Comparison of conventional and alternative vegetable farming systems on the properties of a yellow earth in New South Wales

A.T. Wells, K.Y. Chan, P.S. Cornish

Horticultural Research and Advisory Station, NSW Agriculture, Locked Bag 26, Gosford, NSW 2250, Australia
Agricultural Research Institute, Wagga Wagga, NSW Agriculture, PMB Wagga Wagga, NSW 2650, Australia
University of Western Sydney, Hawkesbury, Centre for Farming Systems Research, Bourke Street, Richmond, NSW 2753, Australia

Received 15 March 1999; received in revised form 25 November 1999; accepted 18 January 2000

Abstract

Intensive vegetable farming has the potential to damage soil health, leading to poor productivity and large environmental impacts. This paper reports on changes in soil properties after three and a half years of vegetable cropping and discusses the implications for sustainability. A vegetable farming-systems experiment began in 1992 at Somersby, in NSW, Australia. The aim of the experiment was to compare five different approaches to vegetable cropping in terms of their productivity, profitability, soil effects and environmental impact. The experimental treatments represent whole production systems, intended to simulate real farms, but under more controlled conditions than is possible on farms. The systems are defined by the goals and values of the farmer rather than by the management practices employed. The actual management practices — nutrition, tillage, rotations, pest and weed management, etc. — were selected to satisfy these goals and values. For instance, to satisfy the goal of ‘maximise profit’, fertilisers and pesticides were applied in excess to ensure high yields of large, undamaged produce which receive the best prices. Conversely, one of the management practices used to satisfy the goal ‘optimise profit while minimising environmental impact’ was to grow cover crops regularly in rotation with vegetable crops. A range of chemical, physical and biological properties of surface soil (0–10 cm) from the farming-systems were measured and compared to baseline measurements. The two alternative systems, which received large inputs of compost, had higher soil organic carbon, microbial biomass, total nitrogen, total phosphorus, exchangeable nutrient cations, water-holding capacity and aggregate stability than the conventional systems. The system that received the largest mineral fertiliser inputs, and the most tillage, had the highest available phosphorus levels, the lowest phosphorus sorption capacity and lower aggregate stability than the alternative systems. Consequently this high input system had the greatest potential to lose sediments and phosphorus to the environment. The two other conventional systems had smaller fertiliser inputs and maintained a phosphorus sorption capacity that was no different from the alternative systems. These more carefully managed conventional systems offer hope that relatively small changes in management can have significant environmental benefits. Yet the broad improvement in soil health achieved by the biological approaches should provide better long-term fertility and lower off-site impacts. It may be wise to make use of both these approaches to management in attempting to balance the short and long-term viability of intensive vegetable farming.

Keywords: Soil health; Compost; Phosphorus; Water stable aggregation; Sustainability; Vegetable farming

* Corresponding author. Tel.: +61-2-43-481900; fax: +61-2-43-481910.
E-mail address: tony.wells@agrimag.ags.gov.au (A.T. Wells)
1. Introduction

Conventional vegetable farming often involves repeated tillage, frequent exposure of soil to rainfall and excessive use of fertilisers, pesticides and irrigation water. These practices can result in severe damage to soil structure, soil erosion, reduced soil fertility and the loss of fertilisers and other chemicals from increased runoff and leaching (Hollinger et al., 1998). In the long-term these effects can reduce productivity and profitability to the farmer due to degradation of the soil resource. Furthermore, they can cause off-site environmental damage. Many farmers and scientists recognise a need to develop alternative production systems that can preserve productivity and minimise environmental impact while maintaining profitability.

Vegetable growing in the Sydney region of NSW, Australia, has a very significant impact on the regional economy. Over 1000 vegetable farms produce a wide range of vegetables including 70% of the tomatoes and 95% of the perishable leafy vegetables sold in the Sydney market (Department of Planning and Community Development, 1993). But, in the early 1990s, the community became concerned about the effect of vegetable growing on the health of Sydney’s major river, the Hawkesbury-Nepean, which was then experiencing toxic blue-green algae blooms. There were, however, virtually no local data about the possible losses of nutrients, or other impacts, from vegetable farms.

In response to this lack of information, a multi-disciplinary team began an experiment at Somersby, a vegetable growing area close to Sydney, in 1992. The experiment aimed to compare the economic and environmental performance of conventional and alternative vegetable farming systems (Cornish et al., 1992).

The soil at the experimental site was one commonly used for vegetable production in the Sydney region: a yellow earth (Stace et al., 1972) derived from Hawkesbury Sandstone. Compared to other soil types in the region it is well drained and easy to cultivate, due to its sandy texture. These factors, along with its closeness to Sydney markets, are its chief production advantages. However, it also has the significant production disadvantages of low water and nutrient holding capacity; farmers need to apply irrigation and nutrients frequently to maintain high productivity. Thus the potential for nutrient losses is high. The soil also has poor structural stability which, in combination with frequent tillage, makes the soil prone to increased runoff, severe erosion and further losses of nutrients.

One strategy for maintaining productivity on this soil type while reducing environmental impact is to improve the properties of the soil (i.e., increase the water and nutrient holding capacity; improve aggregate stability) through management. This research explores the effects of different management approaches on such soil properties after three and a half years of production.

2. Materials and methods

2.1. Site and soil

The experimental site is located on the Somersby section of the Gosford Horticultural Research and Advisory Station, 85 km north of Sydney (lat. 33°23’S, long. 151°21’E), NSW, Australia. The annual rainfall is approximately 1300 mm and the average maximum and minimum temperatures are 25.6 and 16.2°C in January and 16.8 and 6.8°C in July. The site is at an elevation of 250 m above mean sea level on the Central Coast Plateau. The soil is a yellow earth (Luvic Ferrasol) described in detail by McKenzie et al. (1997). The 0–10 cm layer has approximately 150 g kg⁻¹ clay, 80 g kg⁻¹ silt, 550 g kg⁻¹ fine sand and 220 g kg⁻¹ coarse sand. The 70–80 cm layer has 230 g kg⁻¹ clay, 90 g kg⁻¹ silt, 420 g kg⁻¹ fine sand and 270 g kg⁻¹ coarse sand. The site was cleared 60 years ago and has been predominantly used to grow vegetables and citrus.

2.2. The vegetable farming-systems experiment

The experiment commenced in early 1992. It was designed to evaluate the performance of alternative systems of vegetable production, rather than individual management factors (Cornish et al., 1992). The experimental treatments thus represent whole production systems, intended to simulate real farm situations but under more controlled conditions than is possible on farms. The systems were implemented on plots of approximately 0.1 ha replicated four times in randomised blocks. However one system, the Evolving (described later), had only three replications due to space limitations.
The farming systems were defined in terms of the approach to management rather than strictly on the types of practices used. The approach to management was defined for each system by firstly defining the goals and values of a farmer of that system, and then secondly by defining a set of typical management practices. The system goals and values were fixed but the management practices could vary, to some degree, in order to satisfy the goals and be consistent with underlying values. The results of a formal survey of vegetable growers in the Sydney region (Murison, 1995) and focus group meetings (unpublished) helped to establish the goals and values of the systems and their associated management guidelines.

The names of the five farming systems and their defining goals and values follows. Tables 1 and 2 list the management practices used on each system to satisfy these goals and values. During implementation of the systems, farmers representative of conventional and organic approaches to vegetable growing were regularly consulted to ensure that the systems were consistent with commercial practice.

### 2.3. Description of the systems

The systems were separated into conventional or alternative categories largely on the basis of their nutrition strategy. The conventional systems rely mostly on readily available nutrient sources such as granular or liquid mineral fertilisers and poultry manure; they are the District Practice, Agfact and Objective systems. The alternative systems rely mostly on slowly available and biological nutrient sources such as compost, slow release mineral fertilisers, rock dusts and legumes; they are the Organic and Evolving systems. The alternative systems are more dependent on biological process to supply nutrients to crops.

### Table 1

<table>
<thead>
<tr>
<th>System</th>
<th>Tillage</th>
<th>Weed control</th>
<th>Pests and diseases</th>
<th>Irrigation</th>
</tr>
</thead>
<tbody>
<tr>
<td>DP</td>
<td>Multiple tillage</td>
<td>Tillage and herbicides</td>
<td>Chemical control, resistant vars. if yields OK</td>
<td>To excess, spray</td>
</tr>
<tr>
<td>Ag</td>
<td>Reduced tillage</td>
<td>Tillage and herbicides</td>
<td>Chemical control, rotations, resistant vars.</td>
<td>To excess, drip</td>
</tr>
<tr>
<td>Obj</td>
<td>No-till</td>
<td>Plastic mulch, herbicides</td>
<td>Economic thresholds, rotations, resistant vars.</td>
<td>Scheduling, drip</td>
</tr>
<tr>
<td>Org</td>
<td>Minimum tillage</td>
<td>Tillage, cover crops, rotations, mulches</td>
<td>Rotations, resistant vars., ‘natural’</td>
<td>Drip</td>
</tr>
<tr>
<td>Ev</td>
<td>No-till</td>
<td>Cover crops, rotations, mulches, herbicides</td>
<td>Rotations, resistant vars., chemical control if needed</td>
<td>Drip</td>
</tr>
</tbody>
</table>

*a Farming system: DP=District Practice; Ag=Agfact; Obj=Objective; Org=Organic; Ev=Evolving. See Section 2.3 for details.

*b Multiple tillage=soil cultivated with a rotary hoe or discs 2–4 times for each crop; reduced tillage=1–2 times for each crop; minimum tillage=1 time for each crop; no-till=no use of rotary hoe or other implements except to occasionally break-up crop residues on the surface.

### Table 2

<table>
<thead>
<tr>
<th>System</th>
<th>Rotations</th>
<th>Nutrients</th>
</tr>
</thead>
<tbody>
<tr>
<td>DP</td>
<td>Best market potential; no cover crops</td>
<td>Fertilise to excess, heavy dependence on pre-plant applications</td>
</tr>
<tr>
<td>Ag</td>
<td>Some consideration to disease control; occasional cover crops</td>
<td>Soluble mineral fertiliser use guided by extension advise and periodic soil tests, pre-plant plus sidedressing</td>
</tr>
<tr>
<td>Obj</td>
<td>Rotate crops for weed, pest and disease management and soil fertility; occasional cover crops</td>
<td>Fertilisation with mineral fertilisers mostly via fertigation* guided by sap nitrate and soil tests</td>
</tr>
<tr>
<td>Org</td>
<td>Rotate crops for weed, pest and disease management, soil fertility and biotic diversity; frequent cover crops</td>
<td>Compost, legumes, rock dusts</td>
</tr>
<tr>
<td>Ev</td>
<td>Rotate crops for weed, pest and disease management, soil fertility and biotic diversity; frequent cover crops</td>
<td>Compost, legumes, fertigation*, slow release coated fertilisers</td>
</tr>
</tbody>
</table>

*a Fertigation refers to applying soluble nutrients through the irrigation system.
2.3.1. District Practice (DP)

This system aims to maximise profit; the investment made in each crop is rigorously protected; and pest, weed and disease free crops are highly valued. These goals and values often lead to excessive use of fertilisers, tillage, pesticides, irrigation and little use of beneficial crop rotations. High inputs are used to ensure large yields of large, unblemished produce. Such produce receives the best prices. Tillage is generally performed three or four times for each crop with a rotary-hoe.

2.3.2. Agfact (Ag)

This system has similar goals and values to the District Practice system but advice from departments of agriculture, and other sources of information, about proven technology is also valued. The aim is to make more efficient use of inputs and therefore reduce costs. For example, drip irrigation is used rather than spray irrigation, fertiliser rates are based on the results of trials and the number of tillage passes made for each crop is half of those on the District Practice.

2.3.3. Objective (Obj)

This system aims to optimise profit within the constraint of minimum environmental impact. It makes maximum use of objective management tools; optimal inputs are applied to gain high outputs but the maintenance or improvement of measurable aspects of soil health is a key objective. Technology such as irrigation scheduling, fertigation (applying nutrient solutions through the irrigation system) and plastic-sheet mulch are used to reduce environmental risks while maintaining high productivity. This is a no-till treatment but occasionally, in breaking-up large masses of crop residue and during planting, the top 40 mm of soil is disturbed.

2.3.4. Organic (Org)

This system adheres to organic production standards (National Association for Sustainable Agriculture, Australia Ltd (NASSA, 1993)). It aims to produce healthy, wholesome food and to make an acceptable living; natural processes are utilised as much as possible; external inputs are minimised and the improvement of all aspects of soil health is a key objective. This system receives similar tillage to the Agfact system. Nutrient inputs are largely in the form of rock dusts (rock phosphate and basalt) and compost. Approximately 40 Mg ha\(^{-1}\) of compost was applied to the Organic system in February 1995, consisting largely of ground woody material with poultry and horse manure.

2.3.5. Evolving (Ev)

This system has goals and values that are a mixture of those of the Objective and Organic systems: optimum profit with minimum environmental impact; rely on biological processes as much as possible but use technology such as herbicides and synthetic fertilisers when benefits appear to exceed costs. The name of this system indicates that it is more adaptable than the other systems, allowing more freedom to test novel and risky approaches. This is a no-till system but, like the Objective system, the top 40 mm of soil is occasionally disturbed during normal horticultural operations. A large compost application (~65 Mg ha\(^{-1}\)) was applied in February 1995, consisting of ground woody material and sewage sludge.

2.4. Nutrient inputs

As mentioned in the previous section, the systems can be divided into two groups based on the rate of availability of their nutrient sources. In addition, the amount and timing of nutrient inputs to the systems also varied. The District Practice system received the most N, the Evolving system received 81% of this amount, the Agfact 58%, the Organic 52% and the Objective 43%. The District Practice, Organic and Evolving systems received similar high amounts of phosphorus (P), the Agfact received 71% of this amount and the Objective 36%. The Organic and Evolving systems received very large infrequent applications, the District Practice and Agfact generally received large, frequent applications and the Objective system received small, very frequent applications (of N). The N and P inputs on Organic and Evolving were dominated by single, large applications of compost.

2.5. Crop sequences

The sequences of crops grown on each farming system were largely independent of each other because the systems had different rotation strategies (Table 2). However, at least once annually, a common crop was planted at the same time in each system to compare
crop growth, yields and profitability directly. A wide range of vegetable crops were grown; a sample of the range of crops grown in the Sydney region (Fig. 1).

2.5.1. Cover cropping


2.6. Soil sampling

Baseline soil samples were collected in January 1992 before the experiment was established. The samples were collected on a grid layout over each experimental block. Fifty-seven cores were taken in total, each 150 mm diameter to approximately 900 mm depth. Eighteen of the cores were described in detail and the rest only in terms of horizon boundaries. Sub-samples from the intensively described cores were taken for chemical and physical analysis.

Comprehensive soil sampling of the surface soil was again carried out in December 1995 (fourth year sampling). Five subsamples were collected at random from 0–100 mm from each plot and bulked to form a composite sample. All the samples were air-dried and passed through a 6.3 mm aperture sieve. A portion of each sample was further passed through a 2 mm sieve to collect the <2 mm fraction. Fig. 1 shows when soil sampling took place in relation to crop sequences.

A soil sample was also collected from an undisturbed area under native vegetation during the fourth year sampling. This sampling site was approximately 50 m from the experimental plots of replicate 1. The sampling method was the same as that used on the experimental plots: five subsamples were collected and bulked into a composite sample.

2.7. Soil measurements

2.7.1. Baseline measurements

Different sets of soil properties were measured to describe the soil status at the baseline and fourth year stages. The properties that form the intersection of these sets, and which are used to quantify soil changes over this period, are: pH, electrical conductivity (EC), cation exchange capacity (CEC), organic carbon (OC) and Bray No. 1 P. The details of these measurements, and the other measurements made at the fourth year sampling, are set out later.

2.7.2. Soil chemical properties

OC, total nitrogen (N), pH, EC and exchangeable cations were determined on the <2 mm subsamples. OC was determined using a dry combustion technique with a Leco Furnace (Nelson and Sommers, 1982). All the measurements were duplicated. Total nitrogen
was determined using a Leco nitrogen analyser. 12 g of <2 mm soil was shaken with 60 ml of de-ionised water for 1 h after which pH and EC were measured. Then 1.2 ml of CaCl₂ was added and the suspension shaken and allowed to stand for a further hour before repeating the pH measurement. Exchangeable cation concentrations were measured in a 0.01 M BaCl₂ leachate using ICP-AES and the CEC was approximated as the sum of Ca, Mg, K, Na and Al (Abbott, 1987).

Mineralisable N was estimated using an anaerobic incubation assay as described by Keeney (1982). This involved measuring the amount of ammonium-N produced during a 7 days incubation under waterlogged conditions. Keeney (1982) recommends this method as a simple and reliable predictor of soil N availability even though mineralisation in the field is an aerobic process.

Extractable P was determined using Bray extraction (Abbott, 1987). The P adsorption characteristic of the soil samples was studied in 0.02 M KCl. Soil samples weighing 2.5 g were placed into plastic bottles and 50 ml equilibrating 0.02 M KCl solution containing 24.8, 12.4, 6.2 or 0.0 mg P l⁻¹, respectively were added. Two drops of chloroform were added and the suspension shaken for 16 h at 20°C. The suspension was then filtered, the equilibrium P concentration (I) determined in the filtrate and the amount of P adsorbed (Q) calculated by difference. The concentration of solution P at zero adsorption (I₀) as well as the amount of adsorbed P at 0.2 mg l⁻¹ ambient P (Q₁₀) were calculated from the P adsorption isotherms for the different soils following the methods of Jaszbereenyi and Loch (1970). The P adsorption measurements were also carried out on the soil sample under natural vegetation, adjacent to the experimental site.

2.7.3. Soil biological properties

Microbial biomass carbon was estimated using the fumigation extraction method of Wu et al. (1990) on <6.3 mm soils. Samples equivalent of 50 g oven dried soil were equilibrated at field capacity for a week. Half of the samples were fumigated with ethanol-free chloroform for 24 h at 25°C in sealed desiccators. After fumigant removal, both the fumigated and non-fumigated soils were extracted by shaking for 30 min with 0.5 M K₂SO₄. OC in the extract was determined using a Shimadzu Carbon Analyzer. Biomass carbon was calculated from the difference in OC between the fumigated and non-fumigated soils using a conversion factor of 2.22 (Wu et al., 1990).

2.7.4. Soil physical properties

Particle size analysis was carried out on <2 mm soil samples after dispersion by Calgon and shaking following the method of Abbott (1987). Aggregate stability was determined by wet sieving. About 20 g of the air-dried <6.3 mm soil was weighed and wet sieved for 10 min using sieves of 250 μm aperture in a 2 l cylindrical container. Aggregate stability was calculated as the mass of stable aggregates >250 μm expressed as a proportion of the total soil mass. Field capacity soil water content was measured in the field, in the 0–10 cm layer, 48 h after irrigation. Permanent wilting point water content (θ_pwp) was determined on <2 mm subsamples after equilibration at a pressure of 1.5 MPa using a soil moisture extractor.

2.7.5. Statistical analysis

Results were analysed by analysis of variance using Genstat V. Unless otherwise stated differences between treatments were significant at p<0.05. Least significant differences (p<0.05) were calculated for comparison amongst treatment means.

3. Results

The baseline soil properties are briefly presented before detailing the results of the fourth year measurements. Finally the two sets of data are compared to assess the changes that occurred after three and a half years of vegetable cropping.

3.1. Baseline Status

The baseline data (Table 3) show that the soil represents a typical natural yellow earth in many respects — being strongly acid, having a very low CEC, low EC and low OC (Peverill et al., 1999). However, the Bray P levels indicate that the soil had previously received fertiliser applications. The mean Bray P concentration of 87 mg P kg⁻¹ was approximately ten-fold higher than the highest Bray P found in natural soils in the area (McKenzie et al., 1997). Replicate 2 was formerly a
Table 3
Summary of the baseline soil properties of the 0–10 cm depth in January 1992, before any treatments were applied to the Somersby vegetable farming-systems experiment (after McKenzie et al., 1997)

<table>
<thead>
<tr>
<th>Property</th>
<th>Mean</th>
<th>Sd</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH (1:5 soil:0.01 M CaCl₂)</td>
<td>5.4</td>
<td>0.8</td>
</tr>
<tr>
<td>EC (ECe) (dS m⁻¹)</td>
<td>1.96</td>
<td>0.98</td>
</tr>
<tr>
<td>CEC (cmol (+) kg⁻¹)</td>
<td>4.6</td>
<td>2.0</td>
</tr>
<tr>
<td>OC (g kg⁻¹)</td>
<td>11.9</td>
<td>1.83</td>
</tr>
<tr>
<td>Bray-I P (mg kg⁻¹)</td>
<td>87</td>
<td>58</td>
</tr>
</tbody>
</table>

a Standard deviation, n=15.
b ECe: electrical conductivity as a saturated paste extract.

citrus orchard and replicate 4 had been used for tomato experiments.

3.2. Fourth year status

3.2.1. Soil microbial biomass, organic carbon and nitrogen

The Organic and Evolving systems had significantly higher microbial biomass carbon than the other systems in December 1995; the average value for these two systems was 46% higher than that of the other systems (Table 4). The microbial biomass on all systems represented approximately 1% of OC.

The Organic and Evolving systems also had the highest OC and total N levels and the Agfact system had the lowest (Table 4). The OC level on Agfact was only 57% that of Evolving. The OC level of Objective was similar to those of the District Practice and Agfact systems.

The soil N status of the systems was closely related to their OC levels. Differences in total N followed a similar pattern to OC with no difference in C/N ratio amongst the different farming systems. The Evolving system had the highest mineralisable N, which was significantly higher than that of the Organic (Table 4). The lowest level was found in Agfact, which was not significantly different from those of the District Practice and Objective. Mineralisable N was linearly related to soil OC level (r=0.804, p<0.01, n=15).

3.2.2. Soil pH, exchangeable cations and electrical conductivity

District Practice soil was significantly more acidic than the other systems despite receiving two-fold more dolomite than the Evolving, Objective and Organic systems (Table 5 and Fig. 1). Corresponding to the lowest pH, the District Practice had a higher level of exchangeable Al and a lower level of exchangeable Mg. In fact, there were significant differences in the composition of many of the exchangeable cations amongst the different soils (Table 5). The District Practice and Agfact had similar low levels of exchangeable calcium, which were only 59% of that in the Organic and Evolving. The potassium levels of the Organic and Evolving systems were nearly double those of the District Practice and Agfact. As a consequence, the effective CEC of the Evolving and Organic systems (av. 8.03) was 173 and 179% higher than those of the District Practice and Agfact systems.

There was a significant correlation between CEC and OC of the soils:

\[ CEC = -0.931 + 4.46OC \]

\[ r = 0.90, \quad p < 0.05, \quad n = 15 \]  

indicating that the differences in CEC can be accounted for by differences in OC levels.

The Objective system had the highest EC level. It was 134% higher than the average level of the other systems.

3.2.3. Soil phosphorus

The District Practice, Evolving and Organic soils had the highest total P levels, corresponding to the highest P fertiliser inputs (Table 6 and Figs. 2 and 3). But the availability of P on Organic and Evolving, as measured by the Bray No. 1 test, was far lower than on the District Practice. Total P on the Organic was 35% higher than...
Table 5
Soil pH, electrical conductivity, exchangeable cations and effective cation exchange capacity (cmol(+)/kg⁻¹) of 0–10 cm soils after three and a half years of cropping on the five vegetable farming-systems

<table>
<thead>
<tr>
<th>System</th>
<th>pH</th>
<th>Ec b (dS m⁻¹)</th>
<th>Na</th>
<th>K</th>
<th>Ca</th>
<th>Mg</th>
<th>Al</th>
<th>Effective CEC c</th>
</tr>
</thead>
<tbody>
<tr>
<td>DP</td>
<td>4.85 a</td>
<td>1.5 b</td>
<td>0.02 a</td>
<td>0.15 a</td>
<td>3.70 a</td>
<td>0.48 a</td>
<td>0.14 b</td>
<td>4.49 a</td>
</tr>
<tr>
<td>Ag</td>
<td>5.73 bc</td>
<td>1.0 a</td>
<td>0.02 a</td>
<td>0.14 a</td>
<td>3.68 a</td>
<td>0.76 a</td>
<td>0.05 ab</td>
<td>4.65 a</td>
</tr>
<tr>
<td>Obj</td>
<td>5.49 b</td>
<td>3.3 d</td>
<td>0.02 a</td>
<td>0.21 a</td>
<td>4.85 a</td>
<td>0.84 a</td>
<td>0.03 a</td>
<td>5.95 a</td>
</tr>
<tr>
<td>Org</td>
<td>6.03 c</td>
<td>1.4 b</td>
<td>0.06 c</td>
<td>0.25 b</td>
<td>6.21 b</td>
<td>1.48 b</td>
<td>0.02 a</td>
<td>8.01 b</td>
</tr>
<tr>
<td>Ev</td>
<td>5.80 bc</td>
<td>1.7 c</td>
<td>0.04 b</td>
<td>0.30 b</td>
<td>6.26 b</td>
<td>1.42 b</td>
<td>0.01 a</td>
<td>8.04 b</td>
</tr>
</tbody>
</table>

a Means with the same following letter are not significantly different at the 5% level.

b Electrical conductivity as a saturated paste extract (ECe) converted from 1:5 soil water extract using a multiplication factor of 20 for a sandy loam soil (Abbott, 1987).

c Effective cation exchange capacity = sum of exchangeable cations, i.e. Na⁺+K⁺+Ca²⁺+Mg²⁺+Al³⁺.

Table 6
Soil total phosphorus, available phosphorus and phosphorus adsorption/desorption parameters of 0–10 cm soils after three and a half years of cropping on the five vegetable farming-systems

<table>
<thead>
<tr>
<th>System</th>
<th>Total P (mg kg⁻¹)</th>
<th>Bray P (mg kg⁻¹)</th>
<th>Q₁₀₂ (mg kg⁻¹)b</th>
<th>I₀0 (mg l⁻¹)c</th>
</tr>
</thead>
<tbody>
<tr>
<td>DP</td>
<td>810 b</td>
<td>361 c</td>
<td>-70.76</td>
<td>6.47</td>
</tr>
<tr>
<td>Ag</td>
<td>530 a</td>
<td>203 ab</td>
<td>-29.45</td>
<td>2.13</td>
</tr>
<tr>
<td>Obj</td>
<td>530 a</td>
<td>210 ab</td>
<td>-45.82</td>
<td>2.81</td>
</tr>
<tr>
<td>Org</td>
<td>1090 c</td>
<td>168 a</td>
<td>-33.03</td>
<td>1.99</td>
</tr>
<tr>
<td>Ev</td>
<td>970 bc</td>
<td>244 b</td>
<td>-44.02</td>
<td>2.29</td>
</tr>
</tbody>
</table>

a Means with the same following letter are not significantly different at the 5% level.

b Q₁₀₂ is the amount of adsorbed P at 0.2 mg l⁻¹ ambient P.

c I₀₀ is the concentration of solution P at zero adsorption.

on the District Practice yet Bray P on the Organic was less than half of the District Practice level.

Phosphorus adsorption isotherms revealed that the District Practice soil had less P adsorption capacity and a greater tendency to release P than the other systems. The isotherms for the Organic, Objective, Agfact and Evolving systems can be represented by a single line, but the District Practice isotherm lies significantly lower (Fig. 4). The equilibrium P concentration of the solution at zero adsorption (I₀₀) was three-fold higher for the District Practice compared to the other systems (Table 6). Also, while the amount of P adsorbed at I=0.2 mg l⁻¹ (Q₁₀₂) was negative for all the systems (indicating a release of P from the soil) the District Practice had the most negative value: -70.76 mg P kg⁻¹.

Soil from nearby native vegetation had a much greater capacity to adsorb P than the soils of any of the farming systems. The native soil isotherm was far higher than any of the cropped soil isotherms (Fig. 4), and the Q₁₀₂, in marked contrast to the cropped soils, was strongly positive: 71.3 mg P kg⁻¹.

3.2.4. Soil physical properties

Soils from the Evolving and Organic systems had a significantly higher proportion of water stable aggregates >250 μm than soils from the conventional veg-
etable farming systems (Table 7). Also, the water holding capacity (WHC, difference between $\theta_{fc}$ and $\theta_{pwp}$) of Evolving and Organic soils was 27 and 20% higher than that of the District Practice soil. The major influence on WHC was a much higher $\theta_{fc}$ on the Evolving and Organic soils compared to the District Practice (Table 7). A highly significant correlation existed between $\theta_{pwp}$ and soil OC levels of the different soils:

$$\theta_{pwp} = 0.0148 + 0.0255OC$$

$$r = 0.979, \ p < 0.01 \ n = 15.$$  \hspace{1cm} (2)

### 3.3. Changes in soil properties from the baseline status

Taking the level of variability of the baseline measurements into account, the following changes occurred in soil properties after three and a half years of vegetable cropping on the different systems (Fig. 5):

- OC and CEC increased strongly on the Organic and Evolving while OC increased slightly on District Practice;
- none of the systems experienced a decline in OC and CEC levels;
- there is weak evidence that pH rose on Organic and fell on District Practice;
- EC increased on the Objective system and possibly decreased on Agfact; and,
- Bray P levels increased on all systems but did so most on the District Practice system.

The OC levels of the Organic and Evolving systems rose by approximately 65% and CEC by 75%. The decreasing trend in pH on the District Practice, although small compared to baseline variability, may still be an important indicator of system health as the mean baseline level was already very low (pH 5.4). Similarly, the

<table>
<thead>
<tr>
<th>System</th>
<th>Aggregate stability$^b$</th>
<th>$\theta_{pwp}$$^c$</th>
<th>$\theta_{fc}$$^d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>DP</td>
<td>0.35 a</td>
<td>0.052 ab</td>
<td>0.167 a</td>
</tr>
<tr>
<td>Ag</td>
<td>0.30 a</td>
<td>0.044 a</td>
<td>–</td>
</tr>
<tr>
<td>Obj</td>
<td>0.33 a</td>
<td>0.053 ab</td>
<td>–</td>
</tr>
<tr>
<td>Org</td>
<td>0.43 b</td>
<td>0.059 bc</td>
<td>0.194 b</td>
</tr>
<tr>
<td>Ev</td>
<td>0.43 b</td>
<td>0.069 c</td>
<td>0.211 b</td>
</tr>
</tbody>
</table>

$^a$ Means with the same following letter are not significantly different at the 5% level.

$^b$ Mass of water stable aggregates >250 $\mu$m expressed as a proportion of the total soil mass.

$^c$ $\theta_{pwp}$ = soil water content at permanent wilting point, measured with a pressure plate at 1.5 MPa.

$^d$ $\theta_{fc}$ = soil water content at field capacity, measured in the field 48 h after irrigation.
increased EC on the Objective system (while all other systems had a decreasing trend) is likely to cause crop growth problems. Although Bray P levels were already relatively high at the time of the baseline measurements (87 mg kg\(^{-1}\), Table 3) all the systems experienced increases in Bray P concentration, ranging from a 315% increase on the District Practice to a 93% increase on the Organic. However, the large coefficient of variation of the baseline mean (67%) indicates that the increase on the Organic was relatively small.

4. Discussion

The issue of the sustainability of the vegetable farming-systems will be considered here in two contexts: on-site sustainability — factors that directly affect the long-term productivity and profitability of the vegetable growing land itself; and off-site sustainability — the potential for the vegetable growing land to impact on the surrounding environment.

4.1. Overall performance of the systems

The soil health of the systems had generally not deteriorated after three and a half years of vegetable cropping (Fig. 5). Rather, the soil health of the Organic and Evolving systems had improved. Their soil properties demonstrate a clear on-site sustainability advantage over the conventional systems. The Organic and Evolving soils were more fertile: they had higher total N, total P, exchangeable nutrient cations, WHC and microbial biomass. Also, while the soil properties of the Agfact, Objective and District Practice were consistently poorer than those of the alternative systems, the District Practice had the added problem of a tendency to become acidic.

The soil properties of the District Practice system were the poorest in terms of off-site sustainability. From the soil’s high P availability and low aggregate stability we could predict what we have already observed: it is the most likely system to produce large runoff flows with high sediment loads and P content (as yet unpublished data). In contrast, the Evolving and Organic soils provide a more effective buffer between vegetable farming and the environment. They have a greater nutrient and WHC, a potential for more effective nutrient cycling and more stable soil aggregates.

The lower P availability of the Agfact and Objective soils, relative to the District Practice, represents an improvement in off-site sustainability achieved through relatively small changes in management. These systems were similar to the District Practice in that they received a large proportion of their P as superphosphate (Fig. 2). However, they received considerably less P than the District Practice and their P sorption capac-
ity remained higher. In fact it was no different to that of the alternative systems. These two largely conventional systems are, therefore, much less of a threat to the environment than the District Practice.

The differences in OC levels between the vegetable production systems, developed over this period, were much greater than those reported by Chan et al. (1992) after 10 years of extreme tillage and stubble management treatments under rainfed crop production. Also, no difference in OC levels was detected between conventional and organic/biological systems after 6 years under broad-acre rainfed cereal/ley farming by Penfold et al. (1995). The rapid response to management exhibited in the vegetable farming-systems experiment reflects the intensity of horticultural production.

4.2. Comparing management — clues to the causes of the effects

Comparing the management of the systems provides insights into why the Organic and Evolving systems experienced significant improvements in such a broad range of soil properties while the three conventional systems did not. While it is not possible to unravel the many likely interactions between different management practices and the history of each system, it is nevertheless useful to examine whether there are any consistent effects from applying similar practices on different systems.

Tillage did not have a consistent effect on soil properties. The Organic and Agfact systems had similar tillage frequency and intensity and yet the Organic had higher MB, OC, CEC, aggregate stability, WHC and mineralisable N than the Agfact. Conversely, both the Evolving and Objective were no-till systems and yet the Objective experienced few of the soil property improvements that occurred on the Evolving. Yet Adem and Tisdall (1984) found that growing a rye-grass (*Lolium perenne* L.) cover crop on a red-brown earth, used for vegetable farming, improved aggregate stability by 83% compared to cropped soils and 35% compared to an untilled bare control. The lack of a similar improvement in aggregate stability on the yellow earth is likely to be caused by low inherent stability due to its sandy texture. The red-brown earth studied by Adem and Tisdall (1984) had only 30% of particles of sand size (>20 μm) or greater whereas the yellow earth had 77%. The red-brown earth still had an aggregate stability of 58% after intensive tomato production whereas the yellow earth, under the Organic and Evolving systems, had an aggregate stability of only 43% after three-and-a-half years of careful management.

Likewise, other management factors such as irrigation, pest management and crop nutrition do not explain the different soil health of the Organic and Evolving systems. All of the systems besides the District Practice had drip irrigation. Pesticides were excluded from the Organic but not on the Evolving system (similar pesticide usage occurred on the Objective and Evolving systems). While both the Organic and Evolving systems received large P inputs (Fig. 2) the N inputs to the Organic were less than those of the Agfact and similar to the level of the Objective system. The District Practice had the highest nutrient inputs but experienced very few soil health improvements in comparison to the Organic and Evolving.

Compost application is the only major management factor that was common to the Organic and Evolving systems and not the others. Thus it is the most likely single management activity to explain the improved...
soil health of the Organic and Evolving systems. They both received large compost additions (40 and 60 Mg ha\(^{-1}\), respectively) in early 1995, approximately 10 months before soil sampling. The Agfact and District Practice systems also received organic matter additions as poultry manure but these were considerably smaller (28 and 30 Mg ha\(^{-1}\), respectively) and in separate applications at least 1 year apart. Furthermore, poultry manure is less likely to contribute to soil OC since it is very rapidly mineralised (Robinson and Sharpley, 1995).

Porter et al. (1999) also found that organic amendments had a greater effect on soil properties than cover crops. After only one cropping season, soil that had received 67 Mg ha\(^{-1}\) of compost and beef cattle manure had higher OC, CEC and aggregate stability. However, they found no changes in soil properties after 3 years on soils on which a cover crop of pea, oat and hairy vetch (\textit{Vicia villosa} Roth) were grown in rotation with potato (\textit{Solanum tuberosum} L.).

Adem and Tisdall (1984) suggested that it was the fine roots of the earlier mentioned ryegrass cover crop, and associated fungal hyphae, that held red-brown earth soil particles into water-stable aggregates. However, this explanation appears inadequate for the yellow earth at Somersby where aggregate stability did not improve after a grass cover crop but did after large inputs of organic matter. Yet, Tisdall and Oades (1982), studying only red-brown earths, argue that polysaccharides cannot influence the stability of aggregates larger than 50 \(\mu\)m.

4.3. Phosphorus issues

The difference in availability of P fertilisers is demonstrated in the contrasting Bray P levels of the District Practice and Organic systems. Despite these systems receiving similar total P inputs (Fig. 2), the District Practice (using super phosphate and poultry manure) had a Bray P level more than two-fold higher than the Organic (using rock phosphate and compost). Yet the Bray P levels on the Organic (168 mg P kg\(^{-1}\)) were still more than adequate for vegetable growing: best practice guidelines for growing vegetables (NSW Agriculture, 1997) recommend no more P fertiliser need be applied for 1 year or longer when Bray P \(>150\) mg P kg\(^{-1}\).

Reduced inputs of superphosphate on the Agfact and Objective systems also resulted in similar soil P availability to that on the Organic (measured by both Bray P and P isotherms). In terms of reducing environmental impact therefore, it appears that using smaller amounts of highly available P fertiliser can be equally effective to using slowly available P sources; on this soil type at least.

The P isotherm measured on native soil showed that the soils of all the farming systems had far less capacity to absorb P than in their natural state. Thus, the differences in P status among the farming systems are relatively small compared to the change made from the native state to a cropping system. While the District Practice had a much greater tendency to release P to the environment than the Organic system, they are not at opposite ends of a sustainability scale.

The quantity and types of P fertiliser applied to the District Practice were comparable to practices on vegetable farms in the Sydney region. A study of P fertiliser use on 29 vegetable farms conducted by Jinadasa et al. (1997) found mean application rates of \(\sim 450\) kg P ha\(^{-1}\) per year and the District Practice system received, on average, 570 kg P ha\(^{-1}\) per year. Approximately 65% of the P was applied as poultry manure on the surveyed farms whereas on the District Practice it was 46%.

4.4. Soil acidity and salinity

The acidifying ability of ammonium fertilisers was demonstrated on the soil of the District Practice system (much of the fertiliser N was ammonium nitrate) by its lower pH in spite of the quantity of dolomite that had been applied. The acidification was also evident in the balance of exchangeable cations with exchangeable Al replacing Mg on the District Practice system (Chan and Heenan, 1993). The lower levels of Ca and K on the District Practice and Agfact soils compared to the Organic and Evolving soils are also likely to be related to acidification. Goladi and Agbenin (1997) made a similar finding in a long-term (45 year) study: the pH and CEC of plots fertilised with inorganic N fertilisers were lower than native soils and much lower than plots that received cattle manure applications. They attributed the loss of cations on the inorganically fertilised plots to low pH and OC levels.
The apparent decline in soil EC from the baseline state on most systems was probably due to greater leaching under irrigated vegetable production compared to previous land uses. However, applying nutrient solutions under a plastic mulch appeared to cause a marked increase in soil salinity on the Objective system. According to Ayers (1977) the Objective salinity level was high enough to adversely affect the yields of tomato, spinach, cucumber and broccoli; and, according to Lorenz and Maynard (1980) it was sufficient to reduce the yield of cabbages and capsicums by more than 25%. Cornish and Nguyen (1989), on the other hand, working at the same research station, found that soil EC levels similar to those on the Objective did not reduce tomato yields.

5. Conclusions

After three and a half years of vegetable cropping, the soils of the alternative systems — the Organic and Evolving — had increased OC and CEC levels, relative to their baseline state. The soils of the more conventional systems — the District Practice, Agfact and Objective — remained generally unchanged. The Organic and Evolving soils also had higher total N, total P, WHC, microbial biomass and aggregate stability than the other systems. Thus, the management of the Organic and Evolving systems improved soil health whereas the management of the conventional systems did not. It appears that compost applications had the greatest effect on improving the soil health of the alternative systems.

Also over this period, soil available P levels rose on all systems but did so far more on the highest input system, the District Practice. The low aggregate stability of this system in conjunction with its low P sorption capacity is likely to cause considerable environmental impact through loss of sediments and P during runoff events. In contrast, the management of the Agfact and Objective systems, using smaller P inputs, was able to maintain soil P availability to similar levels to those of the alternative systems. This suggests that relatively small and simple adjustments to conventional management can result in substantial environmental benefits.

This research indicates that there are different strategies for achieving more sustainable vegetable farming: one, more careful management of conventional systems (resulting in less risk of losing P off-site but few other soil improvements); or two, a larger shift towards more biological systems (resulting in a broad improvement in soil health). The former approach will be easier to achieve but the latter promises a more long-term basis for sustainable production.

Acknowledgements

We are indebted to the Land and Water Resources Research and Development Corporation and the Horticultural Research and Development Corporation for their generous funding and support of this research. Also, the experiment would not have been possible without the efforts of Wayne Pitt and John Heckenberg who were able to be five different types of vegetable farmer and do extensive sampling and monitoring.

References


