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On-farm assessment of organic matter and tillage management on vegetable yield, soil, weeds, pests, and economics in California

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Abstract

In intensive vegetable production, low organic matter (OM) inputs and leaching of nitrate (NO_3^--N) decrease soil quality with time. Four management regimes were compared for their effects on soils and on production issues in a cooperative research project with a commercial vegetable grower in the Salinas Valley, California, USA, on an 8.3 ha field: minimum tillage with OM (+OM) inputs; minimum tillage with no OM (−OM) inputs; conventional tillage +OM inputs; and conventional tillage −OM inputs. Minimum tillage retained the same raised beds for the 2-year study (four crop cycles), and tilled to approximately 20 cm depth. Conventional tillage used many passes for surface and subsoil tillage, and disturbed the soil to approximately 50 cm depth. In +OM, compost was added two times per year, with a rye (*Secale cereale*) cover crop in the fall or winter, whereas −OM treatments followed the typical practice of only incorporating crop residues. Addition of cover crops and compost increased microbial biomass C (MBC) and N (MBN), reduced bulk density, and decreased the NO_3^--N pools in the 0–90 cm profile, so that leaching potential was lower compared to −OM treatments. Tillage practices had generally similar effects on soils except that surface soil moisture and NO_3^--N in the deep profile were consistently lower with minimum tillage. Minimum tillage tended to decrease lettuce (*Lactuca sativa*) and broccoli (*Brassica oleracea*) yields, but was not associated with increased pest problems. Weed density of shepherd's purse (*Capsella bursa-pastoris*) and burning nettle (*Urtica urens*) were occasionally lower in the +OM treatments. Disease and pest severity on lettuce was slight in all treatments, but for one date, corky root disease (caused by *Rhizomonas suberifaciens*) was lower in the +OM treatments. The Pea Leafminer, *Liriomyza huidobrensis*, was unaffected by management treatments. Economic analysis of the three lettuce crops showed that net financial returns were highest with minimum tillage −OM inputs, despite lower yields. Various tradeoffs suggest that farmers should alternate between conventional and minimum tillage, with frequent additions of OM, to enhance several aspects of soil quality, and reduce disease and yield problems that can occur with continuous minimum tillage.

Keywords: Broccoli; Compost; Cover crops; Lettuce; Microbial biomass; Minimum tillage; Nitrate leaching; Salinas valley; Soil organic matter; Soil quality

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1. Introduction

Participatory research with farmers on commercial fields provides a unique opportunity to study the diverse impacts of management practices on yield, pests, environmental quality, and economics. Since research is performed in situ, findings are representative of typical ecological responses by the populations and communities of organisms within the actual agroecosystem, as compared to research station experiments that often cannot replicate the abiotic and biotic environment of real farms (Witcombe, 1999; Wander and Drinkwater, 2000). Also, the results of on-farm research can be valuable to farmers who are stakeholders in the design and management of experiments (Goma et al., 2001). This is especially true if treatments are conducted at the scale of operations used on the farms.

Ideally, farmer participatory research employs a systems approach that addresses and integrates several aspects of production, biology, economics, social and sustainability issues. In terms of ecology, this might involve investigation of the autecology of organisms, population and community dynamics, and/or biogeochemical flows, e.g., of nutrients and water, as well as the aspects of human ecology that affect decision-making and resource use. From an agronomic perspective, this emphasizes the evaluation of management practices to increase yield and economic gain, and with efficient use of resources.

Trade-offs exist between the benefits and drawbacks of management practices designed to increase soil quality, which concerns the effects of soil management on agricultural productivity, and on the characteristics of soils that contribute to environmental quality (Karlen et al., 1997; Liebig and Doran, 1999). For example, reduced tillage is known to increase soil organic matter (SOM) (Silgram and Shepherd, 1999), but can decrease the productivity of some crops (Carter, 1991; Sims et al., 1998), as well as increase the incidence of some diseases (Jackson et al., 2002). Cover crops decrease the leaching of nitrate (NO_3^--N) below the root zone (McCracken et al., 1994) and can increase N availability and crop yield (Paustian et al., 1992), but a drawback of certain cover crops is as alternate hosts for diseases that can then infect the subsequent cash crop (Koike et al., 1996). Higher financial costs from deeper tillage can be compensated by higher yields and net returns (Popp et al., 2001; Wesley et al., 2001), although higher fuel use contributes to greenhouse gas production (Robertson et al., 2000). Systems research attempts to account for these varied outcomes.

Intensive production for crops such as lettuce, broccoli, and celery (*Apium* sp.) occurs in the Salinas Valley of coastal California, USA, which is a major supplier of these vegetables nationwide. The mild climate and the high inputs of irrigation and fertilizers allow the production of two or three crops per year. Large NO_3^--N leaching and denitrification losses occur in these cropping systems (Jackson et al., 1994; Ryden and Lund, 1980), and NO_3^--N exceeds the public health standard ($10\,mg\,N\,l^{-1}$) in nearly half of the wells in the upper aquifer. Very little OM is returned to the soil after vegetable harvest, but use of cover crops and compost has recently increased. Tillage occurs frequently, ranging from single passes with cultivators for weed control, to disking, subsoiling, and leveling a field between crops.

The impact of reduced tillage and increased OM inputs on vegetable production and soils was evaluated in a participatory on-farm experiment with a Salinas Valley grower, using management regimes that were viable possibilities for farmers, with the use of large plots to represent operations at the farm-scale. Conventional tillage (subsoiling, disking, and surface mulching) was compared with minimum tillage that disked the surface layer of semi-permanent beds, and shanked the furrows. Organic matter was added as both cover crops and compost, with the purpose of incorporating both readily labile and more resistant sources of C. Cover crops increase the active fraction of the SOM for a few weeks to months after incorporation (Crozier et al., 1998; Jackson, 2000; Schutter and Dick, 2002). Manure and compost may contribute more C to slow versus active pools of SOM, partly depending on compost maturity (Paustian et al., 1992; Drinkwater et al., 1998). The objectives of the 2-year experiment (four crop phases) were to compare the effects of alternative tillage and OM management by: (1) monitoring changes in crop yield and nutrient uptake, soil microbial biomass, and N availability; (2) documenting effects on weeds, pathogens, and insect pests; and (3) evaluating the total costs and net returns as a means of assessing the economic viability of adopting practices conducive to increasing soil quality.

Table 1
Soil characteristics in the 0–15 cm layer at the initiation of the study on 4 April 1998[a]

Soil characteristic	Mean	S.E.	*n*
pH	7.0	0.03	4
Cation exchange capacity (cmol kg^{-1})	27.6	1.82	4
Electrical conductivity (mmho cm^{-1})	0.59	0.05	4
Moisture retention at			
−0.03 MPa (g H_2O g^{-1} soil × 100)	21.6	1.18	4
−0.1 MPa (g H_2O g^{-1} soil × 100)	16.4	1.68	4
−0.5 MPa (g H_2O g^{-1} soil × 100)	14.8	1.41	4
−1.0 MPa (g H_2O g^{-1} soil × 100)	14.6	1.43	4
−1.5 MPa (g H_2O g^{-1} soil × 100)	14.4	1.43	4
Sand (g kg^{-1})	280	9.2	31
Silt (g kg^{-1})	520	5.5	31
Clay (g kg^{-1})	200	4.2	31

[a] Samples were composited by block, except for particle size content which was analyzed separately for each sampling point.

2. Methods

2.1. Soils and management practices

The field trial was established in April 1998 on an 8.3 ha site in the Salinas Valley of California. The Salinas silt loam is a fine-loamy, mixed, thermic Pachic Haploxerolls (FAO Haplic Phaeozems) (Table 1). The coastal Mediterranean-type climate has mild, rainy winters, and foggy, cool, rain-free summers. Rainfall was 44.35 cm from 4 April 1998 through 31 March 1999 and 34.93 cm from 1 April 1999 through 26 April 2000. The field was in long-term use for irrigated cool-season vegetable (e.g., lettuce, broccoli, and celery) production, with typically two crops per year. Crops were grown on raised beds.

The field was divided into four replicate blocks each with an independent system of surface drip irrigation. Each block was divided into four 0.52 ha treatment plots. The four treatments were: minimum tillage +OM inputs; minimum tillage −OM inputs; conventional tillage +OM inputs; and conventional tillage −OM inputs.

Conventional tillage followed the typical tillage method for vegetable production in this area, i.e., disking, cultivating with a liliston, subsoiling, and bed-shaping. The soil is disturbed to approximately 50 cm depth. Beds are re-made between every crop. By contrast, the minimum tillage treatments consisted of using the 'Sundance' system (Sundance Farms, Coolidge, AZ), a liliston, rollers, and bed-shaping. The 'Sundance' system utilizes disks and lister bottoms to incorporate crop residues and cultivate the tops and sides of the beds in a single pass. This method tills shallowly to approximately 20 cm depth. No subsoiling was done in the minimum tillage treatments. The same 1 m wide beds remained in place in the minimum tillage treatments for the entire study. For both minimum and conventional tillage, shallow cultivation of the beds and furrows occurred during the cropping periods for weed management.

In treatments receiving added OM, compost was added two times per year, and a Merced rye (*Secale cereale* cv. 'Merced') cover crop was grown during the fall or winter (Table 2). It was incorporated before anthesis. Prior to incorporation by conventional or minimum tillage, the cover crop was flail mowed. This commercially available compost had a mean C:N ratio of 17.7, C content of 20.0%, $NO_3{}^{-}$-N concentration of 96 μg g^{-1}, and ammonium ($NH_4{}^{+}$-N) concentration of 35 μg g^{-1}. Starting materials for the compost were municipal yard waste (30%), waste from salad packing plants (5%), with the remainder composed of horse manure, clay, finished compost, and baled straw. In the treatments receiving no added OM, only the vegetable crop residue was incorporated into the soil. This is the typical amount of OM that has been used in vegetable production in the area, except for occasional manure.

Four vegetable crops were grown during the course of the study (Table 2). Crisphead lettuce (*Lactuca sativa* cv. 'Champ') was planted in May 1998. In January 1999, the west blocks (half of the field) was planted with crisphead cultivar 'Titan', with 'Coastal' on the east blocks. The crisphead cultivar 'Pacific' was planted in June 1999 over the entire field. Broccoli (*Brassica oleracea* L. Italica group, cv. 'Legacy') was planted in November 1999, on the east blocks, and December 1999, on the west half of the field. All crops were direct-seeded.

Sprinkler irrigation was used during the germination and establishment stages of the crops and cover crops. After thinning the cash crops, surface drip irrigation was applied two to three times per month from drip tape placed 4 cm deep in the center of the bed. Irrigation was scheduled by grower assessment, as is

Table 2
Schedule of management events during the 2-year study[a,b,c]

Date	Minimum tillage		Conventional tillage	
	+OM	−OM	+OM	−OM
1998				
April	*Minimum tillage*	*Minimum tillage*	*Disk, chisel*	*Disk, chisel*
			Disk, chisel, list	*Disk, chisel, list*
	Compost: 9 t ha^{-1}		*Compost: 9 t ha^{-1}*	
May	Cultivate, shape beds	Cultivate, shape beds	Cultivate, shape beds	Cultivate, shape beds
	Plant lettuce	Plant lettuce	Plant lettuce	Plant lettuce
June	Thin lettuce	Thin lettuce	Thin lettuce	Thin lettuce
	Cultivate	Cultivate	Cultivate	Cultivate
	Hoe weeds	Hoe weeds	Hoe weeds	Hoe weeds
July	**Harvest lettuce**	**Harvest lettuce**	**Harvest lettuce**	**Harvest lettuce**
	Minimum tillage, roll	*Minimum tillage, roll*	*Disk, subsoil, chisel*	*Disk, subsoil, chisel*
	Compost: 9 t ha^{-1}		*Compost: 9 t ha^{-1}*	
August	Plant cover crop		Plant cover crop	
September	*Minimum tillage cover crop*		*Disk cover crop*	
November	Cultivate	Cultivate	Cultivate	Cultivate
December	Cultivate	Cultivate	Cultivate	Cultivate
1999				
January	Cultivate, shape beds	Cultivate, shape beds	Cultivate, shape beds	Cultivate, shape beds
	Plant lettuce	Plant lettuce	Plant lettuce	Plant lettuce
March	Cultivate	Cultivate	Cultivate	Cultivate
	Thin lettuce	Thin lettuce	Thin lettuce	Thin lettuce
April	Hoe weeds	Hoe weeds	Hoe weeds	Hoe weeds
May	**Harvest lettuce**	**Harvest lettuce**	**Harvest lettuce**	**Harvest lettuce**
	Minimum tillage	*Minimum tillage*	*Disk, subsoil, chisel*	*Disk, subsoil, chisel*
June	*Minimum tillage*	*Minimum tillage*		
	Compost: 9 t ha^{-1}		*Compost: 9 t ha^{-1}*	
	Cultivate, shape beds	Cultivate, shape beds	Cultivate, shape beds	Cultivate, shape beds
	Plant lettuce	Plant lettuce	Plant lettuce	Plant lettuce
July	Cultivate	Cultivate	Cultivate	Cultivate
	Thin lettuce	Thin lettuce	Thin lettuce	Thin lettuce
	Cultivate, hoe weeds	Cultivate, hoe weeds	Cultivate, hoe weeds	Cultivate, hoe weeds
August	**Harvest lettuce**	**Harvest lettuce**	**Harvest lettuce**	**Harvest lettuce**
September	*Minimum tillage*	*Minimum tillage*	*Disc, subsoil, chisel*	*Disk, subsoil, chisel*
			Laser-level	*Laser-level*
	Compost: 9 t ha^{-1}		*Compost: 9 t ha^{-1}*	
	Minimum tillage, list, roll	*Minimum tillage, list, roll*	*Cultivate*	*Cultivate*
	Plant cover crop		Plant cover crop	
November	*Minimum tillage cover crop*		*Disk cover crop*	
			Subsoil, chisel	*Subsoil, chisel*
	Cultivate, shape beds	Cultivate, shape beds	Cultivate, shape beds	Cultivate, shape beds
	Plant broccoli (E)[d]	Plant broccoli (E)	Plant broccoli (E)	Plant broccoli (E)
December	Plant broccoli (W)	Plant broccoli (W)	Plant broccoli (W)	Plant broccoli (W)
2000				
January	Thin broccoli (E)	Thin broccoli (E)	Thin broccoli (E)	Thin broccoli (E)
	Cultivate, hoe weeds	Cultivate, hoe weeds	Cultivate, hoe weeds	Cultivate, hoe weeds
February	Thin broccoli (W)	Thin broccoli (W)	Thin broccoli (W)	Thin broccoli (W)
	Hoe weeds	Hoe weeds	Hoe weeds	Hoe weeds
April	**Harvest broccoli**	**Harvest broccoli**	**Harvest broccoli**	**Harvest broccoli**

[a] +OM and −OM indicate with or without cover crop and compost addition.
[b] Differences between management treatments are shown in italics.
[c] Crop harvests are shown in bold.
[d] The east (E) side of the field was planted with broccoli earlier than the west (W).

typically done. After each crop, the tape was lifted, retrieved, spliced, and wound on reels to be used at a later date. Water inputs (including rainfall) were as follows for the four vegetable crops: 32 cm (1998 lettuce crop); 21 cm (first 1999 lettuce crop); 30 cm (second 1999 lettuce crop); and 59 and 43 cm (2000 broccoli crop, respectively, for west and east sides of the field). For the two cover crops, water inputs were 8 cm (1998 cover crop) and 13 cm (1999 cover crop).

Fertilizer inputs consisted of a banded pre-plant application of 336 kg ha^{-1} of 5:25:25 (N:P:K) before each cover crop and broccoli crop, and one to four applications of liquid 20% ammonium nitrate through the drip tape after thinning each vegetable crop. There was one 336 kg ha^{-1} application of ammonium sulfate prior to planting broccoli. The entire field received the same fertilizer applications. Nitrogen fertilizer inputs were as follows for the four vegetable crops: 15.0 g N m^{-2} (1998 lettuce crop); 9.5 g N m^{-2} (first 1999 lettuce crop); 12.6 (second 1999 lettuce crop); and 16.6 g N m^{-2} (2000 broccoli crop). No reduction in fertilizer inputs was made in the +OM treatments, since the availability of nutrients from these inputs was unknown.

2.2. Soil sampling and analysis

Soil characteristics were measured on soil from the 0–15 cm depth passed through a 2 mm mesh sieve in April 1999 at the initiation of the experiment. Baseline samples were taken from each of the 32 sampling points, then eight samples per block were composited. Only particle size distribution was analyzed separately for each sampling point. Another set of soil samples for bulk density and total C and N was taken in April 2000. The pH was determined from a saturated paste. Gravimetric moisture retention was determined on a pressure plate apparatus. Total N and C were measured by the combustion gas analyzer method (Pella, 1990). These analyses and particle size distribution (Gee and Bauder, 1986), cation exchange capacity (CEC) (Janitzky, 1986), electrical conductivity (EC) (Rhoades, 1982) were performed by the Division of Agriculture and Natural Resources (DANR) Analytical Laboratory at the University of California at Davis. Bulk density was calculated from the dry mass of soil per volume collected in a brass ring (8.5 cm diameter × 6 cm deep). Samples were taken at the surface where roots are abundant (0–6 cm) and in the typical 'plow pan' layer (47–53 cm) from the sides of soil pits in the center of each treatment plot.

Routine sampling of plants and soil occurred at the end of each crop or cover crop, within a week before harvest by the grower: 19 July and 14 September 1998; 10 May, 17 August, and 31 October 1999; and 3 April (east half of field) and 24 April (west half of field) 2000. Each of the 32 sampling points was within a 2 m × 50 m area, which was large enough to avoid coring the same location more than once during the study.

Soil cores (6 cm diameter) were taken in the planting line, and subdivided into 0–15, 15–30, 30–60 and 60–90 cm depth increments. In the field, all samples were immediately put on ice and extractions were initiated within 6–12 h after sampling. For the 0–15 cm layer, two cores were bulked per plot. One core was taken for deeper samples. Soil was mixed and subsampled in the field for gravimetric soil moisture content (approximately 50 g soil), and KCl-extractable NO_3^--N and NH_4^+-N (approximately 10 g soil). For inorganic N, three replicate subsamples were taken from the surface layer, and two from the lower layers. Potentially mineralizable N (approximately 10 g soil) was assessed using a 7-day anaerobic incubation (Waring and Bremner, 1964). Inorganic N was measured by cadmium reduction with a Lachat Quick Chem II Flow Injection Analyzer (Zellweger Analytical, Milwaukee, WI). Additional subsamples (50 g soil) were taken for microbial biomass C (MBC) and N (MBN) using the fumigation–extraction technique, then total MBC was calculated by multiplying the flush of C by 2.64, and total MBN was calculated by multiplying the flush of inorganic plus organic N by 1.86 (Brookes et al., 1985; Vance et al., 1987; Wyland et al., 1994). An irrigation water sample was taken and analyzed for pH (7.7), EC (0.66 mmho cm^{-1}), and NO_3^--N (0.08 mg l^{-1}).

2.3. Plant sampling and analysis

For each crop aboveground biomass samples were collected from two 2 m^2 areas in each plot, except on 14 September 1998 when only 1 m^2 area of biomass was collected. The number of plants in the plot was counted. The fresh weight of the aboveground part of each lettuce plant was taken. A representative portion of the fresh plant was cut and weighed, then dried and weighed. For the broccoli crop, the harvestable portion of the plants, the fresh weight of the top 18 cm of the flower stalks, i.e., the crown, was taken. The samples were taken during the second harvest by the grower, which was by far the largest of three harvests, and thus are considered a good approximation of actual yield. The crown and the rest of the plant were dried together and weighed to obtain the dry weight per plant.

Plant samples were oven-dried at 65 °C, weighed, and analyzed for nutrient content. Additionally a fresh weight was recorded for cash crop plant samples. Merced rye was analyzed for total N. Lettuce and broccoli plant samples were analyzed for total N (Dumas, 1981), P (Horneck et al., 1989), K (Johnson and Ulrich, 1959), and Ca, Mg, B and Zn (Meyer and Keliher, 1992) by the DANR Analytical Laboratory.

Indigenous weed populations were monitored within one microplot (8.1 m × 15.3 m) per treatment plot per sampling date. Weed density counts were taken approximately once per cropping cycle. Weed seedbanks were determined in 20 soil cores (2.5 cm diameter) in each microplot on 17 April 1998, 4 May 1999, and 24 March 2000. Each core was partitioned into 0–15 and 15–30 cm depths. The cores were placed in greenhouse trays, watered daily, and germinating weeds were counted monthly and removed; thereafter weed seeds were extracted from the soil samples using an elutriation system followed by flotation in a salt solution (Fennimore and Jackson, 2003). Seed identity and viability were inspected under a 20× dissection microscope.

2.4. Insect and disease analysis

Insect pest pressure on the field was limited to leafminers. Leafminer populations were evaluated by collecting randomly chosen lettuce heads from each of the treatment plots. Whole plant samples, five per plot on 5 May 1999, and six per plot on 17 August 1999, were placed into individual emergence cages consisting of modified 19 l plastic buckets fitted with mesh side vents and clear plastic tops to allow the leafminers and parasites to complete development. The number of adult flies and parasites that flew and stuck to a yellow sticky card trap were counted 6 weeks after field sampling to ensure development of all leafminers and their parasites.

Key lettuce diseases were monitored and assessed throughout the study. For all treatments, plant stands (number of germinated lettuce seedlings per linear distance of row) were evaluated shortly after plant emergence as a gauge of possible damping-off diseases. Near harvest, the most important foliar disease, downy mildew (caused by the fungus, *Bremia lactucae*) was evaluated. Three important soilborne diseases, corky root (caused by *Rhizomonas suberifaciens*), lettuce drop (caused by *Sclerotinia minor*), and big vein disease (caused by the big vein virus-like agent) were also assessed. Samples were taken at each of the 32 sampling points: plant stands (four replicates of 2.44 m of row); corky root (10 plants); *Sclerotinia*, big vein, and downy mildew (212 m × 4 m area).

2.5. Statistical analysis

The SAS analysis of variance and general linear model procedures (SAS, 1991) were used to test the main effects of tillage (conventional versus minimum tillage) and OM inputs (with versus without cover crops and compost), and the tillage × OM input interaction on soil, crops, weeds, and pests. Block effects are not reported, as no consistent trends were found throughout the study. All statistical analyses were considered significant at $P \leq 0.05$.

2.6. Economic analysis

Detailed management records for the field site were analyzed using the Budget Planner program (Klonsky, 1991) to evaluate the total cost and profitability of the four management treatments within the context of the year-round vegetable cropping system. The grower supplied information for each operation including the date, labor and time required, materials and equipment used. Yield data was also provided for the entire field. These baseline data are unique to this site, but are representative of this production system. Costs and returns were then calculated from the baseline data and crop yields, using actual market prices and costs from local input suppliers. Non-cash overhead includes equipment ownership costs. Rents were estimated to be US$ 2471 ha^{-1} cash per crop in this district. The Budget Planner calculated gross returns, total costs, monthly cash flow and equipment schedules, and summaries of water, fertilizer, energy and labor use throughout each crop and cover crop season for each of the four management treatments. We calculated yield data (boxes ha^{-1} per treatment) by multiplying the yield data from the grower (boxes ha^{-1} for the whole field) by the relative difference in fresh weight m^{-2} between treatments that we measured in our field samplings. For broccoli, no economic analysis is reported, since the yield data from the grower was not utilizable due to multiple harvests over a month-long period. For calculation of total returns, the price for lettuce was US$ 7.50 per box of lettuce, which was the county average for the period of the study (Monterey County Agricultural Commissioner's Office, personal communication).

3. Results

3.1. Soil organic matter and bulk density

In this silt loam soil, total C and N concentrations ($g\,kg^{-1}$) in the surface 0–15 cm layer were higher after 2 years of addition of cover crops and compost, compared to non-amended soils (Table 3). Tillage treatment did not have a significant effect on either total C or N concentrations, nor were there significant tillage × OM interactions. The addition of organic amendments caused a decrease in bulk density in the surface (0–6 cm) layer, but not at the lower depth (47–53 cm) (Table 3). No effects due to minimum versus conventional tillage were observed.

Differences between total soil C and N at 0–15 cm depth on an area basis do not appear to have occurred, based on estimates that were calculated using bulk density values for the shallower depth increment, 0–6 cm. These estimates indicate similar amounts of total C and N (kg C or N ha^{-1} to 0–15 cm depth) in the four treatments (data not shown).

3.2. Microbial biomass and N dynamics at the soil surface

After the first cover crop in September 1998, soil MBC increased in the +OM treatments, and remained higher than in −OM treatments on almost every sampling date thereafter (Fig. 1). Treatment differences appeared after the first fall incorporation of cover crops and compost. MBC in the −OM treatments was typically 30–40% lower than in the +OM treatment from the fall of 1998 through the spring of 2000. Thus, no apparent increase in the relative difference between +OM and −OM treatments occurred through time. Temporal comparisons, however, are difficult to make due to differences in soil moisture, which are known to affect the amount of MBC. Similar timing and magnitude of responses to cover crops and compost additions occurred for MBN with a few exceptions. For example, no difference in MBN between OM treatments was observed immediately after the first cover crop in September 1998, but by February 1999, both MBC and MBN were higher in +OM treatments.

Microbial biomass was little affected by minimum versus conventional tillage during most of the 2-year experiment (Fig. 1). On the last sampling date, however, MBC was higher in the surface layer with minimum than conventional tillage. There was no evidence of a differential response to minimum versus conventional tillage due to OM inputs, as indicated by the lack of a significant interaction between tillage and OM treatments. Tillage treatment did not significantly affect MBN except on the first sampling date, which is difficult to explain given the lack of differences for the rest of the study.

For inorganic N in the surface layer, the largest effect of the OM inputs was to decrease soil NO_3^--N and NH_4^+-N after the cover crops, i.e., September 1998 and November 1999 (Fig. 2). For the soil samples taken after cover crops, the highest inorganic N occurred in the minimum tillage treatment without OM additions, and the lowest values in the minimum tillage treatment with OM additions, as indicated by the significant tillage × OM treatment interactions. Cover cropping thus appears to have slightly different effects on the surface layer of minimum versus conventionally tilled soils, although tillage treatment occasionally had a significant effect on inorganic N on various dates. Otherwise, there were few consistent patterns due to minimum versus conventional tillage. In one instance, however, a time lag appears to have occurred in NO_3^--N availability due to tillage treatment. In February 1999, NO_3^--N was lower with minimum than conventional tillage, but potentially mineralizable N was higher (Fig. 1), and soil moisture was lower (Fig. 2). Three months later, the higher NO_3^--N concentrations in the minimum tillage treatments may have been associated with delayed mineralization of the

Table 3
Total soil C, total soil N, and bulk density in 1998 and 2000

OM treatment	Tillage treatment	4 April 1998 (mean ± S.E.)				5 April 2000 (mean ± S.E.)			
		Total soil C at 0–15 cm depth ($g\,kg^{-1}$)	Total soil N at 0–15 cm depth ($g\,kg^{-1}$)	Bulk density at 0–6 cm depth ($Mg\,m^{-3}$)	Bulk density at 47–53 cm depth ($Mg\,m^{-3}$)	Total soil C at 0–15 cm depth ($g\,kg^{-1}$)	Total soil N at 0–15 cm depth ($g\,kg^{-1}$)	Bulk density at 0–6 cm depth ($Mg\,m^{-3}$)	Bulk density at 47–53 cm depth ($Mg\,m^{-3}$)
+	Minimum	15.2 ± 1.2	1.71 ± 0.11	ND[a]	ND	15.1 ± 0.9	1.63 ± 0.07	1.16 ± 0.04	1.47 ± 0.05
−	Minimum	14.1 ± 0.9	1.61 ± 0.06	1.25 ± 0.01	1.37 ± 0.01	14.1 ± 1.0	1.53 ± 0.08	1.31 ± 0.06	1.46 ± 0.02
+	Conventional	14.5 ± 0.9	1.64 ± 0.06	1.26 ± 0.04	1.40 ± 0.02	14.8 ± 0.7	1.60 ± 0.05	1.25 ± 0.05	1.33 ± 0.05
−	Conventional	13.8 ± 0.9	1.55 ± 0.06	ND	ND	13.7 ± 0.7	1.49 ± 0.05	1.36 ± 0.03	1.41 ± 0.06
Main effect *F* values									
OM		ns[b]	ns	ns	ns	*	*	*	ns
Tillage		ns	ns	ns	ns	ns	ns	ns	ns
OM × tillage		ns	ns	ns	ns	ns	ns	ns	ns

[a] No data was collected.
[b] No significant differences.
* ANOVA for each year with significance at the $P \leq 0.05$.

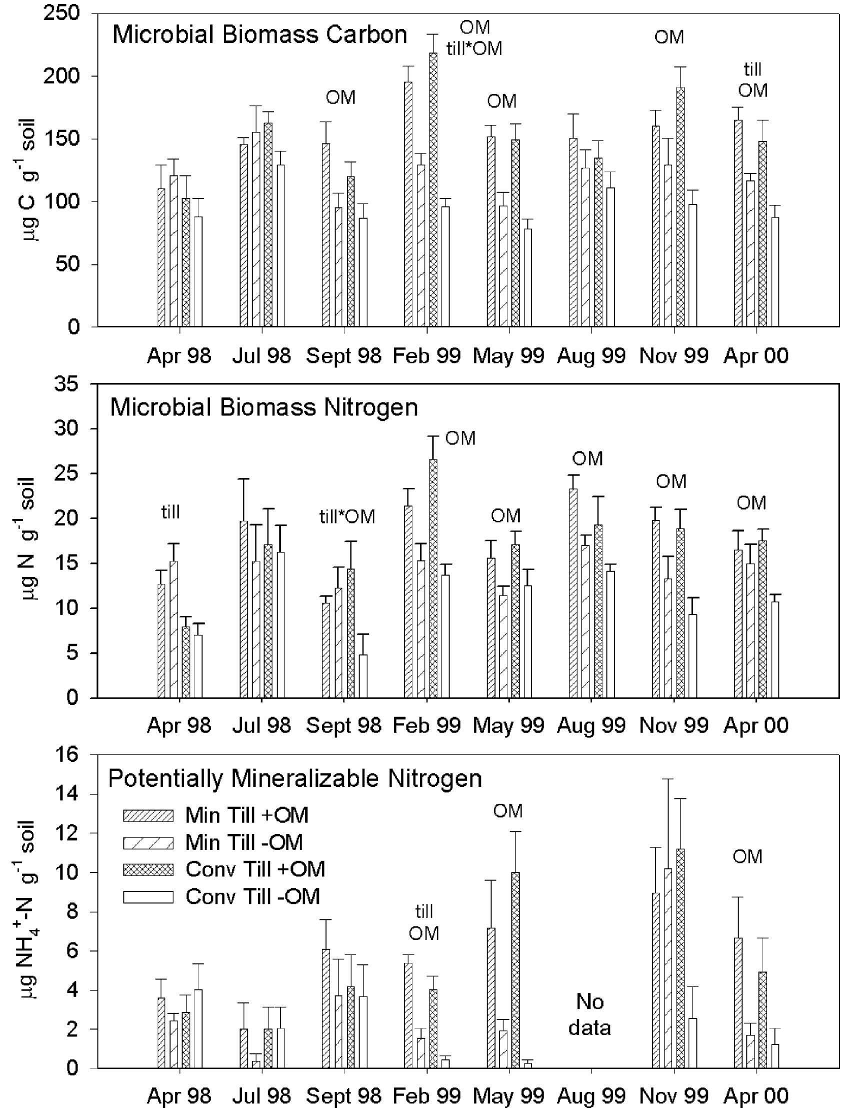

Fig. 1. Microbial biomass C and N (MBC and MBN) and potentially mineralizable N in the 0–15 cm layer of soil on crop and cover crop harvest dates. See Table 2 for management dates. Significant treatment effects ($P \leq 0.05$) are labeled for each sampling date. Mean ± S.E.

readily available organic N compared to conventional tillage.

Moisture content was higher in the surface layer after the irrigated cover crops were grown (Fig. 2). In 1999, this continued through the winter. Minimum tillage also decreased the moisture content in the surface layer beginning with the first cover crop in September 1998. Although the differences were small, i.e., 1–2% gravimetric moisture, they were consistent throughout the latter 1.5 years of the experiment.

3.3. Nitrate pools (0–90 cm depth)

Nitrate in the soil profile from 0 to 90 cm depth was lower in the +OM treatments, beginning with the first cover crop in the fall of 1998 and contin-

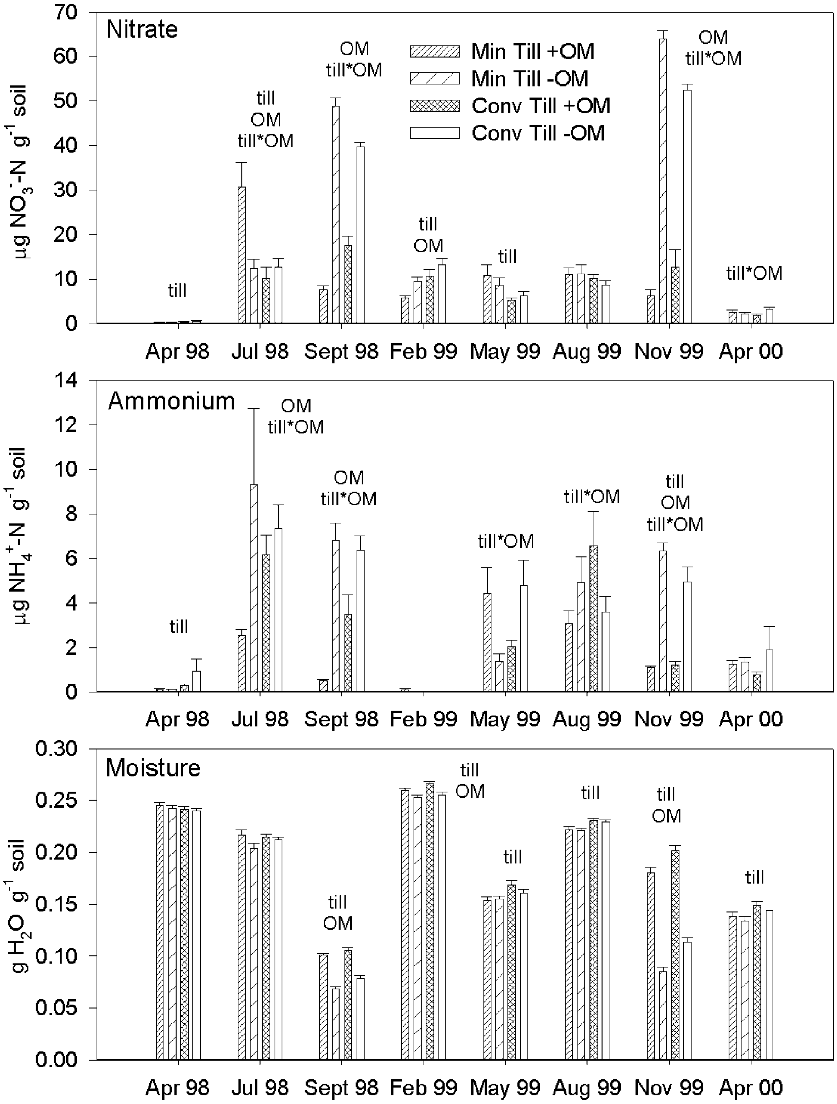

Fig. 2. Concentrations of nitrate and ammonium, and gravimetric moisture in the 0–15 cm layer of soil on crop and cover crop harvest dates. See Table 2 for management dates. Significant treatment effects ($P \leq 0.05$) are labeled for each sampling date. Mean ± S.E.

uing through the rest of the study (Fig. 3). Thus, the effects of cover crops and compost were similar, but more pronounced than in the surface layer alone (Fig. 2). Across both tillage treatments, differences were largest between the +OM and −OM treatments during the fall and winter (approximately 15–35 g NO_3^--N m^{-2}) and less when crops were present (approximately 8–10 g NO_3^--N m^{-2}).

Minimum tillage decreased NO_3^--N in the 0–90 cm soil profile by approximately 5–15 g NO_3^--N m^{-2} compared with conventional tillage across both OM treatments (Fig. 3). The highest NO_3^--N pools tended to be in the conventionally tilled soils with no OM additions. In the spring samples of May 1999 and April 2000, this resulted in significant tillage × OM treatment interactions.

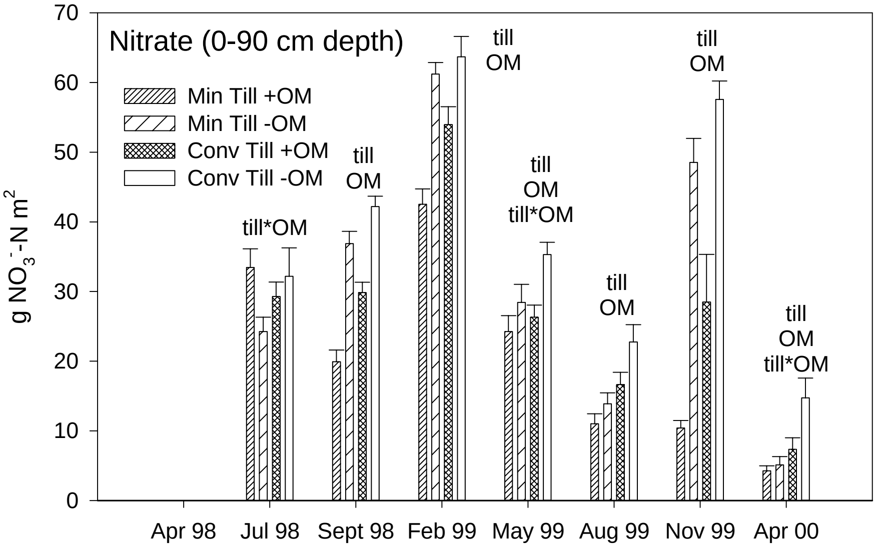

Fig. 3. Nitrate pools in the 0–90 cm profile on crop and cover crop harvest dates. See Table 2 for management dates. Significant treatment effects ($P \leq 0.05$) are labeled for each sampling date. Deep layers of soil were not sampled in April 1998. Mean ± S.E.

3.4. Plant biomass and nutrient content

Fresh weights of the lettuce and broccoli crops that were produced in 1999 and 2000 were highest in the treatment receiving cover crops, compost, and conventional tillage (Fig. 4). For the crops produced in 1999 and 2000, addition of OM increased fresh weight or dry weight (Table 4), or both fresh weight and dry weight, compared to −OM treatments.

For the two 1999 lettuce crops, minimum tillage decreased crop aboveground fresh weight compared to conventional tillage (Fig. 4), but dry weight was not

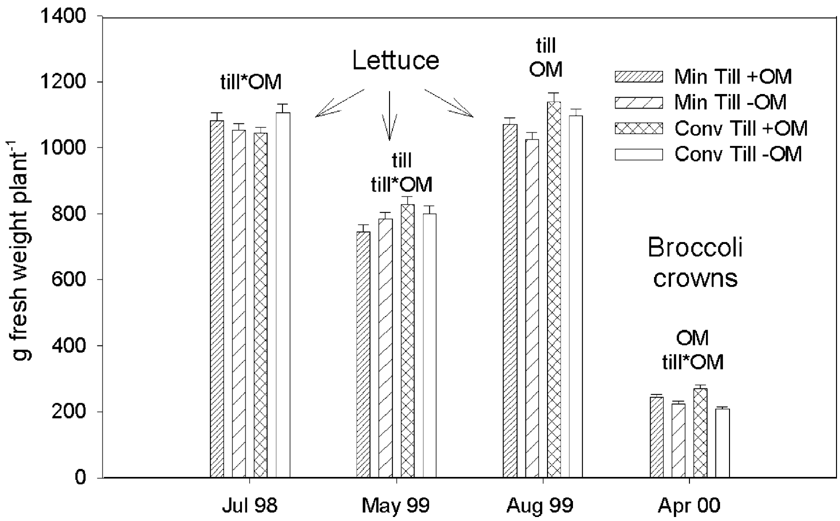

Fig. 4. Fresh weight of the harvestable vegetables. See Table 2 for management dates. Significant treatment effects ($P \leq 0.05$) are labeled for each sampling date. Mean ± S.E.

Table 4
Aboveground biomass and N content per m^2 on four sampling dates at the time of harvest maturity of each vegetable crop

OM treatment	Tillage treatment	20 July 1998 (mean ± S.E.)		10 May 1999 (mean ± S.E.)		18 August 1999 (mean ± S.E.)		3 and 24 April 2000 (mean ± S.E.)	
		Lettuce dry weight ($g\,m^{-2}$)	Lettuce N ($g\,m^{-2}$)	Lettuce dry weight ($g\,m^{-2}$)	Lettuce N ($g\,m^{-2}$)	Lettuce dry weight ($g\,m^{-2}$)	Lettuce N ($g\,m^{-2}$)	Broccoli dry weight ($g\,m^{-2}$)	Broccoli N ($g\,m^{-2}$)
+	Minimum	407.9 ± 8.5	14.2 ± 0.3	280.6 ± 5.3	10.4 ± 0.2	254.5 ± 4.7	9.5 ± 0.2	624.89 ± 13.82	25.53 ± 0.8
−	Minimum	391.8 ± 8.1	12.5 ± 0.3	313.0 ± 11.6	12.1 ± 0.2	241.6 ± 4.6	9.2 ± 0.2	605.68 ± 10.29	24.64 ± 0.6
+	Conventional	389.5 ± 8.4	12.7 ± 0.3	300.8 ± 5.4	11.2 ± 0.2	250.5 ± 5.7	9.9 ± 0.2	644.05 ± 16.34	26.59 ± 0.8
−	Conventional	425.8 ± 10.1	14.3 ± 0.4	295.7 ± 7.2	11.6 ± 0.3	256.5 ± 8.3	10.3 ± 0.3	633.10 ± 9.44	26.40 ± 0.6
Main effect *F* values									
OM		ns[a]	ns	*	***	ns	ns	ns	ns
Tillage		ns	ns	ns	ns	ns	**	**	***
OM × tillage		**	***	**	**	ns	ns	ns	ns

[a] No significant differences.

* Data were significant at the $P \leq 0.05$ level.

** Data were significant at the $P \leq 0.01$ level.

*** Data were significant at the $P \leq 0.001$ level.

affected by the type of tillage (Table 4). There may be a relationship with soil moisture since the surface layer (0–15 cm) was drier in minimum tillage treatments on both sampling dates (Fig. 2). Soil moisture at 15–30 cm depth and in the deep profile (0–90 cm depth), however, was similar between the two tillage treatments for these lettuce crops (data not shown). For broccoli in 2000, dry weight decreased with minimum tillage (Table 4), and fresh weight tended to be lower with minimum tillage, although there was a significant interaction between tillage and OM treatment effects (Fig. 4). Yield differences for broccoli occurred despite some potential sampling error due to multiple harvest times by the grower.

Nitrogen in the vegetable crops did not show consistent treatment effects (Table 4). For example, uptake of N by lettuce was lower with OM inputs only in the May 1999 crop. Uptake of N was lower with minimum tillage in the August 1999 lettuce crop, and the April 2000 broccoli crop. Few significant differences in the tissue concentrations of N, phosphorus, potassium, calcium, magnesium, boron, or zinc were observed for any of the vegetable crops (data not shown). One exception was that tissue N concentration was lower with OM inputs in the May 1999 lettuce crop. Another exception was that minimum tillage resulted in lower tissue phosphorus concentration in both 1999 lettuce crops and the 2000 broccoli crop. Tissue nutrient concentrations were within established critical values for all crops (Piggott, 1986; Bergmann, 1992), except that calcium was low in all treatments for the first two lettuce crops (8.5 and 10.7 g kg^{-1}, respectively, compared to critical values of 14–17 g kg^{-1}).

Aboveground cover crop biomass and N were not affected by tillage treatment in either year (data not shown). Mean values were 464.5 g dry weight m^{-2} and 14.7 g N m^{-2} in 1998, and 298.4 g dry weight m^{-2} and 13.7 g N m^{-2} in 1999.

3.5. Weeds, insects and diseases

The most abundant weed species were shepherd's purse (*Capsella bursa-pastoris*) and burning nettle (*Urtica urens*), and mean densities ranged from 0 to 116 plants m^{-2} depending on the date and treatment (data not shown; see Fennimore and Jackson, 2003). The density of shepherd's purse plants was approximately three times lower where OM inputs had been added for samples taken in July and December 1998, and July 1999. The density of burning nettle plants was reduced two- to three-fold in December 1998 and December 1999 in treatments receiving OM inputs, and by conventional tillage in February 1999. Organic amendments were associated with a three-fold reduction in seed of burning nettle in the soil in 1999, but no other effects of tillage or OM inputs on seedbanks of either species occurred (data not shown).

Leafminers were present on both of the lettuce crops that were sampled, but at higher densities in the fall crop than the spring crop (Table 5). All of the leafminers found were the Pea Leafminer, *Liriomyza huidobrensis*, and only a few parasitic insects were found, mostly *Diglyphus intermedius*. There were no significant treatment effects.

Corky root disease was minimal in the field, but it was lower in the +OM treatments in May 1999 (Table 5). Other diseases were present at low or non-detectable levels and no other significant differences in diseases were observed between treatments. Symptoms caused by *S. minor* infection were observed on <2% of the plants. Downy mildew, the most important foliar disease of lettuce, was absent from all lettuce crops. Big vein disease was only present on the May 1999 crop. No evidence of damping-off diseases was found, and stand counts of germinated seedlings were similar between treatments on all sampling dates (data not shown).

3.6. Economic performance and fuel use

The net returns for lettuce systems did not increase with the addition of OM for either of the tillage systems averaged for the three crop phases (Table 6), but did increase with the cost savings from minimum tillage for both OM management systems. The ranking of net returns for the three lettuce crops combined over the 2-year study is as follows, from lowest to highest: conventional tillage +OM inputs < minimum tillage +OM inputs < conventional tillage −OM inputs < minimum tillage −OM inputs. The typical practice in the area, conventional tillage −OM inputs, was not the most economically advantageous for lettuce.

The economics of the last lettuce crop reflects the cumulative effect of tillage and OM management over a 1.5-year period. For this crop, there were no differences between the tillage systems in net returns

Table 5
Plant disease and pea leafminer evaluations

OM treatment	Tillage treatment	July 1998 (mean ± S.E.)				May 1999 (mean ± S.E.)				August 1999 (mean ± S.E.)			
		Corky root[a] mean rating	Sclerotinia[b] (%)	Big vein (%)	No. of leafminers[c]	Corky root mean rating	Sclerotinia (%)	Big vein (%)	No. of leafminers	Corky root mean rating	Sclerotinia (%)	Big vein (%)	No. of leafminers
+	Minimum	2.9 ± 0.2	1.6 ± 0.8	ND[d]	ND	2.2 ± 0.2	1.2 ± 0.3	3.0 ± 1.3	9.7 ± 1.1	3.1 ± 0.4	0.3 ± 0.2	ND	80.7 ± 13.9
−	Minimum	2.7 ± 0.2	1.8 ± 1.9	ND	ND	2.5 ± 0.2	1.4 ± 0.4	3.4 ± 1.7	10.0 ± 1.8	3.4 ± 0.2	0.5 ± 0.2	ND	98.3 ± 9.1
+	Conventional	2.8 ± 0.1	1.7 ± 0.5	ND	ND	2.2 ± 0.1	1.9 ± 0.6	3.6 ± 1.3	12.2 ± 1.6	3.3 ± 0.1	0.3 ± 0.1	ND	74.2 ± 9.1
−	Conventional	3.0 ± 0.1	1.6 ± 0.9	ND	ND	2.9 ± 0.3	1.7 ± 0.8	2.7 ± 1.3	7.8 ± 1.7	3.6 ± 0.2	0.3 ± 0.1	ND	84.1 ± 7.3
Main effect F values													
OM		ns[e]	ns	–	–	*	ns	ns	ns	ns	ns	–	ns
Tillage		ns	ns	–	–	ns	ns	ns	ns	ns	ns	–	ns
OM × tillage		ns	ns	–	–	ns	ns	ns	ns	ns	ns	–	ns

[a] Corky root was evaluated on a severity scale from 1 (low severity) to 12 (high severity).
[b] The percentage of sampled plants with symptoms of *S. minor* infection or big vein is shown.
[c] The number of pea leafminers that flew and stuck to a sticky card in a bucket cage containing one plant are shown.
[d] No data were collected (see text).
[e] No significant differences.
* Data were significant at the 0.05 level.

Table 6
Economic analysis of all management costs and returns, and fuel use for the three lettuce crops[a,b]

	Lettuce crop harvested (July 1998)				Cover crop + lettuce crop harvested (May 1999)				Lettuce crop harvested (August 1999)			
	Minimum tillage +OM	Minimum tillage −OM	Conventional tillage +OM	Conventional tillage −OM	Minimum tillage +OM	Minimum tillage −OM	Conventional tillage +OM	Conventional tillage −OM	Minimum tillage +OM	Minimum tillage −OM	Conventional tillage +OM	Conventional tillage −OM
Production costs per hectare (US$)												
Fuel, lube, repair	183	183	333	333	371	289	924	627	143	143	346	346
Machine labor	200	200	252	252	371	331	580	442	180	180	301	301
Non-machine labor	1228	1228	1228	1228	1161	1077	1161	1077	1087	1087	1087	1087
Harvest costs	11332	10996	10885	11557	8949	9426	9996	9616	14237	13662	15102	14526
Compost	437	0	437	0	437	0	437	0	437	0	437	0
Other inputs[c]	1549	1549	1549	1549	1569	1470	1566	1467	1702	1702	1702	1702
Cash overhead[d]	2650	2633	2662	2652	2732	2662	2838	2722	2662	2645	2693	2675
Non-cash overhead[e]	128	128	195	195	274	205	625	425	96	96	222	222
Total costs	17707	16917	17541	17766	15864	15460	18127	16376	20544	19515	21890	20859
Returns per hectare (US$)												
Total returns	20096	19498	19298	20494	14783	15571	16514	15885	22247	21348	23593	22694
Total costs	17707	16917	17541	17766	15864	15460	18127	16376	20544	19515	21890	20859
Net returns	2389	2581	1757	2728	−1081	111	−1613	−491	1703	1833	1703	1835
Fuel ($l\,ha^{-1}$)[f]												
Diesel used	261.8	261.8	570.4	570.4	486.2	402.1	1514.7	1037.9	205.7	205.7	570.4	570.4

[a] Costs for the cover crop and its irrigation and incorporation costs are included with the subsequent vegetable crop.
[b] US$ 7.50 per lettuce carton was used in the calculation of returns, which was the Monterey County average for the sampling times of the study.
[c] Includes seed, fertilizer, pesticides, herbicides, custom application, and water.
[d] Includes land rent, property taxes, insurance, and interest on operating capital.
[e] Includes capital recovery cost for equipment and irrigation system ownership.
[f] Fuel use does not include compost application.

(Table 6), despite lower yields with minimum tillage (Fig. 4). The savings in reduced tillage costs in the minimum tillage systems compensated for the decrease in returns due to lower yields. In contrast, the +OM systems realized higher costs and higher yields than the −OM systems. The increase in revenue essentially balanced out the increase in cost resulting in only a slight decrease (7%) in net returns for the last crop. The profitability of all four treatments was thus approximately comparable at this time. It should be noted that no cover crop preceded this crop, and thus, no cover crop costs were included.

Production costs differed with each management system, depending on the amount of tillage and land preparation, the use of a cover crop prior to planting, the addition of compost, and the harvest costs associated with differences in crop yield (Table 6). Fertilizer, herbicide, pesticide, and related application costs were uniform among all four treatments. Averaged over the lettuce crops, compost and cover crop additions on average increased cultural costs (not including harvest costs) by 6 and 5%, respectively. The costs of using a cover crop resulted in additional irrigation, seed, planting, and tillage costs. Switching to minimum tillage from conventional tillage saved 9% of non-harvest cultural costs. Roughly half of these savings was in reduced fuel use. The rest of the savings was in reduced labor and equipment ownership costs. The cost savings from minimum tillage were less than the cost increase from adding OM.

Fall tillage operations to disk, chisel, and shape beds accounted for the largest difference in fuel use between conventional and minimum tillage operations, and these operations were most intensive in the conventional tillage operations to incorporate the cover crop. Fuel use was approximately 2.5-fold greater with conventional tillage than minimum tillage (Table 6). Incorporation of the cover crop and compost utilized 10 and 20% more fuel, respectively, for the minimum and conventional tillage treatments averaged over all lettuce crops.

4. Discussion

Managing a cropping system to promote soil quality has implications for crop yield and economic returns. Addition of cover crops and compost increased soil MBC, and reduced the potential for NO_3^--N leaching loss. These inputs were occasionally associated with lower weed density and corky root disease, which has previously been shown to be suppressed by a rye cover crop (vanBruggen et al., 1990). Although OM inputs often resulted in higher marketable lettuce yields, this did not necessarily increase net returns, because the increase in lettuce yield was not high enough to offset the costs of using the OM inputs. Minimum tillage techniques to retain semi-permanent beds decreased NO_3^--N leaching potential, and by the end of the study, resulted in lower bulk density and higher microbial biomass C in the surface soil compared to conventional tillage, and used less fuel, but minimum tillage tended to decrease crop yield. Even so, their lower costs led to higher net returns than conventional tillage. Participatory on-farm research allowed us to test these tradeoffs with soil conditions and pest populations that occur in the actual cropping system, and with analysis of financial costs conducted with the large-scale operations utilized by local farmers. For improving soil quality and assuring profitability, the complex outcomes of the study suggest that farmers should utilize a combination of conventional and minimum tillage, with frequent additions of OM (see below).

4.1. Soil quality and crop productivity

Adding cover crops and compost increased MBC and MBN for several months after incorporation, yet there was little accumulation of SOM during the 2-year period. The prolonged and consistent increase in microbial biomass throughout the growing season in the cover crop and compost treatments is in distinct contrast to the response of intensively farmed Salinas Valley soils to a one time event of incorporating similar low C:N cover crops, which resulted in a sharp increase in MBC and MBN, then a gradual decrease to pre-incorporation levels after a few months (Wyland et al., 1996; Jackson, 2000). The cover crop C:N ratios in this study were 14 in 1998 and 10 in 1999, assuming that C was 45% of plant dry weight. A protracted increase in MBC or soil C stabilization may not occur if much of the cover crop C is respired, and/or little of the cover crop C is stabilized in aggregates that contribute to protection of SOM

(Gale and Cambardella, 2000). In longer-term experiments with low C:N cover crops (i.e., <20) every year, MBC remained higher throughout the growing season compared to non-cover cropped soils (Schutter and Dick, 2002; Campbell et al., 2001; Sainju et al., 2002).

Few studies have been conducted to compare the effects of adding cover crops versus compost versus both sets of inputs. This was precluded in our study by the constraints of a farmer participatory trial. Our previous results on the lack of a season-long effect of cover crops on microbial biomass and net N mineralization (see above) convinced the farmer to simplify the on-farm experiment by including both cover crops and compost in the +OM treatments. This decision was supported by the observation that most organic farmers in this and other regions use both cover crops and/or organic amendments such as compost or manure (Drinkwater et al., 1995; Liebig and Doran, 1999), as do most research station comparisons of organic and conventional management (Clark et al., 1998; Fließbach and Mäder, 2000). Furthermore, since long-term management of both legume- and manure-based systems result in higher total soil C (Drinkwater et al., 1998), addition of both labile and more-resistant types of OM inputs was hypothesized to enhance the accumulation of soil C, even in the Salinas Valley's intensively managed soils with depleted SOM and MBC. Further research in this cropping system will test the hypothesis that compost provides a 'slow-release' source of nutrients to maintain high microbial biomass after an initial short-lived period of readily available C is provided by incorporating a low C:N cover crop. In these soils, compost alone, without cover crops, may have little effect of MBC, as its decomposition may need to be stimulated by the large, active microbial population such as occurs after the addition of plant material.

Minimum tillage in our project involved disking of the surface soil and retention of semi-permanent beds. Neither SOM or moisture in the surface layer increased with minimum tillage, which might have been expected based on typical responses to no-till or conservation tillage management (Granatstein et al., 1987; Carter, 1992; Reicosky et al., 1995). Compared to conventional tillage, e.g., chiseling or moldboard plowing, no-till and associated surface residues typically lead to lower net N mineralization and $NO_3{}^-$-N accumulation, as well as lower soil temperature, lower bulk density and higher water content (Dao, 1998; Silgram and Shepherd, 1999). But no-till and conservation tillage, which is described as non-inversion tillage, create less soil disturbance and leave more plant residue on the soil surface than the 'Sundance' minimum tillage treatment, and therefore may have a greater relative effect on soil activity and N pools compared to conventional tillage (Paustian et al., 1997).

Frequent surface tillage of semi-permanent beds with minimum tillage probably disrupted the surface layer in an approximately similar fashion as conventional tillage, but may have affected physical properties in the next layer down (Mahboubi et al., 1993), such that lateral and upward movement of water may have been slightly impeded, explaining the lower moisture content in the surface layer of the minimum tillage treatments. No disruption of soil below 20 cm could have resulted in lower temperatures and lower rates of net mineralization in situ, as is typically found in no-till soils (Silgram and Shepherd, 1999), explaining the significantly lower amounts of $NO_3{}^-$-N in the 0–90 cm profile, but little difference in the 0–15 cm layer of minimum tillage soils, compared to conventionally tilled soils. Our minimum tillage treatment may have been slightly N- and P-limited during the last two crops, because tissue N and P concentrations were sometimes lower than with conventional tillage, yet both nutrients were not deficient in the crops. Conservation tillage and no-till management often require additional N fertilizer to meet optimum yields compared to conventional tillage (Sims et al., 1998; Bronson et al., 2001). Reasons for the trend for higher fresh and dry weight in +OM treatments are unclear, but probably cannot be attributed to higher plant N uptake (Table 4) or to net microbial N immobilization (Fig. 1), which has been found to occur in some no-till studies (Clapp et al., 2000), because potentially mineralizable N and soil microbial biomass N were similar in minimum and conventional tillage treatments. Higher soil water availability in the surface layer of the conventional tillage treatments, where lettuce roots are densely congregated (Gallardo et al., 1996), may have contributed to the higher fresh weights of lettuce compared to minimum tillage.

4.2. Feasibility and risks of altering management practices

Adoption of practices to enhance soil quality will be enhanced if: (1) farmers face few economic disadvantages due to the new procedures; (2) the start-up costs and effort are feasible; and (3) new practices do not result in delayed onset of new problems. The benefit of on-farm research is that these concerns are dealt with by including farmers in the design and implementation of experiments.

The alternative practices used in this study were chosen because they could be readily adopted by farmers, at least on part of their acreage. Most growers have the 'Sundance' tillage system for use in fields that have subsurface drip irrigation, as well as for tillage in between summer vegetable crops because it reduces time and costs of labor and fuel compared to fully disking and re-shaping beds for a second crop. Winter cover crops permit less flexibility in planting dates, especially in winter seasons with high precipitation, and this would limit the production and profitability of spring vegetable crops. For this reason, our grower-cooperator planted fall cover crops so that vegetables could be planted predictably during the winter, though this would not be possible in fields with late fall vegetable crops.

Nutrient limitation is a risk that may arise if plant demand is not synchronous with the release of N and P from organic amendments, or tillage practices alter the timing of mineralization activity in the soil. Concentrations of inorganic nutrients may not always be good indicators of availability, because availability is partially regulated by rapid soil microbial transformations that release nutrients without accumulation of nutrient pools. Many growers, including this cooperator, are hesitant to reduce inputs without clear testing procedures or demonstrations of successful replacement of inorganic fertilizers by organic amendments. Even though soil P was not measured in this study, organic amendments can become a problem due to P runoff into surface waters (Sharpley et al., 2001). Economic issues also affect choices regarding amendments. The highly processed compost used in this study is more expensive than manure or composted manure. Substituting manure for compost would decrease input costs, but manure application to lettuce is known to increase the public health risk of transmission of *Escherichia coli* to humans, which can cause infection (Solomon et al., 2002).

Weeds are another example of a pest risk that may change with time. Further analysis of the data from this experiment suggests that increased activity and biomass of soil microbes may have been associated with the decrease in density of certain weeds with the addition of OM inputs (Fennimore and Jackson, 2003). Longer-term data would have been desirable. In one long-term study, weed biomass increased with organic management, yet weed seed banks declined with time (Menalled et al., 2001).

Less is known about risk of pest problems that may occur after longer-term adoption of minimum tillage practices or OM addition. For example, *S. minor* was not significantly different between minimum versus conventionally tilled treatments in this study. In another study, however, 2 years of tillage with the 'Sundance' system resulted in a higher percentage of lettuce plants with sclerotinia symptoms and decreased lettuce yield compared to deeper tillage methods (Jackson et al., 2002). Increased infection is most likely caused by accumulation of the sclerotia near the soil surface. Deep plowing is known to decrease the incidence of this disease, even though viable sclerotia buried in earlier cropping cycles may be brought to surface again by tillage (Subbarao et al., 1996). By contrast, *Sclerotinia sclerotiorum*, which also affects lettuce but is rarely found on lettuce in this region, was lower in soybean (*Glycine max*) in no-till than tilled soils (Kurle et al., 2001). This species, unlike *S. minor*, produces apothecia that eject ascospores into the air, which is enhanced in tilled soils. For *S. minor* in coastal California vegetable production systems, few options exist for cost-effective control measures, so minimum tillage is only recommended for short periods, e.g., in between vegetable crops.

Growers face complex tradeoffs and risks in their decisions to adopt new tillage and organic matter management practices. Minimum tillage +OM inputs ranked highly in terms of a qualitative assessment of soil quality, yet it poses a risk for lettuce drop disease and lower yields. Minimum tillage −OM inputs, in contrast, had the consistently highest net returns, but with little advantage in terms of enhanced soil quality. The typical practice in the area, conventional tillage −OM inputs, did not excel economically nor environmentally.

5. Conclusions

Addition of cover crops and compost, and a combination of minimum and conventional tillage methods appear to be the most attractive management option to farmers for coping with various production, economic, and soil quality tradeoffs. Although OM inputs increased some attributes of soil quality (higher MBC and MBN in the surface layer, lower bulk density in the surface layer, and less propensity for NO_3^--N to leach below the rootzone), and resulted in some production benefits (reduction in corky root disease and some weeds, and higher yields) growers must balance these benefits against lower net financial returns. Alternating between conventional and minimum tillage would pose less disease risk for *Sclerotinia* than long-term minimum tillage. Intermittent minimum tillage, e.g., between summer crops or to incorporate a cover crop, may be a viable strategy to reduce tillage costs and fuel use yet avoid the reductions in yield that were observed when minimum tillage was used continuously during the 2-year period.

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