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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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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 ($\mathrm{cmol\,kg^{-1}}$)	27.6	1.82	4
Electrical conductivity ($\mathrm{mmho\,cm^{-1}}$)	0.59	0.05	4
Moisture retention at			
−0.03 MPa ($\mathrm{g\,H_2O\,g^{-1}}$ soil × 100)	21.6	1.18	4
−0.1 MPa ($\mathrm{g\,H_2O\,g^{-1}}$ soil × 100)	16.4	1.68	4
−0.5 MPa ($\mathrm{g\,H_2O\,g^{-1}}$ soil × 100)	14.8	1.41	4
−1.0 MPa ($\mathrm{g\,H_2O\,g^{-1}}$ soil × 100)	14.6	1.43	4
−1.5 MPa ($\mathrm{g\,H_2O\,g^{-1}}$ soil × 100)	14.4	1.43	4
Sand ($\mathrm{g\,kg^{-1}}$)	280	9.2	31
Silt ($\mathrm{g\,kg^{-1}}$)	520	5.5	31
Clay ($\mathrm{g\,kg^{-1}}$)	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%, $\mathrm{NO_3}^-$-N concentration of 96 $\mu\mathrm{g\,g^{-1}}$, and ammonium ($\mathrm{NH_4}^+$-N) concentration of 35 $\mu\mathrm{g\,g^{-1}}$. 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 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 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

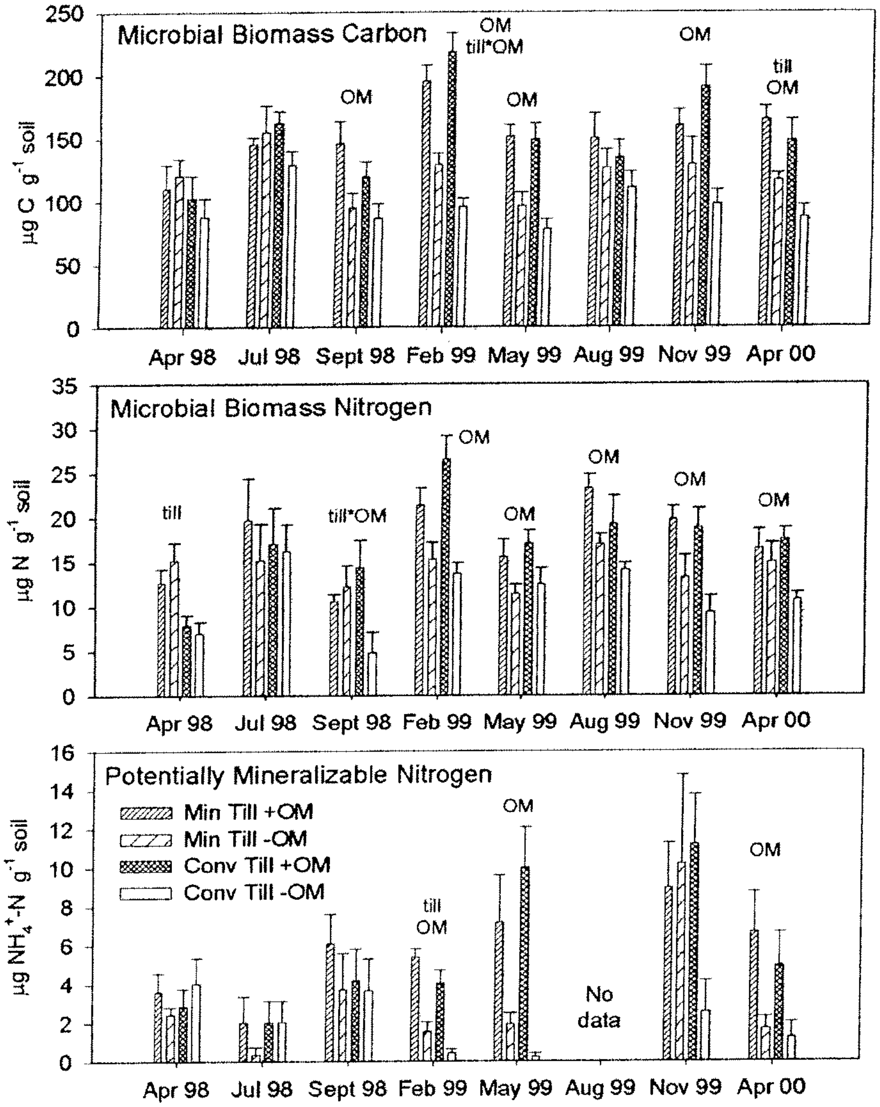

Fig. 1. Microbial biomass C and N (MBC and MBN) and potentially mineralizable N in the 0–15 cm layer of soil on crop and cover crop harvest dates. See Table 2 for management dates. Significant treatment effects ($P \leq 0.05$) are labeled for each sampling date. Mean ± S.E.

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-

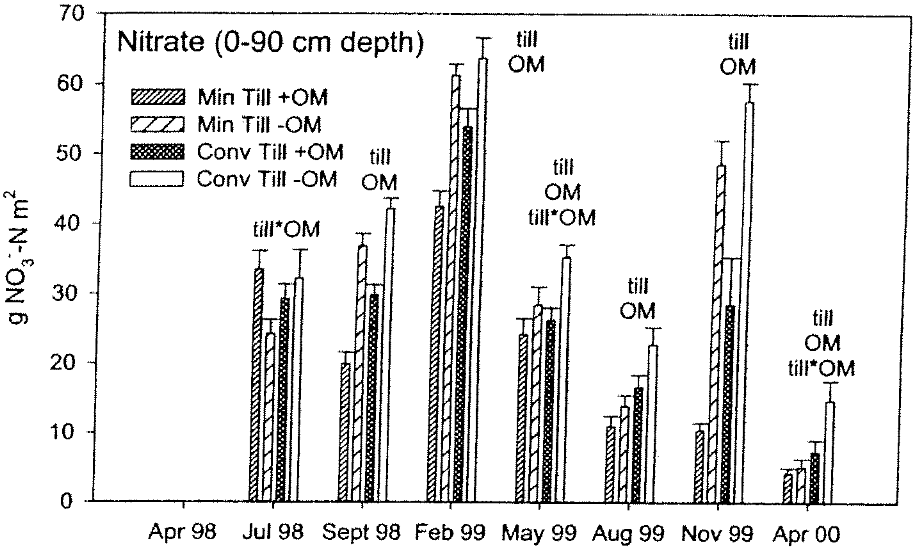

Fig. 3. Nitrate pools in the 0–90 cm profile on crop and cover crop harvest dates. See Table 2 for management dates. Significant treatment effects ($P \leq 0.05$) are labeled for each sampling date. Deep layers of soil were not sampled in April 1998. Mean ± S.E.

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

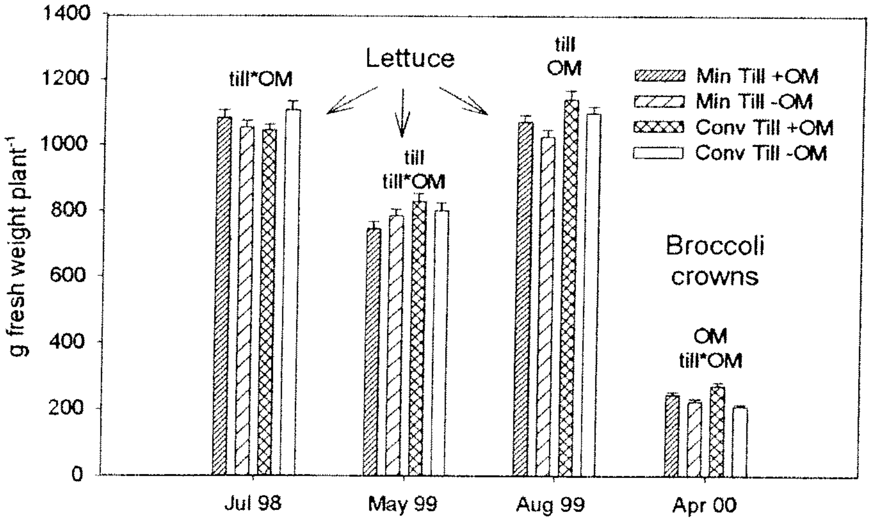

Fig. 4. Fresh weight of the harvestable vegetables. See Table 2 for management dates. Significant treatment effects ($P \leq 0.05$) are labeled for each sampling date. Mean ± S.E.

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 $\mathrm{g\,kg^{-1}}$, respectively, compared to critical values of 14–17 $\mathrm{g\,kg^{-1}}$).

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 $\mathrm{m^{-2}}$ and 14.7 $\mathrm{g\,N\,m^{-2}}$ in 1998, and 298.4 g dry weight $\mathrm{m^{-2}}$ and 13.7 $\mathrm{g\,N\,m^{-2}}$ 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 $\mathrm{m^{-2}}$ 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 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 ($\mathrm{l\,ha^{-1}}$)[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.

(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.

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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