interrow system (Table 8). Four organic sites were correctly classified, but one site was incorrectly classified as having a conventional production system (Table 8). In total, when the classification was unknown, the leaving-one-out approach was only able to correctly classify 15 out of the 28 individual sites into the correct vegetable production system (Table 8).

Table 8: Leaving-one-out analysis table of sites allocated to different farm practices (*P*=0.002)

System	Compost	Conventional	Interrow	Min till / mulch	Organic
Compost	1	4	0	0	0
Conventional	2	7	0	0	1
Interrow	0	0	0	1	0
Mulch/no tillage	0	0	2	3	0
Organic	0	2	1	0	4
Total sites	3	13	3	4	5

Discussion

Soil health indicators were good at predicting and measuring changes in practices, but were poor at determining the differences between farming systems. In general, the more complex the system, the more subtle the changes in management, or the less time between changes in soil management practices, the greater the number of indicators that were required to be able to detect differences in soil properties. For example, in the classification of the vegetable production systems, the analysis was unable to correctly classify all of the interrow sites, but was only able to correctly classify 80% of the organic and 75% of the minimum tillage/mulch systems.

There are three possible explanations why the indicators were not able to detect accurately the differences between production systems. Firstly, the indicators were not sensitive to change or were inappropriate for the farming system. However, when soil tests were conducted to compare practices, a set of indicators were able to discriminate between the practices. This suggested that selected indicators were sensitive to single practice change like nutrient management, organic matter additions or traffic management. The second explanation for the failure of indicators to detect differences between farming systems was that some farming systems had not changed soil properties compared with the conventional systems. This is more likely than the first explanation, as changes in soil properties can occur slowly and depending on the changes in the production system, changes may have needed to been in place for a long period of time to alter soil properties. Some of the farming systems only had subtle changes in management compared with conventional systems, so that there were overlapping differences in soil properties. Finally, the variability due to soil types was another factor that was not able to be fully accounted for due to the limited size of the study and may have had confounding effects on the different vegetable production systems.

In order to fully understand the differences that were occurring in the soil with different farming systems and relate them to the soil functions that support vegetable production, it is necessary to have physical, chemical and biological soil indicators. The division of farms into groups based on nutrient levels was not explained with physical and biological indicators, requiring only the chemical indicators nitrate nitrogen, $P_{Colwell}$, CEC and Na% to be able to differentiate between groups. However, when viewing vegetable production in a systems context, a greater number of indicators are required to demonstrate differences in soil properties and functions.

The indicators measured tend to focus on how soils function in relation to nutrient supply, soil structural stability and pest and disease suppression. Less attention was given to other soil functions like water storage and supply and toxins in the soil. This is because nutrient management and pest and disease suppression are seen as factors within the production systems that are able to be managed by altering farm practices, such as product application or rates. Soil structural stability is relevant to clay soils that are compactable or where the loss of soil aggregate formation is possible. However, the indicators for aggregate stability are often slow to change which means that soil structural stability is not given the same priority as nutrient and pest and disease management. While there are indicators that can be used as surrogates for soil nutrient and soil structural stability functions within vegetable production systems, there are few that have been related to suppression of pests and diseases. In this study, we used a bean bioassay as well as soil nematode assemblages, but there is still a lack of information on how these indicators correlate to pest and disease suppression in different vegetable production systems. This meant that pest and disease suppression was not given as high a priority as nutrient management and maintaining soil structural stability in determining what constitutes a healthy vegetable production system. However, the ability of soils to function in sustainable vegetable production systems also requires knowledge of the inherent constraints placed on the system by soil type and environment (Moody and Cong 2008; Sanchez *et al.* 2003).

Soil texture was a good indicator of the inherent physical, chemical and biological properties of the soil. Therefore, any assessment of soil health needs to account for the differences in soil type even if it is using broad groupings of soil texture such as clay, loam and sand soils. Soil texture impacted on not only soil physical properties (penetrometer resistance and soil bulk density), but also chemical properties (pH, PBI, organic C and Na%) and biological properties (nematode diversity, FDA hydrolysis and B/(B+F)). This suggested that clay soils had a greater capacity for nutrient storage and supply, with some buffering capacity against changes. This is evident from the neutral soil pH, greater PBI, greater resistance to penetration, increased FDA activity and nematode diversity in clay soils relative to sandy soils. Therefore, any comparison of indictors across soil types should be adjusted for the soil type differences. The inclusion of soil type differences as a covariate may have helped to give better predictions of farming systems and indicators of farming systems on soil indicators. Due to the small data set, it was not possible in this study to perform this type of analysis with confidence.

Farm managers can have a large influence on the soil nutrient status through the application of fertilisers. The ability of the soil to retain and supply nutrients could largely be attributed to soil textural differences. Most of the sites included in this survey had adequate nutrients, with an over supply of nutrients evident at some sites. However, only four indicators were needed to be able to discriminate between nutrient management, which were nitrate-nitrogen, phosphorus, CEC and Na%. The CEC and Na% are mainly related to inherent soil properties, although they can be modified to a limited extent by management. However, nitrogen and phosphorus contents of the soil are largely based on farm management inputs. All soil sampling was conducted prior to the first harvest of the various vegetable crops to standardise crop physiological aspects. Based on the means from the different nutrient groups formed in the cluster analysis of soil chemical test results, the sites in group 1 tended to have low inherent capacity to retain nutrients, low CEC, nitrate and $P_{Colwell}$ results.

This suggested that soil in this group of sites was either unable to retain nutrients or fertiliser application was low and the nutrients were used by the end of the cropping cycle. Sites belonging to group 2 had moderate capacity to retain nutrient (CEC = 14.1), moderate nitrate nitrogen levels in the soil, but very high P. This would suggest that these sites tended to have an over use of P inputs, while being able to manage nitrogen inputs. The sites, which were placed into group 3, had high nutrient holding capacity, relatively high P and very high nitrate N compared with the other nutrient groups with the nutrients being retained after the cropping phase. This suggested that the sites placed into this group tended to overuse nitrogen inputs, while having better management of P inputs, although P levels are still greater than 150 mg kg^{-1} which is a maximum threshold suggested by Chan *et al.*(2007). In vegetable systems surveyed, it appeared that nutrient inputs need to be better matched to crop needs to improve nutrient use efficiency and reduce nutrient loss off the farm.

The implementation of organic production systems incorporates many different practices and can reflect the goals of the land manager. During the survey, it was apparent that some managers had adopted organic practices with the desire to develop a better farming system, while others had adopted organic practices in order to take advantage of increased market prices for organic produce. Therefore, changes in soil properties in organic production systems were influenced by the attitude of the farm manager. The attitudes of land managers to soil health and their social position have been found to be an important factor in studies on soil health and influenced farmers acceptance of new practices (Brodt *et al.* 2006; Lobry de Bruyn and Abbey 2003; Vanclay 2004).

The minimum tillage/mulch systems were correctly identified three out of four times using the leaving-one-out method of classification of farming systems. This suggested that soil properties at sites where this system had been introduced had changed to the extent that they could be uniquely identified from conventional systems. The sites surveyed were long term minimum tillage systems, which had allowed time for soil properties to change. Because minimum tillage systems represent a change in farming systems rather than adoption of a single practice or substitution of inputs, it had a greater effect on changes to soil properties. The farms that had adopted minimum tillage mulch systems had committed to change and invested in new machinery and adoption of their production systems to ensure the success of the system and, therefore, their attitude to soil health was different from other sites.

The addition of organic matter is seen by many growers as being able to increase soil health and was found to affect physical, chemical and biological soil properties. The results from this survey suggested that soil resistance (0-10 cm), bulk density, nematode diversity, FDA, pH, PBI, Na%, Organic C, B/(B+F) and EC were all sensitive to changes in organic matter management practices. Sites that had additional organic matter applied in the forms of compost, mulches or green manures, tended to have greater organic C, microbial biomass C and CEC. Furthermore, sites that received additional organic matter tended to favour a bacterial decomposition pathway of nutrients as determined by a lower channel index. The bulk density of sites with additional organic matter was lower than sites not receiving any additional organic matter inputs, but the penetration resistance in the top 10 cm tended to be greater, where additional organic matter had been applied.

However, the leave-one-out method incorrectly classified one site with additional organic matter, BaCom, and two sites which did not receive additional organic matter, SyCon and Doc. The incorrect classification of the BaCom and DoC site may have occurred because the sites were on sandy soils. The soil texture contributed significantly to the soil properties and there was only a small data set of sites on sandy soils, resulting in the difficulty of the leave-one-out method to be able to correctly classify the site. The SyCon was on a light clay soil that had been used for vegetable production for greater than 50 years and was compared with a site that had received a single application of compost two months prior to planting cabbage in 2008. The application of the compost had not changed the soil properties relative to the conventional site and may have contributed to the misclassification of the SyCon site.

The addition of compost is a practice that has been recently adopted by some vegetable producers because of the availability of the product as well as the desire to quickly improve soil carbon levels. The sites that had incorporated compost had applied it as an opportunistic practice. Results from the farming system analysis showed that addition of compost was difficult to discriminate from conventional farm management practices. In contrast, other methods of organic matter management that integrated farming practices, such as minimum tillage/mulch systems were able to be discriminated with better accuracy from conventional sites. This would suggest that compost addition should not be seen as a quick fix practice to improve soil health, but rather it needs to be integrated in with other farm practices to be able to have a positive benefit on soil properties. However, further work is required to determine the quantity, quality and time needed for organic matter additions to impact on soil properties and improve soil functions.

The movement of traffic across the soil surface is of growing concern amongst vegetable producers especially on clay soils susceptible to compaction. The type of traffic management could be determined using penetration resistance (0-10), bulk density, nitrate N, CEC, organic C, β-glucosidase, Ca, Mg and bean bioassay ratings. The indicators selected reflect some of the inherent soil properties influenced by traffic management. For example, clay soils are more likely to have issues with traffic management than sandy soils. The data set was not large enough to be able to separate out the covariate influence of soil textural groups on traffic management indicators. This may have led to the misclassification of the Le5 and WiM sites, which had controlled traffic, but had a loam texture, whereas all other controlled traffic sites, except Le1, were on clay soils. The leaving-one-out method may have incorrectly classified the KoW site, which had normal traffic, but was incorrectly classified as controlled traffic due to confounding effects of being sampled from wheel tracks on a soil with sub-soil compaction. The wheel track area had high penetration resistance due to the traffic movement and the neighbouring row area had sub-soil compaction which contributed to lateral movement of irrigation water with nutrients confounding the chemical soil properties in the wheel tracks.

The sites with controlled traffic management had higher CEC, Ca and Mg contents relative to sites with normal traffic types. It would not be expected that these indicators would change with traffic management, but reflect the inherent soil properties where traffic management is an important issue. However, other physical factors such as bulk density and penetration resistance would be expected to change depending on traffic management. Interestingly the penetrometer resistance and soil bulk density are in contrast to one another. The penetrometer resistance reading in the top 10 cm would suggest there is greater soil resistance with controlled traffic management, but the bulk density measurements would indicate greater compaction under normal traffic management. The higher bulk density measurement may be partly attributed to soil type differences, as sandy soils tended to have a higher bulk density.

Traffic management was also able to impact on the biological soil properties, organic C, β-glucosidase and the bean bioassay results, which all tended to be greater in controlled traffic management sites. This suggested that there is a strong interaction between physical and biological soil properties and management of traffic movement. Therefore, careful management of the physical properties in clay soils is also beneficial for the soil biology and organic C conservation, increasing activity and favourable biological characteristics.

The multivariate statistical approach of reviewing the survey data allowed the interaction of soil physical, chemical and biological properties of vegetable production systems to be assessed in terms of different soil functions, practices and farming systems. Further validations of the indicators that have been developed from this survey are required, particularly in farming system type experiments where there is greater control between the variability of farming systems.

Conclusion

Soil health indicators were able to detect changes between management practices, but were not as accurate at detecting differences between vegetable production systems. Differences in indicators depended on the type of practice change being adopted and the length of time for which the practice change had been adopted. Soil type, based on soil textural differences was a major factor influencing soil management in vegetable production and the constraints of the different soil types need to be managed. Further work is needed to develop a framework or decision tool that allows vegetable growers to decide the best set of practices to overcome the constraints relating to their soil type. Once this has been decided, the indicators relating to soil functions can be used to determine and monitor changes occurring in physical, chemical and biological soil properties.

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Part B: Technology transfer

Technology transfer has been an integral part of the project VG06100, to collect and disseminate information on soil health to vegetable growers. The soil health manual will continue to be disseminated after the life of the project. Stakeholders involved in the project were kept up to date of the progress of the project through a newsletter. Information days for growers were held in vegetable production areas to keep growers informed of the results from the project and get interaction on what they considered to be important in soil health research for the vegetable industry. Furthermore, presentations were made at a national level in 2007 and 2009 at the national vegetable industry conference. A presentation was also made at the IV International ISHS Symposium - Toward Ecologically Sound Fertilisation Strategies for Field Vegetable Production, which was held at in Malmo, Sweden from the 22-25th September 2008.

The project achieved many of the original objectives by increasing the knowledge and awareness of soil health within the vegetable industry. The target regions for the project were vegetable producers in Queensland, New South Wales and Western Australia. However, collaboration with the Department of Primary Industries in Victoria through VG06090 allowed greater project synergy and extension of project findings into other states. Over 2500 newsletters highlighting project activities were distributed four times over the life of the project.

A greater understanding of the motivation for growers to adopt soil health management practices was obtained during the project. Information days which highlighted project activities, demonstrated practice changes being made by growers, allowed hands on demonstration of soil health monitoring techniques and provided a forum for feedback from vegetable growers. While, improved profitability was not always the primary motivator for grower's interest in soil health, it was assumed by growers that healthy soil systems would be more profitable in the long term. Growers that had converted to "more sustainable practices" suggested they changed to find "a better way to farm". However, there was still confusion about soil organic carbon, the best way to increase soil carbon levels and the benefits it would achieve.

Many vegetable growers routinely take soil tests for nutrient analysis and fertiliser recommendations. This data is useful in soil health monitoring but is largely unutilised by growers because of the lack of tools that enable the data to be scrutinised in terms of soil health management. Growers were reluctant to do soil health monitoring due to time restrictions, but many were interested in the results. Therefore, other tests for soil health monitoring would be dependent on industry service providers. For example, as a result of this project labile carbon testing is being offered by an industry service provider for his clients.

Vegetable growers have become interested in soil health management practices as a result of this project. In particular, there is increasing interest in minimum tillage / mulch systems. This has the advantage of reducing farm inputs and increasing soil carbon. Growers were also experimenting with compost applications on their farms. The technology transfer attached to the research survey allowed a greater two-way exchange of information to develop a greater understanding of soil health in vegetable crops.

Soil health manual

While one of the project outcomes, the soil health manual was not the main thrust of the project and was very much a product developed at the end of the project. Extension of the manual was not planned as a core outcome of this project, and could not have been achieved within the timeframe and resources allocated to developing the manual as part of the project. Also time and resources have not allowed a more rigorous scientific review of the manual, particularly relating to the soil biology aspects. Similarly we were not able to develop accurate practical measures of soil biology within the time and scope of the project. Hence the manuals title as a draft.

Despite the above, project team members see value in getting what has been developed out to the industry, and plans are in place to pursue getting all or part of the manual onto the DEEDI website and Australian Vegetable Industry Soil and Land Management Knowledge Exchange web site. The manual will be hosted on the web site of the Department of Employment, Economic Development and Innovation, Queensland Primary Industries and Fisheries (http://www.deedi.qld.gov.au/) and the Australian Vegetable Industry Soil and Land management Knowledge Exchange (http://knowledge-exchange.ausveg.com.au/). The availability and the web address of the manual will be advertised to the vegetable industry. In the event of successful follow up funding for a new soil health project more resources will be used into getting the manual onto the web and improving its content over time, particularly in the area of soil biology.

We have sent the manual out to a few industry people for review with positive feedback, and have allowed them to pass it onto colleagues or to use in the course of their work. We will not be offering training or developing hard copies of the manual for distribution.

A short summary of the manual has been developed into a AUSVEG Vegenote issue 12, "indicators of soil health" available from AUSVEG.

Appendices\Soil Health Manual _final report_.pdf

VegPASH newsletters

Four newsletters were distributed both electronically and as hard copies to vegetable growers and industry service providers. The newsletter were distributed as a mail out to 1200 vegetable producers in Queensland, 900 vegetable producers in New South Wales and 450 vegetable producers in Western Australia. Further electronic copies of the newsletter were sent to Department of Primary Industries and Fisheries staff in Queensland and 200 were sent nationally to the industry development officer network, throughout Australia. However, with changes in the industry development officers network within Australia, particularly within the vegetable industry the final newsletter had not been disseminated as widely as hoped. Three newsletters have been posted on the Australian Vegetable Industry Soil and Land management Knowledge Exchange http://knowledge-exchange.ausveg.com.au/programs.php?id=12 and the final newsletter will also be placed on the web site.

A summary of the newsletters is given below:

Volume 1: June 2007

What are the aims of the VegPASH project?

The project is a two year scoping study that aims to increase the awareness of the importance of soil health in vegetable production, explore practical solutions for improving and measuring soil health and provide information on soil health to the vegetable industry.

There are four parts to the project:

1. Set up grower reference groups in six districts around Australia to provide soil sampling sites and ensure that the project remains on track and practical.
2. Sample soils on 12 farms around Australia and measure chemical, physical and biological properties of these soils.
3. Analyse results to develop diagnostic tools sensitive to changes in soil management and plant health in the vegetable industry.
4. Extend the results and outcomes of the project to the vegetable industry using field days, soil health manuals and this newsletter.

What makes a healthy soil?

There are many ways to describe a healthy soil. We are looking for an easy to understand, short, elegant but down to earth definition of what makes a healthy soil. So get thinking, jot down some words and send them to the VegPASH news editor

VegPASH news Jun 2007: http://knowledge-exchange.ausveg.com.au/programs.php?id=12

Volume 2: November 2007

Results from Gympie farms

Two bean farms were sampled in Gympie. One uses a low-till permanent mulch system; the other farm grows beans conventionally. The conventionally farmed soil had 5% more pore space than the low-till soil (calculated from bulk density readings). This slight difference in soil compaction can largely be accounted for by deep ripping and cultivation for seed bed preparation in the conventional site. Water infiltration took twice as long at the low-till site compared to the conventional site in dry soil and 2.5 times as long in wet soil which is consistent with this difference in pore spaces and compaction.

These results reflect differences in the way the low-till and conventional growers are addressing soil erosion. On the low-till farm, permanent mulch and minimal soil disturbance protect the soil whereas on the conventional farm deep ripping aids water infiltration while summer cover crops increase organic matter levels and protect the soil surface from high rainfall events. The other interesting fact was that the low-till mulched site had a higher level of soil microbiological activity than the conventional site, even though both had a similar organic carbon content of 1.7% (or 3.8 % organic matter). A useful measure of soil carbon that is related to soil biological activity is labile (or active) carbon. Labile carbon includes some microorganisms and the carbon readily changed by microorganisms such as simple carbohydrates (sugars and starches), some proteins, celluloses, lipids, waxes, tannins and even small amounts of lignins, which are important building blocks of humus. The low-till site had 5% more labile carbon compared to the conventional site, 10 times more microbial activity (measured using soil enzyme activity) and 45 % greater nematode diversity. This suggests that the low-till soil is better equipped to recycle nutrients and suppress soil borne pests and diseases.

Low-till operation – Bob Euston plants beans into a standing mulch crop that was sprayed with herbicide several days in advance. Mulch is mown (front of tractor) then the beans are planted in one operation.

Results from the Lockyer Valley

Two farms with different practices were investigated in the Lockyer Valley. Both farms were growing broccoli on medium clay soils. The first farm had implemented minimum tillage using a sweetcorn, green bean and broccoli rotation to help reduce input costs. Crops were direct seeded and previous crop residues were raked into the wheel tracks as part of seed bed preparation. The grower was concerned about soil compaction in the permanent wheel tracks.

From the sampling results, it is difficult to say if crop residues in the wheel tracks had any impact on soil compaction. The crop residues did lead to higher organic carbon (50% increase), labile carbon (8% increase) and microbial activity across several different indicators in the wheel tracks when compared to the interrows.

On the second farm, organic broccoli was compared with conventional broccoli production. Overall, there were very few differences between the two sites with some conflicting results for several of the soil health indicators. For example, while the conventional site had 20% more organic carbon and 2% more labile carbon, microbial activity was higher in the organic site for several different indicators. This is not unexpected as the organic block is only in the third and final year of transition with major changes in soil health unlikely in this short time frame.

The Lockyer Valley sampling team – from left to right, horticulturist Steve Harper, farmhand Peter Case, nematologist Jenny Cobon and experimentalist Ron Herman all from DPI&F

VegPASH news Nov 2007: http://knowledge-exchange.ausveg.com.au/programs.php?id=12

Volume 3: July 2008

Results from North Queensland

Six sites were sampled in the Bowen and Burdekin areas comparing:

- Compost application with no compost in green beans (medium clay)
- Minimum till with conventional zucchini production (clay loam)
- 5 year old minimum till zucchini block with newly renovated minimum till block (clay loam)

The application of compost at the bean site had little effect on soil properties. This was to be expected after only one application however some valuable lessons were learnt about using compost to supplement nutrients. Despite the overall high total nitrogen content and low carbon to nitrogen ratio of the compost, the nitrogen was not readily available to the crop as a nutrient source and affected yields adversely.

At the first zucchini site an experimental block using a minimum till system had been in place for 8 years but not maintained continuously. This site was more compacted than the comparison conventional site, but had three times higher organic carbon, two times higher labile carbon levels and improved water infiltration.

At the second zucchini farm, beds are tilled and reshaped every 4 or 5 years and results indicate that renovating minimum till beds had little effect on chemical and biological soil properties but did improve physical soil properties by increasing soil porosity and decreasing compaction. This suggests that strategic tillage operations in minimum till systems can provide important physical soil health benefits by loosening the soil and counteracting compaction without negatively impacting on the biological and biochemical processes of the soil.

Vegetable growers Lionel Williams and John Lewis discussing the merits of low till at Paul LeFeuvre's zucchini farm

Results from Western Australia

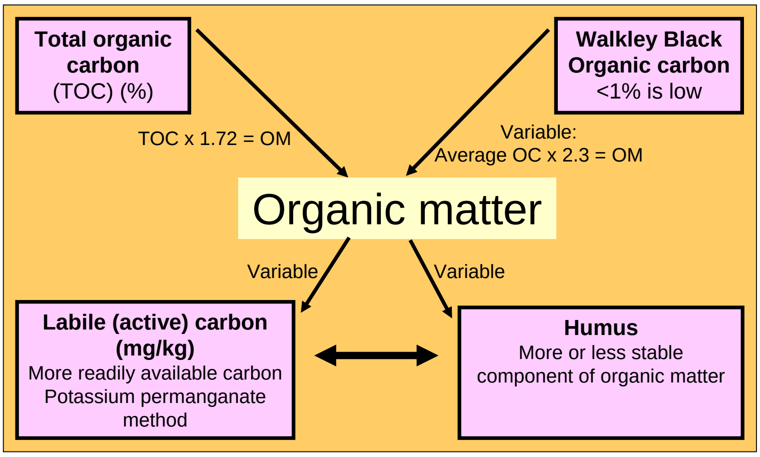
Four sites were sampled in the Perth district looking at the benefits of adding composts and manures to sandy soils. Two adjacent sites north of Perth grow loose leaf vegetables and have done so for the last 17 years being continuously cropped with 6 to 8 crops per year. At the organic site, rotary hoe use is minimised and soil amendments, usually in the form of raw manures are added prior to planting. At the conventional site, manures have not been added for the past two years. The organic site had 3 times higher cation exchange capacity (CEC), 3 times higher water-holding capacity, 3.5 times higher organic carbon levels but only slightly higher labile carbon levels. This site had greater soil biological activity but also higher soil phosphorus levels.

Two sites south of Perth were on typical coarse sands of the Swan coastal plain and continuously cropped with summer carrots and winter potato. The property has been involved in compost trials for the past 8 years maintaining an untreated area for comparison. Rotary hoe cultivations have been halved over recent years at both sites. Compost applications stopped two years ago mainly due to pending urbanisation but also because yield improvements were relatively small. The ex-compost site had almost twice the level of organic carbon, 90% better water-holding capacity, 25% better CEC and greater biological activity and diversity than the comparison site. Phosphorus levels were only slightly higher.

Results indicate that the addition of organic amendments to the sandy WA soils increased organic carbon levels, improved CEC and water-holding capacity. However, care is needed when supplying nitrogen through organic sources to ensure they do not excessively elevate soil phosphorus levels.

Measuring carbon in the soil

To make sure you are comparing apples with apples, it's important to know what method is used to measure a soil property. Organic matter is a good example of where there might be some confusion. Organic matter is not measured directly but calculated from soil organic carbon. We used the WalkleyBlack method and also measured labile (active) carbon. The diagram illustrates the relationships between these different "soil health indicators".



VegPASH news Jul 2008: http://knowledge-exchange.ausveg.com.au/programs.php?id=12

Volume 4: February 2009

Results from New South Wales

Four sites on three separate farms were sampled in the Sydney basin

- Conventional compared to reduced tillage/organic inputs in sweet corn on two neighbouring farms near Windsor in western Sydney (clay loam)
- Compost application compared to no compost in cabbage on a farm near Camden in south western Sydney (light clay)

Near Windsor, a conventional sweet corn block was compared with a reduced tillage block were synthetic fertilisers had been replaced with organic materials like chicken manure for over 10 years. The result is a dramatic improvement in soil structure as illustrated by the "drop test" result in the picture. The reduced tillage/organic input site had lower soil bulk density, better soil porosity, higher water infiltration rates and greater aggregate stability leading to improved drainage through the soil profile. This pays off in prolonged wet weather and, as grower Mario reports, better yields with the crop at the conventional site noticeably shorter and less dense than the sweet corn at the reduced tillage /organic inputs site.

The Camden farm has been continually cropped for several years and suffers from fertility and nematode problems. In mid 2008, compost was applied to one section of a field prior to planting cabbage. As expected, the one-off application of compost had little effect on most soil properties with little change in soil organic carbon levels. However, the compost application did increase nematode biodiversity by 6%. Further applications of compost are required for real differences to appear.

Drop test result at the Windsor farm three days after heavy rain conventional site left and reduced tillage and organic matter inputs site right.

Four sites on two farms were sampled in the Cowra district:

- An organic farm comparing capsicum row area to wheel tracks (clay loam)
- Deep tillage using a mouldboard plough compared to standard tillage practices to manage compaction and poor physical soil properties (clay soil)

At the first Cowra farm, where the capsicum row area was compared with the wheel tracks, the trafficked area, not surprisingly was highly compacted. It had a 17% higher bulk density and water took 2.5 times longer to soak into the soil than in the row area.

However, penetrometer measurements revealed a sub-soil compaction layer in the row area at 20 and 30 cm depth indicating that current practices were creating a plough pan. This could prevent water from draining deeper into the soil profile so forcing it and any dissolved nutrients to drain into the interrrow. Nitrate-nitrogen levels in the wheel tracks were twice as high as in the row under capsicum.

At the other Cowra farm, the deep tillage trial using a mouldboard plough in a soil with >5% sodium saturation had no impact on measurable soil health properties compared to the standard tillage methods used. In sodic soils, care needs to be taken so that deep tillage does not bring sodic sub-soil to the soil surface as this can increase problems with poor structure, dispersion and surface crusting.

Soil health indicators

While a standard soil analysis test is usually done primarily for nutrient management reasons, it also provides a good starting point for building a profile of the health of your soil as the table below illustrates. The table also lists additional indictors that the project has identified as useful for measuring and monitoring soil health.

Indicator	**Why is it important?**	**Clay**	**Loam**	**Sand**
Indicators available as part of a standard soil analysis test				
Soil organic carbon	Central to all soil properties including nutrient supply and retention, water holding capacity and infiltration, structure, biological activity. A measure of soil organic matter.	✓	✓	✓
Nitrate-nitrogen	Immediate nitrogen supply; readily leached	✓	✓	✓
Extractable phosphorus – Colwell method	Related to available phosphorus when interpreted with PBI.	✓	✓	✓
Phosphorus buffering index (PBI)	Measures ability of a soil to fix added phosphorus.	✓	✓	✓
Cation Exchange Capacity (CEC)	Nutrient cation (Ca2+, Mg2+, K) storage +	✓	✓	✓
Sodium saturation	Sodicity, impacts on soil structure	✓	✓	✓
Indicators requiring additional measurements				
Bulk density	Indicates compaction, water infiltration, measures soil porosity/aeration	✓	✓	✓
Aggregate stability	Impacts on soil structure, surface crusting, erodability	✓	✓	✗
Penetrometer	Detects hard pans, changes in soil structure	✓	✓	✓
Emerson dispersion test	Sodicity, dispersion, slaking, responsiveness to gypsum	✓	✓	✗

Some indicators still under development that show promise as biological indicators include labile (active) carbon, nematode diversity, bean bioassays, Flourescein diacetate (FDA), β-glucosidase, potentially mineralisable N and microbial biomass.

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Soil health information days

Soil health information days were held in Menangle, Bowen, Ayr, Gympie, Mareeba, Melbourne and north and south Perth. The aim of the information days were;

- To highlight the findings from the project, in terms of practices being used to improve soil health
- To highlight to growers indicators used to measure changes in soil health.
- To demonstrate in-field methods of measuring soil health, in particular measurement of labile C, pH, electrical conductivity (EC), nitrate-nitrogen, aggregate stability and soil penetration resistance.
- To receive feedback from growers and agribusiness personnel about soil health issues that they thought were important

Ten information days were held through out Australia. Unfortunately, some of the information days planned for New South Wales were not able to be integrated in with planned vegetable dissemination activities, due to disbanding of grower organisations. A separate soil health information day was thought would not be well attended in New South Wales. However, information days in NSW were integrated with groups visiting the NSW DPI Elizabeth Macarthur Agricultural Institute at Menangle NSW.

Centre	**Date**	**Attendees**
Menangle	12th June 2007	~ 12
Bowen	19th March 2008	~ 10
Ayr	20th March 2008	~ 10
North Perth	18th May 2008	~ 10
South Perth	19th May 2008	~ 10
Melbourne	28th May 2008	~ 20
Gympie	23rd October 2008	~ 15
Mareeba	2nd April 2009	~ 15
Menangle	22nd April 2009	~ 5
Menangle	23rd June 2009	~ 15

The soil health information day covered information on:

- What is soil health
- Soil functions in vegetable production
- Practices being experimented by growers to improve soil health
    - Minimum tillage / mulch
    - Composts
    - Organics
    - Controlled traffic
- Indicators of soil health
    - Physical
    - Chemical
    - Biological
- Soil health issues for the vegetable industry
    - Nutrient management
    - Soil carbon management
    - Pest and disease suppression
    - Compaction and sodicity of clay soils
    - Nutrient and water holding capacity of sandy soils

- Comments from other growers on soil health
    - "How to save me and make me money"
    - Long term demonstration plots and trials.
    - Yields and economic data.
    - "Transition" period between practice changes.
    - Unlikely to use soil health tools but interested in seeing changes.
- Questions for discussion
    - Was there anything you found particularly interesting this afternoon?
    - What functions do you want from your soil?
    - Which indicators look useful?
    - What would you like to see followed up?
- Wrap up

Outcomes from information days

While the information days allowed project information to be passed onto vegetable growers there were wider outcomes from the meetings. The outcomes from the information days were:

- An increase in the knowledge of soil health systems being used in vegetable production. However, more information on soil biology and soil carbon was being sought.
- Increased interest in indicators of soil health particularly measuring labile C as an indicator of soil health, which was being taken on by one consultant in Western Australia as and additional service to his vegetable production clients. There was also interest from a number of other growers and industry service providers.
- Increased interest in minimum tillage / mulch systems by vegetable growers particularly when they learnt that it was being used successfully in commercial zucchini production in north Queensland.
- Increase use of compost to amend soils with low organic carbon levels. Two farms were applying compost as a result of their involvement in the project.

As a result of the information days there have been planned activities by vegetable producers that will extend beyond the life of the project. For example a group of Mareeba vegetables growers have planned a field trip to visit minimum tillage / mulch systems that are being used commercially in the Burdekin district of Queensland.
One of the aims of the project was to highlight innovative soil health management and to be able to document the changes that have occurred in the soil due to soil management practice changes. This philosophy was successful in highlighting the benefits of the minimum tillage / mulch system for tropical vegetable production attracting attention to the benefits and how it had been used successfully in commercial practice. Interest in the system is also occurring from other vegetable production areas in Australia, such as Victoria and Tasmania.

Plate 1: Demonstration of soil health measurements at a soil health information day in Bowen QLD.

Plate 2. Demonstration and discussion of soil health at an information day held in Perth WA.

Presentations to national vegetable conference

Presentations were made at the national vegetable industry conference in Sydney 2007 and Melbourne in 2009. The presentation made at the Sydney conference focused on soil biology, what was in the soil and how to measure it. The presentation made at the Melbourne conference focused the key findings from VG06100 and how they were derived from farm surveys and measurements.

Sydney 2007: Appendices\veg sydney.ppt
Melbourne 2009: Appendices\Pattison Vege conference 09.ppt

Travel report to IV International Symposium - Toward Ecologically Sound Fertilisation Strategies for Field Vegetable Production,

Participation at the IV International ISHS Symposium - Toward Ecologically Sound Fertilisation Strategies for Field Vegetable Production, 22-25 Sept 2008, Malmo Sweden, **http://ishs2008.slu.seis**

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Background

In VG06100 Vegetable plant and soil health project, two issues were determined as nationally important regardless of soil type, region or crop. These were nutrient management and carbon management. Elevated phosphorus and high nitrate-nitrogen levels at harvest in many of the soils sampled were of concern as this indicates poor nutrient use efficiency and presents risks to the environment through off-site nutrient movement. These findings are supported by other researchers in Australia (Stork et al 2003, Chan et al. 2007, Bainbridge et al 2007). Part of the problem may be that science-based tools for improving nutrient management practices at the farm level are not readily available for a number of vegetable crops.

The ISHS symposium was a great opportunity to showcase activities in soil health and vegetable nutrition in Australia as well as gather intelligence on world's best practice for ecologically sound fertilisation strategies in field grown vegetable crops. We submitted a paper to the symposium which was accepted for oral presentation (Title, authors and abstract included at end of this trip report).

The symposium

Twenty-eight counties were represented at the symposium with 90 people attending and 96 posters or presentations contributed. With the exception of South America, all continents were represented although the majority of participants were from the more temperate regions of Europe. Some researchers were unable to have visa issues resolved in time for the symposium (Africa, South America).

The conference was organised by the Swedish University of Agricultural Sciences (SLU) which consists of a network of campuses and a series of experimental stations across Sweden. The country has a population of only 9 million people and 80% of horticultural production occurs in Skåne, the southern province of Sweden.

According to the conference organisers, the Baltic sea is on the verge of ecological catastrophe due to industrialisation and leakage of nutrients from agricultural fields into the sea. An example given during the field trip was that a small river could carry 200t/ha of nitrogen into the sea per year. A comment was made that this type of data was generally available for other catchments.

EU countries appear strictly regulated with regards to environmental risk management. For example, within the EU, there is a common legislation since 1991 (91/676EEC Nitrates Directive) which requires each member state to identify areas vulnerable to nitrate pollution and establish a plan of action to recue nutrient leaching from agriculture. Sweden's plan of action includes some very specific directives on spreading and storing of manures and inorganic fertilisers as well as requirements of green cover during high risk periods. For example, in Skåne, 60% of land needs to be under cover crop during autumn and winter and organic fertilisers may not be spread between 1 January and 15 February. Late winter appears to be the high risk time for off site nutrient losses as snows melt.

The field trip

Torup gardens – ornamental plant nursery

- Previously grew vegetable seedlings but these are now imported from Holland
- Part of a 65 grower organisation – common pattern is for cuttings to be imported into Holland eg from South Africa, then plants are shipped to Sweden for "finishing off" for the Swedish market
- Water recycling system as nothing unclean is allowed into the environment from "industry" such as this greenhouse complex. Have installed biological water cleaning unit from RaaTec based on filter system using zeolite. UV could be added to system if virus were a problem
- Innovative heating system based on Glycol – similar to refrigeration heat exchange concept – glycol is periodically heated to 15C using oil which heats hot water by 10C. Reduced oil use by 85%, simple and clean – 1KW returns 3KW

Potato growing area north of Helsingborg

- 400 growers of early potato – a grower can look after 18 ha but size of cultivation is between 35-200 ha depending on growers ability to lease land and level of mechanisation
- 60% of land must be under cover crop by regulation
- Moraine type clay soil – do not leak P internally?
- Other vegetables grown in district are leeks, brassicas, 100 ha of baby leaf including English spinach & including rocket
- Grower visited – harvesting machine for baby leaf , well for collection of water from fields and monitoring of water quality

Findus Sverige – vegetable processors

- The company works closely with around 500 contract growers and over the past 20 years has developed it own environmentally friendly growing system called Low Input Sustainable Agriculture (LISA). According to Findus, the LISA system has increased production yields while simultaneously reducing the use of herbicides and insecticides due to use of disease resistant varieties, healthier soils as a result of continuous monitoring, more consistent quality and reduced waste
- Findus have been sampling soils to select "healthy soils" since 1961. The focus is on assessing soils for disease incidence prior to planting crops, for example, *Aphanomyces* sp. in soils to be planted to peas.
- Findus have conducted 12 years of systematic studies comparing their LISA system with organic production and found no nutritional differences except that dry matter content was higher in organically produced product.

- Their number one priority with regards to research is plant protection however plant breeding is seen as always important
- Also have problems with pesticide registrations for vegetable crops – Findus supports the plant protection industry with collection of residue data
- Up until 5 years ago, 180 scientist where employed at Findus Sverige however when Nestle bought the company out this was reduced to 8 scientists.

Vegetable grower and packing shed north of Lund

- Producing variety of temperate vegetables primarily leeks and stem celery but also asparagus, chives, parsley, Brussels sprouts and baby leaf salad.
- Baby leaf is an expanding industry and according to the grower, limited by the land available for its production. Supply is to the southern EU countries in the summer while these in turn supply baby leaf into Sweden into the winter (especially Italy)
- Labour issues – large percentage of workers are from the Eastern European countries.
- Baby seedlings are direct seeded but seedlings for other crops (except leeks?) are sourced from Holland. No seedling nurseries left in Sweden as it is too small.
- Working with SLU to address key issues identified with a checklist for "Environmentally certified crop growing". These were increase N utilisation to >50%; safe storage of motor fuels by building a caisson under roof; and reduced input of chemical pesticides with help of reliable prognosis methods and technical advances.

Key outcomes

(i) Technical information obtained and contacts made to augment largely empirical data of nutrient requirements of tropical field grown vegetables with critical limits data to strengthen an environmental risk management package "Safegauge for Horticulture" currently under development by DPI&F & DNR&W. This package aims to provide practical tools for protecting the Great Barrier Reef Marine Park from off-site nutrient movement.

(ii) Discussions held with European researchers re EU simulation models N_ABLE and EU_Rotate resulting in invitation to collaborate in testing of both tools using Queensland vegetable production systems. This activity has the potential to expand thinking in the areas of environmental risk management, nutrient management and soil health while building collaborative links with a cutting edge group of international researchers

(iii) Access to recent developments in slow release fertiliser technology as a means of minimising off-site nutrient movement risks. Leads to be followed up and resulting information discussed and distributed to Queensland scientists.

Issues to consider:

(i) Phosphorus as a limited, non-renewable resource and impact of this on future ability to meet world food demands – critical time span of 50 to 200 years was proposed

(ii) Limited participation of Chinese and Indian researchers in ISHS vegetable committee

To be progressed by encouraging ISHS vegetable committee to take both issues forward

Abstract of paper submitted

Vegetable Production in the Dry Tropics – Nutrient and Soil Management Strategies from Queensland Australia

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Agricultural industries located in coastal catchments adjacent to the Great Barrier Reef Marine Park in Queensland, Australia are facing increasing pressure to demonstrate that their production systems are environmentally sustainable. Our experiences show that research and technology to improve productivity and profitability can also address environmental issues associated with off-site movement of nutrients. Due to limited water availability, vegetable farmers in the region utilise trickle irrigation and fertigation, often combined with polyethylene mulch film and seedling transplant technology. This system conserves water and allows for accurate and timely placement of fertiliser. The challenges for vegetable production systems in a dry tropical environment are: periods of high summer rainfall on fallow land; inherently low soil carbon with associated impacts on soil health properties (nutrient cycling, resistance to soil erosion); potential for denitrification under mulches; and salinisation of the soil profile. Fertiliser recommendations are based on empirical data rather than calibrated soil and plant tissue diagnostic indices. There is a need to develop science-based tools for objectively assessing and facilitating improved best practice nutrient management on a soil-, site- and crop- specific basis. A soil health scoping study has confirmed low organic carbon levels in soils under vegetable production while highlighting high available phosphorus and nitrogen levels in some soils. Complementary work to modify a decision support tool (Safegauge for Horticulture) for assessing the risk of off-site movement of nitrogen and phosphorus is identifying large gaps in available input data (critical soil P test levels, crop growth cycles, nutrient uptake and removal data) for a number of vegetable crops. To ensure the tool is practical and user-friendly we are collaborating with local vegetable farmers. The potential of the package to deal with the complexity and variability needed to support best management practices for nutrients in vegetable cropping systems is discussed.

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Part C: Recommendations for the advancement of soil health for the Australian vegetable industry

Introduction

The findings from the "snapshot" of soil health issues for the Australian vegetable industry provide a platform for the advancement of soil health management for Australian vegetable growers. The research surveys done on-farm highlighted that growers had already adopted different practices to improve soil health. However, in many cases changes to soil properties could not be distinguished from conventional practices due to a lack of quality scientific information and tools to guide growers to assess improvements or changes on their farms.

Advancement in soil health research can be made by understanding the limitations and issues that are affecting vegetables. The limitations of sustainable vegetable production can be addressed by investigating methods of overcoming the physical, chemical and biological limitations, development of sustainable farming systems and ensuring a good communication network.

In determining the limitations to soil health and vegetable production, it was important to distinguish between inherent and dynamic soil properties. Inherent soil properties were those properties that were associated with the specific soil types. For example, sandy soils were identified as having large pore spaces, high bulk density, poor aggregate stability, low cation exchange capacity, low organic carbon and bacterially dominated decomposition of nutrients relative to clay soils. Dynamic soil properties are those that change due to soil management.

Issues for soil health were divided into two main categories;

- **National** – issues that affected all vegetable producers regardless of region or soil type.
- **Soil type** – issues that affected vegetable growers on broad soil type classes – i.e. clay, loams and sands

National issues

Three issues were determined to be nationally important regardless of soil type, region or crop. These were nutrient management, carbon management and pest and disease suppression.

Nutrient management

Background

The findings from the "snapshot" of soil health in the vegetable industry suggested that the 28 vegetable locations included in the survey could be grouped broadly into three categories of nutrient levels depending on nitrate, $P_{Colwell}$, CEC and Na%.

All groups tended to have high P levels in the soil at the harvest. Our work suggested that he amount of P needed to grow vegetables crops needs further investigation to determine if and how nutrient use efficiency can be improved.

The low nutrient level group had relatively low residual nitrate nitrogen and phosphorus (Colwell) in the soil at the time of sampling.

The high N level group had on average 68 mg kg^{-1} of nitrate N in the soil at the time of crop harvest. This was 3 times higher than the average of other nutrient categories, revealing inefficient use of N based fertilisers, which could potentially be lost through leaching.

The high P level group had on average 309 mg kg^{-1} of $P_{(Colwell)}$, which was 1.5 to 2 times more than the other nutrient categories. The amount of P that is fixed in the soil can be determined by the phosphorus buffering index (PBI), with a higher value indicating greater P fixation in the soil. There was very little difference in PBI between the group with high P levels and the group with high N levels, which suggested that high P levels found at some sites were not related to the PBI of the soil. This suggests that some growers would benefit from reviewing their P inputs against the PBI of their soil and estimated P demand of the crop grown. This could improve P use efficiency and reduce potential risk of P attached to soil particles moving off the farm and into the environment.

Adapting the results from Moody (2007), critical $P_{Colwell}$ levels for high and low P demanding crops for changes in phosphorus buffering index could be determined (Figure 6). However, when the results from the farm survey of PBI and $P_{Colwell}$ were plotted on the same graph the amount $P_{Colwell}$ far exceeded the upper limits for critical P for high demanding crops in most cases (Figure 6).

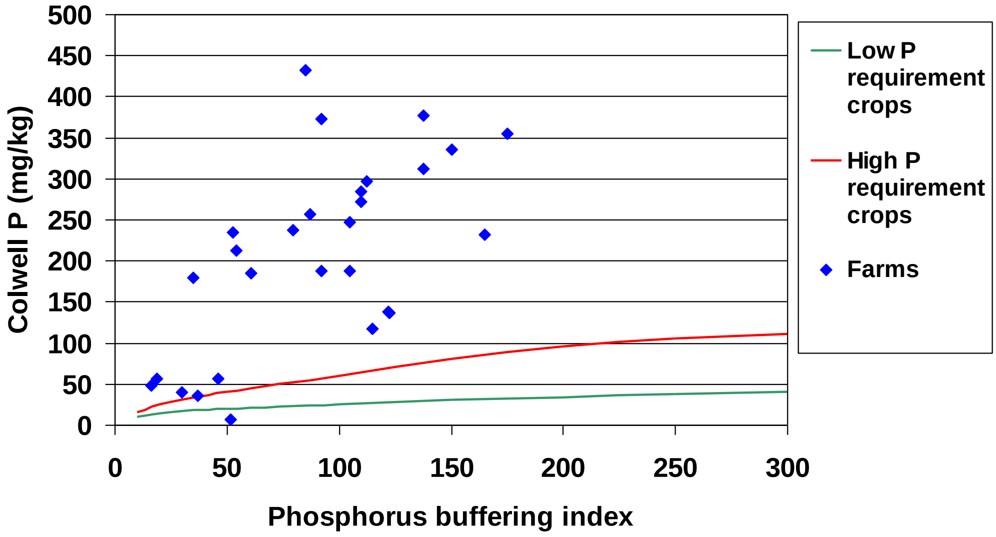

Figure 6: Critical soil phosphorus levels (measured by the Colwell method) for high P demand and low P demand crops for soils of different PBI values. (Source: Moody 2007)

A constraint for growers is the lack of science-based, soil specific information and tools available for nutrient use across the range of vegetable crops that would assist in reviewing and improving decisions about fertiliser use.

Recommendations

Further research is required to demonstrate the critical levels of nutrients, particularly N and P for major vegetable crops. Emphasis needs to focus on developing efficient nutrient management based on nutrients budgets, with recognition and measurement of losses of nutrients from the system.

Modification of existing decision support tools for use in the vegetable industry and improved knowledge of the nutrition needs for vegetable crops are required to make more efficient use of fertilisers. Grower tools that are currently being developed or could be modified for vegetable growers include:

- SafeGauge for nutrients
- SCAMP (Soil Constraint and Management Package)
- Bananaman (fertiliser diary and nutrient calculator)
- Nutrient calculator (partial nutrient budget tool)

These tools are currently being used in different agricultural industries and with modification could be made into a single package that is able to be used by a wide range of vegetable growers. Training and awareness workshops would be needed, but the packages do not require any specialised measurements or information gathering than currently exists on farms.

Potential project areas

Potential projects that could be implemented across a national level to address nutrient management should include:

- Determining the critical N and P levels required on different soils used in vegetable production.
- Tools to help growers manage nutrient inputs on-farm.
- Development and demonstration of tools to manage efficient use of fertilisers.

Soil carbon and organic matter

Background

Depletion of soil organic matter remains a concern for many vegetable growers. Organic matter is central to soil health as it impacts on soil physical, chemical and biological properties. However, there is confusion amongst growers and service providers about soil carbon. Most vegetable growers recognised soil carbon was important for soil functions, but the benefits have not been clearly demonstrated. Soil type interactions in the role of organic carbon in the soil need to be clarified. For example, an increase of 1% of organic carbon in a sandy soil would have a different impact on soil properties relative to a 1% increase in clay soils.

Some of the confusion that existed around organic matter and organic carbon included;

- **Terminology** – e.g. Organic carbon, total soil carbon and organic matter, are reported to vegetable growers in commercial soil tests, but the measurements are not always consistent in methodology and units used.
- **Forms** – carbon can be added to the soil in different forms as organic matter, labile carbon, humates, humic acid and charcoal. Their effects on soil health need to be determined.

- **Practices** – there is confusion about how practices may affect soil carbon levels, how quickly the levels change and the time required to effect changes.
- **Benefit** – there was confusion to the benefits of improving soil carbon. For example the question was asked "what will happen if I increase my soil carbon by 1%"?

Recommendations

Information on clear definitions for soil carbon terms and what they mean for vegetable production is required. With a greater awareness by vegetable growers of the importance of soil carbon in vegetable production and the desire to improve soil carbon, clearer definitions and relationships would help vegetable growers make more informed decisions on sequestration of soil carbon.

A "carbon calculator" is required to help vegetable growers determine how vegetable management practices impact on soil carbon levels. The carbon calculator needs to be simple to use and give an indication of whether practices increase or decrease soil C levels accounting for some of the variability in soil types and production and climatic regions.

The impact of soil management practices needs to be clarified in terms of their impacts on soil organic carbon and interactions with other soil properties. However, the impacts may differ depending on the soil type and suitability will depend on the crops being grown. Practices that impact on soil C levels could include:

- tillage
- cover crops
- amendments
- nitrogen management
- incorporation of residues

The impact of increased soil carbon needs to be demonstrated to growers. What will a 1% increase in soil carbon give growers in terms of physical, chemical and biological soil properties, crop production and yield? The increase in soil carbon would need to be demonstrated on soils with different textures, clay, loam and sand, showing how it impacts on other inherent soil limitations.

Potential project areas

Potential projects that could be implemented across a national level to address soil carbon should include:

- Development of a "soil carbon calculator", including a glossary of terms and conversions between different reporting values.
- Soil management practices to increase soil carbon for vegetable production. Practices should not only focus on adding organic matter to the soil but include a substantial component for exploring ways of preserving carbon in the soil, for example, through reduced/controlled tillage practices.
- Changes in soil properties following a 1% increase in soil carbon.

Pest and disease suppression

Background

Pests and diseases remain a biological constraint to vegetable production. Although no specific pests and diseases were identified within the project, because of the wide range of crops surveyed, the different soil types and intervention management by growers, pests and diseases remained a primary concern for vegetable growers.

There is an opportunity to determine the soil characteristics that induce, as well as suppress soil borne pests and diseases. An understanding of how soil physical, chemical and biological properties increase or decrease the incidence of soil borne pests and diseases can be used as part of a risk assessment strategy to minimise losses in vegetable production.

In the investigations of changes in management practices, the changes in soil borne pest and disease levels also need to be investigated. In the short term it may be that additional organic matter may increase some seedling diseases. However, long term changes in soil biological properties may be able to increase the natural suppressiveness of soils, reducing the need for pesticides. Similarly, weed management may be difficult in alternative systems until management practices are refined.

Recommendations

A risk assessment strategy for soil borne pests and diseases needs to be developed. A Strategy would aim to identify the critical control points where intervention may take place to reduce losses to soil borne pests and diseases. Soil factors that lead to soils becoming conducive to soil borne pests and diseases, as well as factors that make soils suppressive, need to be determined so that growers can better assess the limitations of their soils and determine the risks of disease losses.

Soil and crop management that can suppress the incidence of soil borne pests and diseases needs to be determined. The changes in soil properties that may be associated with the changes in practices need to be understood in order to develop more suppressive cropping systems and reduce the reliance on soil applied pesticides. Practices that impact on soil borne pest and disease levels include:

- tillage
- cover crops
- amendments
- nitrogen management
- incorporation of residues

Potential project areas

Potential projects that could be implemented across a national level to address soil borne pests and diseases should include:

- Development of a soil risk assessment tool for growers to major soil borne pests and diseases. This would include an understanding of soil limitations inducing disease as well as soil factors contributing to pest and disease suppression.

- Soil management practices that lead to pest and disease suppression in vegetable crops.

Soil type issues

Different soil types have different inherent properties. The inherent soil properties will affect a number of other soil properties, but will also set limitations on how specific soil properties can be improved. Two issues were identified as being important on different soil types; the structural stability of clay and loam soils and improving nutrient and water holding capacity of sandy soils.

Structural stability of clay and loam soils

Background

The structural stability of clay and loam soils was integral in the soil function and sustainable vegetable production. There were three factors involved in maintaining structural stability of those soils;

- Biological stability – such as the break down of organic matter; increasing aggregate stability. Specifically, increasing fungal decomposition of organic matter in the soil was related to more stable aggregates.
- Chemical stability – soils with high sodium (Na) were less structurally stable and dispersed in water. Conversely, increasing the Ca content of the soils helped to increase their stability.
- Physical stability – preventing soils from undergoing compaction due to traffic movement and tillage.

Recommendations

The advantages of maintaining and improving structural stability of clay soils need to be investigated so benefits can be demonstrated to vegetable growers. The changes in soil physical, chemical and biological properties as well as the economic benefits need to be investigated in a farming systems approach using commercial scale research.

Alternative management practices that need to be investigated that could improve the structural stability of clay soils include:

- Controlled traffic
- Minimum tillage
- Cover crops
- Mulch systems
- Organic amendments
- Calcium amendments

Potential projects

Potential projects that could be implemented across clay soils to address the structural stability include:

- Controlled traffic systems for vegetable production – improvements in soil health, productivity and economics.
- Increasing organic matter in clay soils to retain and improve soil aggregate stability and resist erosion.
- Managing sodicity and salinity in soils for vegetable production.

Nutrient and water holding capacity of sandy soils

Background

Sandy soils have inherently low nutrient and water holding capacity. Therefore, practices that increase the nutrient and water holding capacity result in greater efficiencies in irrigation and fertiliser use. For example, the addition of organic matter was able to increase nutrient holding capacity.

Methods of adding organic matter to soils and how to preserve and sequester carbon on soils with low inherent and nutrient holding capacity need to be investigated.

Recommendations

Systems to improve the nutrient and water holding capacity of the sandy soils have been investigated to a limited extent. Additional organic matter added to sandy soil has been able to increase the soil's nutrient and water holding capacity. However, in root crops, disease issues have been reported with increased organic matter, which has limited the adoption of techniques to increase soil C levels in sandy soils.

Further investigations are needed to look at the effect of adding organic matter to sandy soils. Some of the factors that should be included are:

- Organic amendments
- Cover crops and green manures
- Age and decomposition of organic matter
- Amounts of organic matter required
- Frequency of organic matter additions
- Changes in other soil properties e.g. heavy metals, salts, micronutrients.

Potential projects

Potential projects that could be implemented across sandy soils to address low nutrient and water holding capacity include:

- Increasing the nutrient and water holding capacity of sandy soils used in vegetable production in Australia.

Development of a soil health program

The vegetable industry has invested in research activities which indirectly influence soil health. There is a need for greater co-ordination of current research activities through developing a framework that allows past research to be "unlocked" so that it can be implemented and adopted by growers. Furthermore, it may be possible to "value add" to current research projects, whose primary focus is not soil health, in order to develop a greater understanding of soil health in vegetable production. For example, there are currently projects within the vegetable IPM diseases program that are investigating methods of suppressing soil borne diseases in vegetable crops. The soil health program could add to these research efforts by developing a greater understanding of changes in soil physical, chemical and biological soil properties and changes in soil functions that may be attributed to suppression of the diseases. The soil health program would focus on "why" suppression occurs, which is an important concept if the results are to be duplicated at other sites.

To coordinate research activities on soil health, it is recommended that a structure be put in place similar to vegetable IPM disease program, consisting of subprograms. The soil health program could have 5 sub-programs with projects under each (Figure 7). However, there would be the need integrate the research into a vegetable farming system, which would require a sub-program, where new production systems could be compared to existing systems.

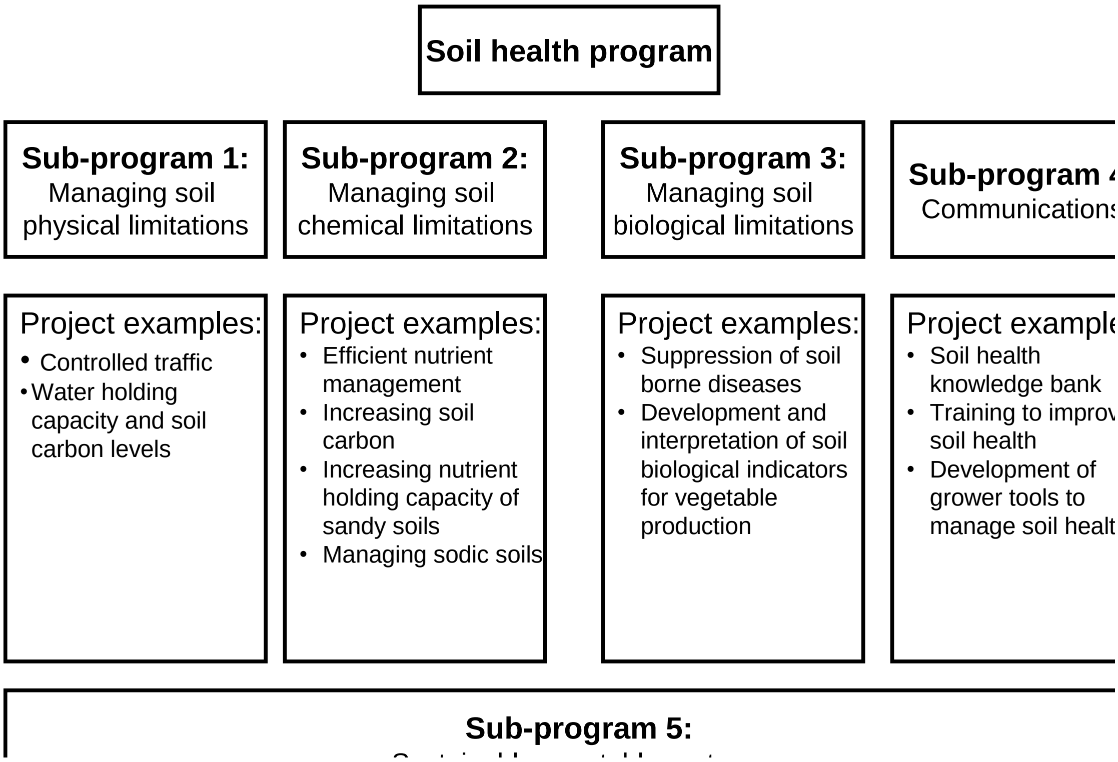

Figure 7: Proposed structure of soil health program within HAL AUSVEG to coordinate research activities

Conclusion

The project VG06100 has identified two areas of national importance for the vegetable industry; nutrient management and greater clarification on soil carbon management on soil health. Furthermore, issues were identified that were related to soil type. For example, in clay soils, the need to maintain good soil structure by managing compaction and sodicity risks and in sandy soils, the need to increase nutrient and water holding capacity. Other issues such as pest and disease suppression and salinity and sodicity were considered more site specific.

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Project team members also sincerely thank the many vegetable growers who contributed to this project by allowing us to sample their soils, by providing information on their production systems and by giving valuable feedback on ideas and direction.

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Appendices

Appendix 1: Protocols for measuring soil health

Appendices\Protocols_Manual.pdf