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Yield increases during the organic transition: improving soil quality or increasing experience?

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Abstract

Reported increases in crop yields over the first few years of organic farming (especially during the 3-year "transitional" period established in US law) have been attributed to gradual improvements in soil properties, such as the capacity of the soil microbial community to mineralize N or to suppress disease. To test the hypothesis that yield increases with years of organic farming are due to improvements in soil properties, we compared identically managed organic and transitional plots differing only in duration of organic management (>5 versus <1 year). Conventional plots were included for reference purposes. There was no difference in tomato (*Lycopersicon esculentum* Mill.) growth or yield between established organic and first-year transitional plots, but both outperformed the comparable conventional system. Even no-compost subplots within the transitional plots had yields similar to established organic plots, so the yield advantage relative to conventional plots was apparently due to beneficial effects of a winter legume cover crop in a wet year. Soil inorganic N did not differ between transitional and organic plots. Conventional and organic plots differed in soil microbial community composition, but transitional plots were not intermediate between conventional and organic. In the second year of the organic transition, when maize (*Zea mays* L.) was grown, yields were again not significantly different from the established organic system. This result is inconsistent with the hypothesis that yield-limiting differences in soil quality between organic and conventional systems take at least 3 years to develop. An alternative hypothesis, not tested directly, is that previously reported yield increases result from improved management with increasing experience, not improving soil quality.

Keywords: Soil quality; Organic farming; N mineralization; Tomato; Maize

1. Introduction

Some of the soil properties that determine crop yield, such as total organic matter content, typically change significantly only over decades (Johnston, 1986). Other properties may change quickly in response to changes in crop and soil management. For example, researchers comparing conventional and organic practices reported that "fundamental differences" in the microbiology of the soil can develop after only a few years of organic management (Drinkwater et al., 1995).

Certified organic farmland accounted for only 0.2% of all US farmland in 1997 (Greene, 2000),

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but research on organic and alternative approaches may yield insights useful in designing more sustainable agricultural systems. In particular, changes in soil properties during transitions to or from organic methods, and crop responses to these changes, may provide information on the resilience of critical ''ecosystem services'' (Constanza et al., 1997), such as the decomposition of crop residues by soil microorganisms.

During the ''organic transition'' period, defined under US national organic standards as the first 3 years after switching from conventional to organic management, crop yields are often reportedly lower than in conventional systems (USDA, 1980). Yields may eventually increase (Liebhardt et al., 1989; Temple et al., 1994), but the expectation of initially lower yields can be ''a strong deterrent to those farmers who may wish to make such a change'' (USDA, 1980).

Initially lower yields on organic farms have been attributed to the negative effects of conventional practices on the soil microorganisms that mineralize soil organic matter, or that control soil-borne pests (MacRae et al., 1990). If so, gradual changes in microbial community structure could be responsible for increasing yields over time. Gradual improvements in ''soil quality'' (Visser and Parkinson, 1992; Arshad and Coen, 1992; Karlen et al., 1992) are at least a plausible hypothesis to explain increasing yields with years of organic management. Harwood (1984) hypothesized that ''for many soils the form and availability of soil N is central to the conversion phenomenon''.

We tested, i.e., attempted to disprove (Kinraide and Denison, 2003) the hypothesis that yield increases over the first few years of organic farming are due to improvements in soil properties. For brevity, we will call this the ''soil-quality hypothesis''. This hypothesis is based on three subsidiary hypotheses (MacRae et al., 1990):

1. early in the organic transition, natural biological processes are inadequate to supply nutrients, control pests and diseases, or to provide other essential functions previously provided by chemical inputs;
2. soil quality improves with organic management, with the most important improvements taking 3 years or more;
3. improving soil quality results in higher yields.

The soil-quality hypothesis therefore predicts that plots in the first year or two of organic management should yield less than plots under conventional management (subsidiary hypothesis 1) and also less than plots that have been managed organically for several years (subsidiary hypotheses 2 and 3). Subsidiary hypothesis 2 also predicts that soil properties in transitional plots would initially resemble those in conventional plots, but would approach those in established organic plots over a period of about 3 years.

A few studies have reported differences in soil properties between transitional and established organic systems (Scow et al., 1994; Drinkwater et al., 1995), but it was not clear whether these differences were responsible for any yield differences. Yield data consistent with the soil-quality hypothesis have been published (Liebhardt et al., 1989; Temple et al., 1994). However, yield trends with years of organic management are not always positive (Stanhill, 1990). More importantly, previous controlled and replicated tests of the soil-quality hypothesis, as opposed to uncontrolled comparisons among commercial farms, have involved comparisons among different years. Any positive trends could therefore reflect improvements in crop management, rather than improving soil quality. For example, changing to a shorter-season maize variety following a green manure crop (Liebhardt et al., 1989) or changing from direct seeding to transplanting of tomatoes (Temple et al., 1994), could be responsible for the reported yield increases during the organic transition. Comparisons among commercial farms differing in years of organic management (Tamaki et al., 1995; Elmholt, 1996) could also be confounded by differences in grower experience.

To eliminate the effects of improving management with grower experience, we compared an established organic system (managed organically for >5 years) with an identically managed transitional system, in its first year of organic management. A conventional system with the same crop rotation was included for comparison, but the performance of organic systems relative to conventional ones was not a primary focus of this 2-year study. See a companion paper (Denison et al., 2003b) for comparisons between conventional and alternative systems over 9 years.

2. Materials and methods

2.1. Site characteristics

This work was conducted at the UC Davis Long-Term Research on Agricultural Systems (LTRAS) site, 10 km west of Davis, CA. LTRAS compares the long-term performance of 10 cropping systems differing in inputs such as water, nitrogen, and organic matter (Denison et al., 2003b). At the start of this study, LTRAS was in its fifth cropping year. Each management system used in this study utilized a 2-year rotation of processing tomato (*Lycopersicon esculentum* Mill.) and maize (*Zea mays* L.), having three replicate 0.4 ha plots (64 m × 64 m). Soils at LTRAS have been characterized as Rincon silty clay loam and Yolo silt loam (Hasegawa et al., 1999). Field scale equipment (e.g. mechanical tomato harvesters, combines, land-planes), were used in all systems.

2.2. Treatment protocol

The key comparison is between the organic system (managed organically since 1993), and the transitional system (managed conventionally prior to November 1998). These two systems were managed identically once this experiment began in November 1998, with the exception of subplot treatments described below. Organic management included spring applications of composted poultry litter and a spring-incorporated winter legume cover crop (LCC) of vetch (*Vicia dasycarpa*) and pea (*Pisum sativum*). Some data for a conventional system, which was fallow each winter, and for an alternative system with a LCC in alternate winters, are included for comparison. These two systems received synthetic fertilizers and herbicides. All four systems were irrigated, with conventional tillage supplemented by hand-hoeing of tomatoes. Yield data from a conventional wheat–tomato rotation are also included. Details on long-term management and yields of these systems (except transitional) are given in a companion paper (Denison et al., 2003b), which uses abbreviations OMT, CMT, LMT, and CWT.

To investigate the mechanistic basis of any yield differences among the main treatments, compost rate subplots and N and P microplots were included within the transitional plots in 1999. Because only a small fraction of N in compost may be released during the first season after application (Hartz et al., 2000), new organic farmers may apply extra compost in the first year or two of the transition. Three compost rates: 0×, 1×, and 2× the 5.8 Mg dry weight ha^{-1} (containing 92 kg N ha^{-1}) applied to the organic plots, were randomly assigned to 18 m × 64 m subplots within transitional plots. Within each 1× subplot, randomly assigned microplots (18 m × 14 m) received no fertilizer, 90 kg N ha^{-1}, 112 kg P ha^{-1}, or both, 6 weeks after tomato transplanting in 1999. Where compost or fertilizer addition are not specified, references to the transitional system refer to the unsupplemented microplots within the 1× subplots, which received exactly the same inputs as the organic plots. In autumn 1998, immediately prior to the start of the transition, all systems were disked, but early onset of winter rains did not allow preparation of tomato beds until spring.

Processing tomato seedlings (cv. Halley 3155), were transplanted in the conventional, transitional, and organic systems between 29 April and 1 May 1999. They were planted in single rows on 1.5 m beds, at a density of 25,900 plants ha^{-1}. Furrow irrigation commenced the day after transplanting in all systems. Starter fertilizer (15–15–15), at 46 kg NPK ha^{-1} and ammonium sulfate at a rate of 112 kg N ha^{-1} were applied to conventional tomatoes at 2 and 6 weeks after transplanting, respectively.

In the second year of the study, maize was grown in all plots. In addition to the LCC, composted poultry litter was incorporated in both the established organic and transitional organic systems at 6.8 Mg DW ha^{-1}, containing 147 kg N ha^{-1}. Pioneer 3162 was seeded in the conventional system on 24 March 2000 and NC + 4616 was seeded in the organic and transitional systems on 5 May 2000, both at a target density of 80,300 plants ha^{-1}. NC + 4616 is a shorter-season cultivar, shown to outyield Pioneer 3162 within the time constraints imposed by the LCC (Denison et al., 2003b). Because conventional maize yields reflect earlier seeding and a different cultivar, yield comparisons for the second year emphasize the transitional and established organic systems.

The conventional plots received 112 kg P ha^{-1} in autumn 1999, to prevent P limitation. Side-dress applications of 46 kg NPK ha^{-1} (15–15–15) and 197 kg N ha^{-1} as urea, were applied to the conventional maize 6 and 7 weeks after planting, respectively.

Prior to planting and 6 weeks after planting, N-fertilizer as urea was applied to transitional + N microplots at 46 and 206 kg N ha^{-1}, respectively.

2.3. Crop growth and yield

Final aboveground LCC biomass in organic and transitional plots was measured, prior to planting tomatoes in 1999, using two hand-harvest areas (1.53 m × 3.04 m) per plot. In the second year of the transition, two locations of the same size were used in the established organic plots, and one location was used in each of the smaller transitional subplots. After removal from the field, biomass samples separated into pea, vetch, and weeds were dried and weighed separately.

Early season vegetative growth of tomato was estimated nondestructively using a scanned laser probe to measure leaf area index (LAI) (Denison and Russotti, 1997). During the second season (2000), vegetative growth of maize was characterized using a vegetation index based on aerial photos, as previously described (Denison et al., 1996). Maize growth was also measured by destructive harvests of 1 m × 0.76 m areas at 35 days after planting (DAP) and at anthesis, about 80 DAP. Aboveground plant material was removed and dried for total dry weights.

Tomatoes were hand harvested from four 2.0 m × 1.52 m sampling areas per plot subplot and one sampling area per microplot. Maize yields were assessed in 2000 with similar hand-harvest areas and sampling pattern.

2.4. Soil chemical and physical properties

Soil samples were collected at the beginning of the transition and the end of the first year, in November 1998 and 1999. Twenty, 2.5 cm cores from diagonal transects, were composited by depth (0–30 and 30–60 cm) by plot, kept on ice and then frozen until extraction. Subsamples were thawed and air-dried, ground to pass through a 2 mm mesh sieve and analyzed for pH with a 1:1 w/w soil to deionized water solution. Plant available soil P was measured by the method of Olsen et al. (1954). Exchangeable soil Mg, Ca, and K were determined in 1N ammonium acetate extracts (Knudsen et al., 1982; Lanyon and Heald, 1982) using AES (Franson, 1985). Air-dried soil was further analyzed for total C and N by combustion (Pella, 1990).

Soil samples for inorganic N analysis were collected similarly, at monthly intervals, and analyzed for nitrate and ammonium as previously described (Hasegawa et al., 1999) via electrical conductivity in a continuous flow apparatus modified from Carlson et al. (1990). Water-stable soil aggregates were determined by the method of Kemper and Roseneau (1986) as modified by Amezketa et al. (1996), using air-dried 3.8 cm cores to 15 cm, sieved to 1–2 mm.

2.5. Soil microbial communities

Soil was sampled to 15 cm (several composited cores per plot) for microbial analysis, several times per year. To assay substrate utilization, a 150 μl aliquot of each sample (diluted with sterile saline to 10^{-4}) was incubated with one of 95 different substrates (Garland and Mills, 1991) using a Biolog GN plate (Biolog Inc., Hayward, CA) and incubated at 22 °C for 3 days (Buyer et al., 1999). Plates were read at 595 nm for color changes associated with reduction of a tetrazolium dye, indicating substrate utilization. Analysis of lipids extracted from the soil was used to measure total microbial community structure as previously described (Gagliardi et al., 2001; Buyer et al., 2002).

2.6. Plant sampling and analysis

Plant tissue nutrient analysis was done during both growing seasons. Tomato leaflets, the third or fourth from growing tip, were sampled at first fruit and at 10% red fruit, dried at 65 °C, and ground to pass through a 1 mm sieve screen for P and K analysis, and to 250 μm for total N combustion analysis. At 35 DAP, entire maize plants were harvested, dried and ground for nitrate analysis, whereas the leaf below the lowest ear was sampled at anthesis. Prior to maize harvest, stalks from 15 to 35 cm were harvested and dried for nitrate analysis (Binford et al., 1990).

Chlorophyll meter readings (Minolta, SPAD-502) were taken concurrently with plant tissue nutrient samples. Tomato leaflets, third or fourth from growing point, were read at 10 or more locations per plot. Chlorophyll meter readings of maize leaves were taken on two dates during the second growing season.

Total plant N was determined by nitrogen gas analyzer (Sweeney, 1989), total P determinations were done on microwave acid digests by atomic emission spectroscopy (ICP-AES) (Sah and Miller, 1992), and total K was quantitatively measured with AES (Franson, 1985) on 2% acetic acid extractions (Johnson and Ulrich, 1959). Plant nitrate-N was also extracted with 2% acetic acid and analyzed by zinc reduction and conductimetric analysis (Carlson, 1978).

2.7. Statistical analysis

Values obtained for the various measurements taken were averaged by treatment and subjected to ANOVA tests. Separation of means was done on significant ANOVA tests with Tukey HSD ($P < 0.05$) using the JMP statistical package.

Microbial data were analyzed using methods detailed by Buyer et al. (1999) and Buyer and Drinkwater (1997). Statistical analysis was done with SAS software (SAS Institute, Cary, NC) using a general linear model with ANOVA and MANOVA. Results from Biolog GN plates were separated into six substrate categories (polymers, carboxylic acids, carbohydrates, amino acids, amines and amides, and miscellaneous). Absorbances averaged by category were used as the variables in the MANOVA. The absorbance of the blank well was used as a covariate. Fatty acids, summed within seven categories based on taxonomic groups (Table 1 of Buyer et al., 1999), were used as variables in the MANOVA. Canonical variates were generated by MANOVA to identify linear combinations of variables that best separated the treatments. The results from this analysis were used to generate plots that summarize group differences, with the mean of each treatment displayed in figures. Since there were only three treatments in our study, the two canonical variates add up to 100% of the variation explained.

3. Results

3.1. Crop growth and yield

According to the soil-quality hypothesis, crop yields should have been lower in transitional than in established organic plots. Instead, tomato yields in the organic plots were not significantly different from identically managed first-year transitional plots (Fig. 1a). Within the transitional plots, subplots without compost or with extra compost or fertilizer were also not significantly different. Conventional maize–tomato plots, however, had significantly lower yield than the organic and transitional plots. The legume–maize–tomato system had intermediate yield. This system was managed identically to the conventional system in 1999 but had a LCC grown and incorporated in alternate years, most recently in 1998.

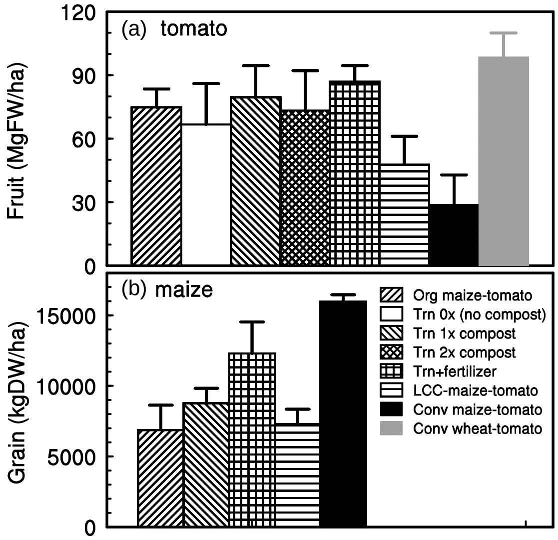

Fig. 1. Fruit yield of tomato in 1999 and grain yield of maize in 2000. The legend applies to both years. Org: established organic; Trn: transitional; Conv: conventional.

The low tomato yields in the conventional rotation were not typical for this system. In most years, there has been little difference in tomato yield between conventional and organic systems (Denison et al., 2003b), although results similar to 1999 also occurred in 1995. Both years had heavy winter rainfall and wet soil during spring preplant preparations. The conventional wheat–tomato system had yields in 1999 at least as great as the organic systems (Fig. 1a), perhaps because earlier harvest of wheat, relative to maize, allowed most plot preparation to be completed the previous autumn, rather than in spring. As discussed below, soil compaction resulting from these spring plot operations may have been more severe in the conventional plots than in the transitional or organic plots.

Table 1
Total aboveground biomass and total nitrogen in the organic and transitional winter legume cover crop at time of incorporation

Year	System[a]	Dry matter (kg ha^{-1})			N (g kg^{-1})	Total N (kg ha^{-1})	C:N
		Legume	Weed	Total			
1999	Org	2543	139	2682	44.1	118.28	9.6
	Trn	2518	0	2518	45.5	114.57	9.3
2000	Org	2963	1103	4066	31.9	129.71	13.2
	Trn	4615	45	4661	40.1	186.91	10.8

[a] Org = established organic; Trn = transitional.

Total cover crop biomass in transitional plots was also similar to that in organic plots at the time of incorporation, in both the first and second years (Table 1). A higher fraction of the total was weeds in the established organic plots, especially in the second year. This may explain the higher N content in the biomass incorporated in the transitional plots in 2000, relative to the organic plots.

Maize yields in 2000 also did not differ significantly between the identically managed organic and transitional systems (Fig. 1b), which both used the same cultivar. Maize yields were significantly higher for conventional maize, which used a different cultivar. Part of the yield difference was inherent in use of a LCC, which limited length of the growing season for organic and transitional maize. Maize cultivar differences in disease susceptibility may also have contributed to yield differences (Table 2). We attempted to maximize productivity of the organic and transitional systems by using an appropriate short-season cultivar, shown in a 3-year test to outperform that used in the conventional system when both are grown following a LCC (Denison et al., 2003b). However, disease pressure may have been less, during those test years, than the observed incidence of soil-borne *Fusarium* after multiple cycles of a 2-year crop rotation. Results with other cultivars could be different, as disease susceptibility is not an intrinsic feature of all short-season cultivars.

Table 2
Smut (*Ustilago*) and *Fusarium* incidence in maize prior to harvest in the second year of the transition study at LTRAS[a]

System	Smut				*Fusarium* (%)
	None	<25%[b]	>25%[c]	Total	
Conv	1.7 b[d]	97.4 a	1.3 b	1.3 c	2.6 c
Org	18.0 a	45.3 c	18.0 a	36.7 a	54.7 a
Trn	11.3 a	59.3 bc	12.7 a	28.0 b	40.7 ab

[a] Incidence based on visual inspection of ears of maize at maturity on 50 consecutive plants in two locations per plot. Each ear was scored for smut and/or for *Fusarium* infection.

[b] Less than 25% of kernels on the cob infected with *Fusarium* fungus.

[c] Greater than 25% of kernels on cob infected with *Fusarium* fungus.

[d] Means within a column followed by the same letter are not significantly different (Tukey HSD, $P < 0.05$).

Measurements of vegetative growth were consistent with yield data, for both crops. Leaf area growth of tomato in 1999 did not differ between transitional and organic plots, but both were greater than in the comparable conventional plots (Fig. 2a). Conventional tomatoes had similar or greater leaf N, P, K, and chlorophyll content (Table 3), so slower growth of conventional tomatoes was apparently not the result of nutrient deficiency. Organic and transitional tomatoes did not differ in any of these parameters.

In 2000, transitional and organic systems did not differ significantly in maize growth, as indicated by biomass (Fig. 2b) or NDVI (Fig. 2c). Transitional and organic maize also did not differ in leaf or stalk nitrate concentration or chlorophyll readings (data not shown). Despite 7 years of compost applications, maize biomass growth was less in the organic system than in the microplots of the transitional system that were supplemented with N (Fig. 2b), suggesting that even repeated use of compost made little contribution to crop N supply.

3.2. Soil chemical and physical properties

The lack of differences between transitional and organic plots in crop growth and yield suggests that there was no overall improvement in soil quality with

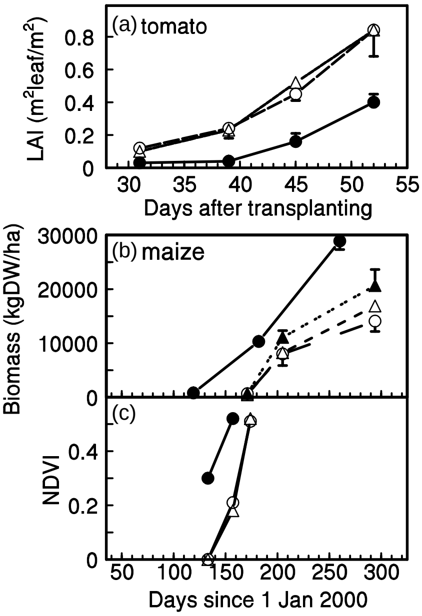

Fig. 2. Vegetative growth of tomato and maize as indicated by (a) leaf area index, (b) biomass harvest from subplots, and (c) normalized difference vegetation index calculated from infrared aerial photos. Symbols: (open circles) organic; (filled circles) conventional; (open triangles) transitional; (filled triangles) transitional plots with supplemental N.

duration of organic management, at least beyond the first few months. There were no differences in percent water-stable aggregates, which was approximately 93% for all systems. Some soil properties did differ, however.

In November 1998, when the transitional plots were switched from conventional to organic management, the organic plots, which had already received five annual applications of composted poultry manure, had about twice the available phosphorus, 27% more total N, and slightly lower pH than the conventional plots (Table 4). Organic plots had significantly higher soil P, K, N, and C than transitional plots.

At the end of the first year of the transition, after tomato harvest, total soil N was significantly higher in both the conventional and organic systems than in the transitional system (Table 4). There was no significant change in soil C in the transitional system over the first year, despite C inputs from compost and LCC.

3.3. Soil inorganic N and microbial community structure and function

If there were differences between organic and transitional plots in the ability of the soil microbial community to mineralize organic N sources, we would have expected differences in soil inorganic N levels, because plant N uptake was similar. However, in the first year of the transition, there were no significant differences between organic and transitional systems in soil inorganic N at 0–30 or 30–60 cm depths (Fig. 3a and b). Concentrations in the surface layer began to rise in the organic and transition systems following the incorporation of the LCC at the end of March, reaching a peak for both systems of about 10 μg g^{-1} soil at the end of May, approximately 6 weeks after incorporation. In the second year, the transitional plots tended to have lower soil inorganic N during the rainy winter months, relative to the organic and conventional systems, especially in the 0–30 cm layer (Fig. 3c and d). Without data on water movement, we cannot estimate N leaching rates from these data. During the

Table 3
Tomato in-season leaf tissue total N, P, and K levels taken at first fruit stage and at 10% red fruit stage and leaf chlorophyll (SPAD) meter readings in 1999

System	Total N		Total P		Total K		Chlorophyll 10% red (g kg^{-1})
	First fruit (g kg^{-1})	10% red (g kg^{-1})	First fruit (g kg^{-1})	10% red (g kg^{-1})	First fruit (g kg^{-1})	10% red (g kg^{-1})	
Conv	36.5 b[a]	28.9 c	2.4	1.6	26.1 a	13.0 a	68 a
Org	30.2 a	19.2 ab	3.3	1.9	30.4 ab	8.6 a	51 b
Trn	31.0 ab	17.1 a	3.0	1.8	32.0 ab	8.2 a	44 b
Trn + N	43.8 c	23.5 b	3.0	1.6	34.9 b	10.4 a	53 b
	–	–	NS[b]	NS	–	–	–

[a] Means within columns followed by the same letter are not significantly different (Tukey HSD, $P < 0.05$).

[b] Means within a column are not significantly different ($P < 0.05$).

Table 4
Soil chemical characteristics (0–30 cm) at the beginning of the transition (November 1998) and after 1 year (November 1999)

System	Olsen-P ($\mathrm{mg\ kg^{-1}}$)	x-K[a] ($\mathrm{mg\ kg^{-1}}$)	x-Ca ($\mathrm{cmol\ kg^{-1}}$)	x-Mg ($\mathrm{cmol\ kg^{-1}}$)	Total N ($\mathrm{cmol\ kg^{-1}}$)	Total C ($\mathrm{g\ kg^{-1}}$)	pH[b] ($\mathrm{g\ kg^{-1}}$)
1998							
Conv	11.8 a[c]	200.0 ab	9.1	15.5	1.1 a	9.9 ab	7.20 b
Org	24.2 b	238.3 b	8.8	14.2	1.4 b	11.1 b	7.03 a
Trn	10.8 a	188.7 a	8.3	14.6	1.2 a	9.4 a	6.99 a
	–	–	NS[d]	NS	–	–	–
1999							
Conv	16.5 a	209.7	8.8	15.2	1.2 b	9.8	7.20
Org	25.1 b	238.7	9.0	14.6	1.3 b	10.9	7.14
Trn	11.4 a	186.0	8.6	14.5	1.1 a	9.2	7.15
	–	NS	NS	NS	–	NS	NS

[a] "x" represents exchangeable cations in the soil.

[b] Soil pH was measured with a saturated solution.

[c] Means followed by the same letter within a year and column are not significantly different (Tukey HSD, $P < 0.05$).

[d] Means within a column for a single year are not significantly different ($P < 0.05$).

second growing season, inorganic soil N levels in transitional plots were variable and not significantly different from those in organic plots, but higher than bulk soil levels in the conventional system. Fertilizer placement in bands limits our ability to estimate N availability to the conventional crop from these bulk soil measurements.

Using the first two canonical variates of the FAME biomarker (Fig. 4a), the organic system was almost completely distinguished from both conventional and transitional systems, indicating differences in species composition or in relative abundance. Differences over time in the first canonical variate showed consistent differences between microbial communities of conventional and organic systems (Fig. 4b). However, the hypothesized pattern of a transitional system intermediate between conventional and organic systems, and gradually converging towards

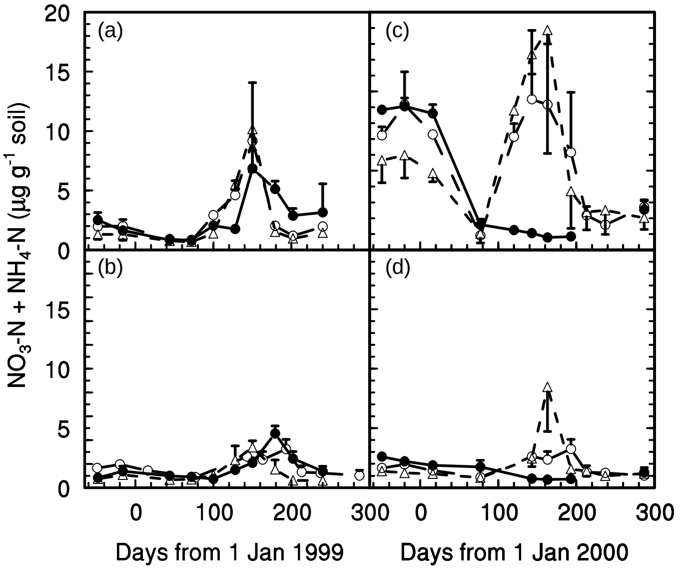

Fig. 3. Soil inorganic N at 0–30 cm (a, c) and 30–60 cm (b, d) depths. Error bars are 1 S.D. Symbols as in Fig. 2.

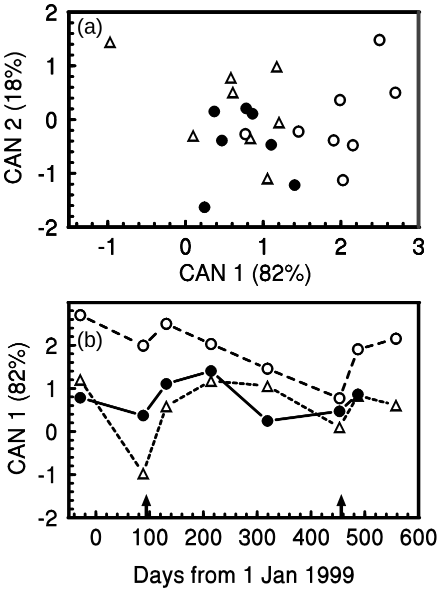

Fig. 4. Soil microbial community composition, as estimated using FAME analysis: (a) first two canonical variates for the entire experiment; (b) trends over time in the first canonical variate. Symbols as in Fig. 2.

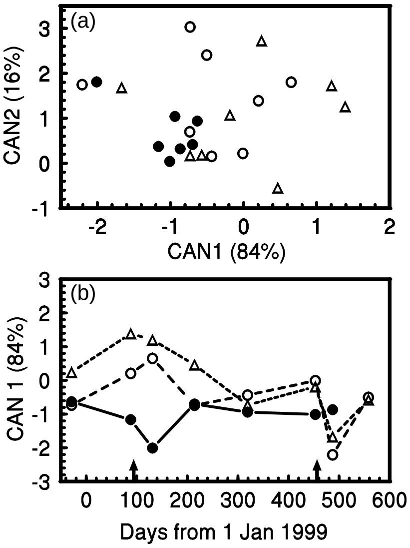

Fig. 5. Soil microbial community function, as estimated using the Biolog assay. Symbols as in Fig. 2.

the latter, was not observed. During the first growing season, FAME profiles for the conventional system were actually intermediate between those of the transitional and organic systems (Fig. 4b). Although there appeared to be some convergence between organic and transitional systems during the first growing season, they diverged again by the end of the second growing season.

The heterotrophic substrate utilization potential of the soil microbial community, based on Biolog analysis, showed a somewhat different pattern (Fig. 5a). Based on canonical variates 1 and 2, the organic and transitional systems appeared to overlap considerably, and both generally differed from the conventional system. The outlying points towards the left of the graph were taken 2 weeks after tomato transplanting in the conventional plots during the first season and prior to maize planting in the organic and transitional systems in the second season, when there would be little or no C substrate available from root exudates. The organic system was usually intermediate between the conventional and transitional systems throughout the first growing season (Fig. 5b). Thus, changes in microbial populations with years of organic management appear to be more complex than predicted by the soil-quality hypothesis.

4. Discussion

Our results are inconsistent with the soil-quality hypothesis stated in Section 1 and with at least two of its three subsidiary hypotheses.

First, tomato yields in the first year of the transition were higher, not lower, than those of the most similar conventional plots. This result is inconsistent with the hypothesis that natural biological processes are inadequate to provide essential functions during the first few years of organic farming.

Second, some soil properties in the established organic plots (P, K, total N and total C; Table 4) were significantly different, and arguably superior, than in the transitional plots. This result is consistent with the soil-quality hypothesis and with some earlier studies (Scow et al., 1994; Drinkwater et al., 1995). However, soil properties and processes in the transitional plots were generally not intermediate between conventional and organic plots, as would be expected with a gradual transition. This is most apparent for the microbial community data in the first year (Figs. 4 and 5).

Third, those soil properties that showed the clearest difference between transitional and organic plots had no clear connection with crop yields. Despite lower soil fertility (Table 4), first-year transitional plots had tissue nutrient levels similar to organic plots (Table 3), consistent with the lack of yield differences.

There are at least two possible explanations for the lack of yield differences between transitional and organic plots, despite differences in some soil properties. Properties like soil C and P content might have little effect on yield once some minimum threshold is achieved. Alternatively, the lack of yield difference could reflect a balance between improvements in some aspects of soil quality and worsening of others. For example, higher weed biomass in the organic LCC (Table 1) is consistent with a possible increase in the weed seed bank with years of organic management. Additional weed data will be published separately.

Although the yield data alone are sufficient to reject the soil-quality hypothesis, the adequacy of the methods used to characterize soil microbial communities is still an important issue. These methods have previously been shown to detect changes in soil microbial communities due to season, soil type, and management effects. Buyer and Drinkwater (1997) found that both the substrate utilization assay and soil fatty acid analysis distinguished between organic and conventional management systems. In another study, phospholipid fatty acid profiles were found to differentiate organic, low-input, and conventional systems (Bossio et al., 1998). Schutter et al. (2001) found that the substrate utilization assay and fatty acid analysis were affected by cover cropping. However, the substrate utilization assay measures the community structure of rapidly growing culturable aerobic heterotrophic bacteria (Buyer et al., 1999), which are a tiny fraction of the total microbial community. Although certain fatty acids are linked to specific taxonomic groups, none is necessarily absolutely confined to a particular group. Fatty acids associated with plant material and organic matter may obscure differences in microbial communities.

Either the microbial assays used or the statistics used to summarize them could give insufficient weight to the particular species and processes, such as N mineralization, that are most important to crop growth. Inorganic N data were consistent with net N mineralization being at least as great in the transitional system as in the organic system (Fig. 3), given similar plant uptake. Harwood's (1984) soil N hypothesis does not appear to be correct under our conditions. We suggest that indices of soil quality should be viewed with greater skepticism, until a consistent link to the actual performance (yield, nitrate leaching, etc.) of cropping systems has been demonstrated.

For example, Mäder et al. (2002) reported that organic farming ''enhanced soil fertility'', by various measures. But that purportedly higher fertility apparently did not increase organic yields, which were 20% lower than in the conventional system. Mäder et al. (2002) also reported that the organic system had higher energy efficiency, despite its lower yields, mainly due to the energy cost of fertilizer used in the conventional system. However, the validity of any extrapolation to commercial agriculture depends on whether fertilizer rates used in their experiment were optimum, a question that was apparently not addressed. If their conventional system was overfertilized, relative to most conventional farms, energy efficiency would be atypically low. The analogous question of whether differences between our conventional and organic systems could result from suboptimal management of one system or the other is addressed in a companion paper (Denison et al., 2003b). This question is of limited relevance to this paper, however, as our main conclusions are based on comparisons between identically managed organic and transitional plots.

Our data are inconsistent with the hypothesis that yield-limiting aspects of soil quality consistently improve with years of organic management. Although soil organic matter content may increase, there is no reason to expect soil microbial communities to ''self-organize'' over years for the benefit of the crop (Denison et al., 2003a,c). Our results are consistent with Stanhill's (1990) review finding ''no evidence for a significant transition effect'' in four field experiments.

The specific reasons for higher tomato yields in the organic systems in 1999, relative to their conventional counterpart, may provide some indication of the generality of this result. Direct negative effects of synthetic chemicals are an unlikely explanation, because a second conventional system (the wheat–tomato rotation) had tomato yields at least as great as the organic systems (Fig. 1a). Because tomato yields in transitional subplots without compost were not significantly lower than organic plots with compost, we conclude that 6 years of compost application had little effect on yield-limiting soil properties in 1999. We therefore attribute the higher yields of the organic and transitional plots mainly to the winter legume cover crop. Higher yield in 1999 of the legume–maize–tomato system, which had a LCC incorporated most recently in spring of 1998, is somewhat surprising but consistent with this hypothesis. The LCC protects the soil from the impact of winter rain (Folorunso et al., 1992), extends roots through dense soil layers, and transpires soil water. Spring 1999 measurements at the nearby Sustainable Agriculture Farming Systems project showed higher soil water content at 1050 to 1950 mm depth in a conventional system, relative to a system with a LCC (Joyce et al., 2002). Drier soil (from transpiration and improved drainage) and canopy cover during winter rains would be expected to reduce soil compaction in spring, although there were no consistent differences in soil bulk density a few months later (data not shown).

This is the only published study of the organic transition to completely eliminate grower experience as a confounding variable. Previous experimental studies of the organic transition, documenting changes in soil properties and simultaneous increases in yield, provide no conclusive evidence that soil quality trends were actually responsible for the yield trends. It would be risky to generalize and apply the results from our study to other crops or locations, however. Until there have been additional controlled and replicated comparisons of plots differing only in the duration of organic management, we can only conclude that yield-limiting aspects of soil quality do not necessarily improve beyond the first few months of organic farming.

5. Conclusion

With expert management, an organic system can achieve its full yield potential in the very first year, at least under some conditions. Previous comparisons among years may reflect trends in experience—a ''learning curve''—rather than in soil quality. Additional controlled comparisons between replicated plots differing only in the duration of organic management are needed to test the generality of this conclusion.

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