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Transition to large-scale organic vegetable production in the Salinas Valley, California

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Abstract

Studying the management strategies suited to large-scale organic production, particularly during the mandated 3-year transition period from conventional management, is a unique research challenge. Organic production traditionally relies on small, diverse plantings and complex management responses to cope with soil fertility and pest pressures, so research should represent decision-making options of an organic grower at the farm scale. This study analyzes crop, soil, pest and management changes during the organic transition period on two ranches (40 and 47 ha) in the Salinas Valley, California in cooperation with a large conventional vegetable producer, Tanimura and Antle, Inc. Permanent transects were established across the two ranches at the onset of adoption of organic practices, and soil and plants were sampled at harvest of almost all crops, while all management operations were recorded by the co-operator. The ~10 ha blocks were divided into many small plantings, and 17 different cash crop and cover crop species were planted during the transition period. Management inputs consisted of a range of organic fertilizers and amendments, sprinkler and drip irrigation, cultivation and hand-hoeing, and several types of organic pesticides. Results from the 3-year period followed these general trends: increase in soil biological indicators (microbial biomass and arbuscular mycorrhizae), low soil nitrate pools, adequate crop nutrients, minor disease and weed problems, and sporadic mild insect damage. Multivariate statistical analyses indicated that some crops and cultivars consistently produced higher yields than others, relative to the maximum yield for a given crop. Multi-factor contingency tables showed clear differences in insect and disease damage between crop taxa. Although Tanimura and Antle, Inc. used some of the principles of organic farming (e.g., crop diversity, crop rotation, and organic matter (OM) management), they also relied on substitution-based management, such as fertigation with soluble nutrients, initially heavy applications of organic pesticides, and use of inputs derived from off-farm sources. Their initial production of a large number of crop taxa in small plantings at staggered intervals proved to be an effective strategy for avoiding risks from low yields or crop failure and allowed them to move towards a smaller number of select, successful crops towards the end of the transition. This study demonstrates the feasibility of large-scale producers to transition to organic practices in a manner that was conducive to both production goals and environmental quality, i.e., increased soil C pools, low soil nitrate, and absence of synthetic pesticides.

Keywords: Organic; Transition; Soil; Cropping systems; Regression trees; Canonical correspondence analysis

1. Introduction

Organic agricultural production is undergoing a rapid transformation as the demand for healthier food and more environmentally sound production increases globally (Dimitri and Greene, 2002). Large producers are adopting organic practices to meet the growing demand (Giles, 2004; Klonsky, 2004). Organic farming is no longer typified solely by small family run operations, marketing their products locally, but also by large-scale corporate producers distributing to national and international marketplaces

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(Guthman, 2000). As the scale of production increases, the strategies employed to grow food without synthetic fertilizers or pesticides are expected to change as will the challenges in making the transition from conventional to organic production.

Developing new strategies suited to large-scale organic production particularly during the transition period also provides unique research challenges. As organic production traditionally relies on small, diverse plantings and complex management responses to cope with soil fertility and pest pressures, research should represent decision-making options of an organic grower at the farm scale. Past research has primarily been focused on comparisons of organic and conventional production, often on research station trials (Jenkinson, 1991; Reganold et al., 2001; Colla et al., 2002; Denison et al., 2004), rather than on the methodologies that optimize organic systems for crop production and resource use, or that smooth the transition from conventional to organic management on actual farms. Direct comparisons between the two sets of systems are problematic as it is difficult to select best management practices that are comparable, particularly as switching to organic production often entails changes not only in nutrient and pest management, but in product selection.

Agricultural transition periods inevitably require a learning curve and adaptive management to meet production goals in an environmentally sound fashion (Röling and Wagemakers, 1998; FAO, 2003). Repeated and consistent sampling is necessary to capture changes in crop yields, pest damage, and soil properties, and for this reason, organic transition periods remain largely unstudied under the conditions of dynamic decision-making on the scale of actual farms. Indicator variables are often used in large-scale studies, e.g., yield, nutrient content, pest damage indices, and soil properties, instead of process-oriented measurements that show rates of growth, nutrient transformations or energy flow (Burger et al., 2005; Pimentel et al., 2005; Carr et al., 2006). Multivariate statistics can analyze complex data sets to understand the linkages between management factors, environmental conditions, and crop performance (Roel and Plant, 2004; Rotenberg et al., 2005), and generate hypotheses regarding factors that accelerate or impede the success of the transition to organic production.

A noteworthy transition from conventional to organic vegetable production occurred in the Salinas Valley, California where one of the United States' largest cool-season vegetable production companies converted two ranches according to the California Certified Organic Farmer (CCOF) guidelines for organic production. This study was a cooperative research partnership with this company, who suggested that the most useful approach would be a project that monitored the temporal and spatial progress of the organic transition across the ranches. These ranches were in the middle of a conventional, highly productive, and intensive agricultural production area. The standard management strategy for conventional vegetable production in the Salinas Valley uses typically more than 150 kg of synthetic nitrogen (N) fertilizer per crop, frequent application of pesticides, and intensive hand labor for weeding, thinning, and harvesting. High-input conventional production has occurred for more than 50 years in this region and the soil has undergone large decreases in organic matter (OM) (Wyland et al., 1996; Steenwerth et al., 2003).

The Salinas Valley's productivity can be attributed to its deep, rich agricultural soils, mild Mediterranean maritime climate, and availability of water for irrigation. The climate is characterized by warm, dry summers, and cool, wet winters. During the summer, high temperatures in the inland Central Valley create a low-pressure gradient pulling moisture off the ocean, with fog in the Salinas Valley for much of the summer period. Vegetable growers in Salinas typically grow two cash crops a year, selecting from five main taxa lettuce, broccoli, cauliflower, celery, or spinach.

Our objective was to monitor changes in management during the mandatory 3-year period in which this conventional grower made the transition to organic certification, and to evaluate the results in terms of changes in crop species, yield, insects, diseases, weeds, soil properties, and soil microbiology. Discussions with this company set these parameters as a high priority for improving their own operations, and these are also useful for disseminating information to the larger community in the area that was gaining interest in organic farming methods. This participatory research program addressed these local concerns: that yields would be variable and occasionally nutrient-limited; insect and disease pest outbreaks would be greater during high pressure periods in the Salinas Valley; and that soil microbial biomass and soil organic matter (SOM) would be slow to increase, impacting soil fertility and productivity. On two ranches, both of which were generally uniform in past management and soil type, a network of points was sampled at nearly every crop and cover crop harvest for a set of indicators for productivity, pest pressure, and soil status. The expectation was that there would be high seasonal and spatial variation in responses across the ranches. This variation would supply information, along with management practices supplied by the grower and with weather data, which could potentially be useful in understanding the factors that determine successful organic production and environmental quality.

During a transition period, success might be defined in terms of the farms' ability to supply high quality products, e.g., with minimal damage from disease or insects, while reducing non-renewable inputs and minimizing environmental externalities, e.g., nitrate losses. Our design provided a large data set and a variety of different conditions that were conducive to analysis by multivariate methods, i.e., classification and regression trees (CART) and canonical correspondence analysis (CCA) to describe ecological relationships (McCune and Grace, 2002) but also suggest pathways for management improvement. In a larger context, a number of questions have arisen regarding the transition to organic production, particularly at large scales (Trewavas, 2004). The objective of this study was to address the following questions: Is a decline in yields inherent in the organic transition process? Does biological diversity play a role in the successful transition to organic production? When situated in the midst of a conventional growing region, do organic farms suffer high pest incidence, serving as a pesticide-free haven for insect, disease or weed outbreaks? Does the depletion of SOM during intensive conventional production preclude the build-up of biological activity and fertility for organic supply of nutrients to crops? Can organic management strategies developed for small-scale production be applied to large-scale systems? How can intensive monitoring of multiple ecological interactions at the farm scale provide useful information in the analysis of the transition period?

2. Materials and methods

2.1. Site description and field management

The field project began in June 2000 at the onset of the 3-year period required for organic transition by the California Organic Food Act and National Organics Program (2007) on two ranches in the Salinas Valley owned by Tanimura and Antle, Inc. Sampling ended in March 2003 so that there was a common end point for all transects prior to planting the crops for the spring season. Due to late spring rainfall, most of the 2003 cover crops had still not been incorporated by this date, so it was highly unlikely that any crops would be harvested between March and June, and thus this 2.75-year project gave an accurate portrayal of the 3-year transition period. Sampling at different periods of the year, however, may have confounded the comparisons of samples taken at the onset and end of the transition period. Those comparisons therefore are limited to soil properties that would be unaffected by the seasonal timing (e.g., total C and N, and Olsen P).

Both the Storm (47 ha) and Daugherty (40 ha) Ranches are located on the edge of the zoned housing areas in the city of Salinas, California, USA (Fig. 1), making them prime targets for urban concerns related to the high use of agricultural chemicals in conventional vegetable production. The mean annual temperature and precipitation for 3 years of the transition (from 2000 to 2003) were 12 °C and 41 cm, respectively. All weather data was recorded from a California Irrigation Management Information System (CIMIS) weather station that is 8 km northwest of the Storm Ranch. The soil type at these two ranches is mainly Salinas clay loam (Fine, montmorillonitic, thermic Chromic Pelloxererts), an alluvium derived from sandstone and shale, and a small area of Cropley silty clay (Fine-loamy, mixed, thermic Pachic Haploxerolls) on the Daugherty Ranch, a silty clay alluvium derived from sedimentary rock.

The grower meticulously recorded all management operations over the course of the 3-year transition. The organic management of these cool-season vegetables relied on intensive tillage. In most cases, crops were direct seeded into beds that had been tilled and shaped between each crop. Drip tape was buried for irrigation at a 3 cm depth after bed-shaping, and was recovered for re-use between crops. Cover crops were usually planted once every year, either in late summer or fall. Cover crops consisted of mainly Merced rye (*Secale cereale* L. cv. ‘Merced’), or a legume mix (50% bell beans (*Vicia faba* L.), 40% cowpeas (*Vigna unguiculata* (L.)

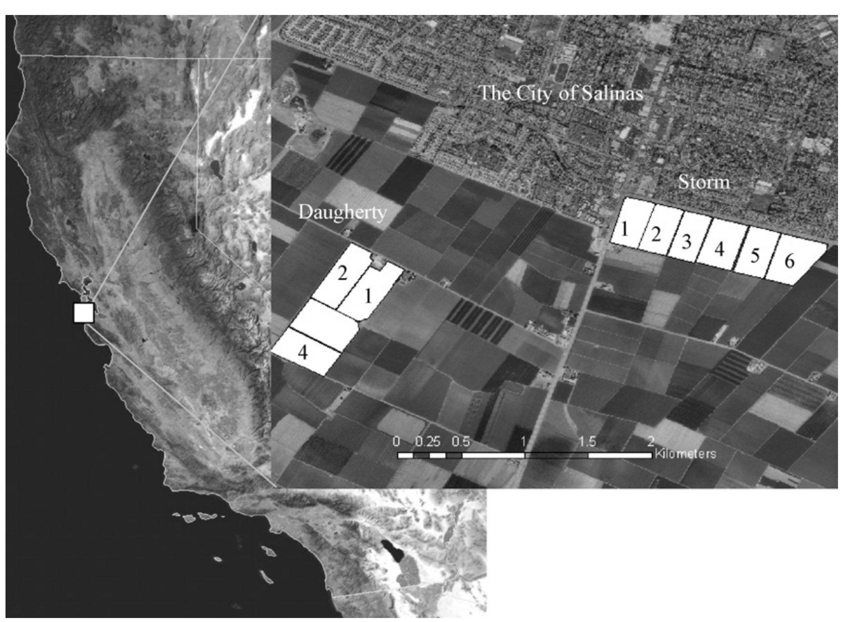

Fig. 1. Tanimura and Antle, Inc.’s Storm Ranch (46.7 ha) and Daugherty Ranch (39.5 ha), located in the Salinas Valley, California. Three transects were established on each of the six management blocks of Storm Ranch and three of four management blocks of the Daugherty Ranch for a total of 27 transects and 81 sampling plots.

Table 1
Summary of mean of application rates of compost, chicken manure pellets and Biolizer-soluble fertilizer for the 2.75-year study

Lot[a]	Ha	Compost (Mg ha^{-1})	Pellets (kg ha^{-1})	Biolizer (L ha^{-1})	Number of plantings[b]
D1	9.6	9.9	1054	238.5	24
D2	9.5	7.9	1101	174.1	20
D4	8.7	9.8	1058	185.4	11
S1	7.0	9.1	1121	191.1	15
S2	7.0	9.1	1087	189.6	15
S3	6.8	10.3	1121	137.5	12
S4	8.7	12.6	1121	168.0	8
S5	7.6	13.3	1121	226.0	11
S6	9.6	10.4	1031	151.0	17

[a] D and S refer to Daugherty and Storm Ranches, and the associated number refers to each management block.
[b] The number of total crop and cover crop plantings.

Walpers ssp. *unguiculata*), and 10% cayuse oats (*Avena sativa*)), and a legume mix/Merced rye mix (1:1 ratio). Compost was applied at least once per year (Table 1). Starting materials were municipal yard waste (30%), waste from salad packing plants (5%), with the remainder composed of horse manure, clay, finished compost, and baled straw. The compost C:N ratio averaged 18, according to the producer (Cranford, Inc., Salinas, CA), and previous measurements (Jackson et al., 2004). Britz pelleted chicken manure fertilizer (2.5–2–2.5) was applied prior to plantings (1100 kg ha^{-1} supplying 28 kg N ha^{-1}). Then a soluble fertilizer (Biolizer XN (6.0–0.4–0.2)) was applied multiple times through the drip tape during each crop growth cycle at total application rates ranging from 25 kg N ha^{-1} for baby greens to 244 kg N ha^{-1} for celery (Table 2). Except for hoeing costs, no other financial information was provided by the grower.

A number of different organically certified pesticides were utilized throughout the transitions based on decisions made by the grower and a Pest Control Advisor (PCA). Insecticides, intended mainly for aphids, included Mycotrol (*Beauveria bassiana*), Pyganic (Pyrethrins), Neemix (Azadirachtin), Aza-direct (Azadirachtin), and soap- and oil-based products such as Natur'l Oil (soybean oil) or Green Valley plant wash (salts of fatty acids). Bt in the form of either Javelin (85% *Bacillus thuringiensis*, subspecies *Kurstaki* solids, spores and lepidopteran active toxins, 15% other ingredients (Certis USA, LLC)) or Agree (50% *Bacillus thuringiensis*, subspecies *aizawai* Strain GC-91 solids, spores and Lepidopteran active toxins, 50% other ingredients (Certis USA, LLC)) was used to control lepidopteran larvae. To control powdery mildew (*Erysiphe cichoracearum*) and downy mildew (*Bremia lactucae*), the PCA applied Serenade (*Bacillus subtilis*), Kaligreen (potassium bicarbonate), Trilogy (clarified hydrophobic extract of neem oil) or Micros (sulfur).

2.2. Field sampling

The ranches had been divided into lots by the grower many years before, and these were treated as management blocks for this study. Three transects were established across nine of the management blocks (six at Storm Ranch and three at Daugherty Ranch), totaling 27 transects. One of the blocks at the Daugherty Ranch was not used since variability in SOM had been created by an earlier experiment (Jackson et al., 2004). Along each transect, three sampling plots (5 m × 5 m), were evenly placed at least 35 m apart, for 81 plots in total (54 at Storm Ranch and 27 at Daugherty Ranch). Soil samples were taken from all 81 plots in June 2000 at the beginning of the 3-year transition period and again in March 2003 before organic certification. This composes the soil properties data set.

In addition, throughout the transition, crops and soils were sampled within 1 week of harvest of each transect. This composes the crop and soil monitoring data set. Approximately 5–10% of the crop harvests were missed inadvertently. At each sampling, two 2.5 cm diameter cores were taken midway between two plants in the planting row at the 0–15 and 15–30 cm depth, composited, homogenized and put on ice before processing, which usually took place within 72 h. Crop plants were dug from a 1250 cm^2 area (50 cm × 25 cm from the center of the bed to the center of the furrow) in each plot and inspected visually for insects, shoot damage, and root disease. Presence/absence insect damage data was further refined by ranking the damage as minor, mild, moderate or severe depending on the type and amount of lesions, discoloration, stings, tracks on leaves, and signs of herbivory such as holes on leaves. It was impossible to attribute damage to specific insects and diseases, but we surveyed each transect for insects, which were then identified (UC IPM, 1987; Fake et al., 2000).

The harvested portion of the plant was removed, and weighed after drying at 65 °C. For most of these crops, this was the entire shoot, such as for lettuce, but for others such as broccoli, only the marketable heads were taken. Harvested biomass was used to determine a relative yield as a means of evaluating the collective success of the diverse set of crops grown during the transition period. This allowed the comparison of yields of large crops such as broccoli and smaller crops such as baby lettuce in the same analysis. Relative yield is defined here as the observed yield of each crop divided by the observed maximum yield ever measured for that crop during the 3-year period, expressed as a percentage.

Table 2
Summary of management information by cash crop, showing the mean value of inputs per crop planting

Crop name	Number of times planted	Planting size (ha)	Drip (cm)	Sprinkler (cm)	Biolizer (L)	Biolizer N (kg ha^{-1})	Biolizer P (kg ha^{-1})	Biolizer K (kg ha^{-1})	Plant N (mg g^{-1})	Plant P (mg g^{-1})	Plant K (mg g^{-1})	Soap (L ha^{-1})	Neem (L ha^{-1})	Bt K (kg ha^{-1})	Mildew (kg ha^{-1})	Mildew (L ha^{-1})
Baby greens[a]	23	2.9	0	14	359	25	0.71	0.68	40.7	5.9	59.5	4	0	1	0	0
Broccoli[b]	7	3.4	15	14	1191	82	2.34	2.26	34.0	2[c]	40.0	571	35	10	0	0
Celery[d]	5	1.8	50	24	3556	244	6.99	6.74	15.0	8.3	70.0	94	13	11	5	0
Cilantro[e]	42	0.8	9	15	1017	70	2.00	1.93	33.8	2.5	67.5	0	0	0	0	0
Endive[f]	32	1.5	17	14	1172	80	2.30	2.22	32.5[c]	1.3[c]	62.5	70	9	8	0	0
Escarole[g]	32	0.4	11	13	1046	72	2.05	1.98	33.8	1.3[c]	68.8	50	7	7	0	0
Fennel[h]	62	0.8	19	11	1987	136	3.90	3.77	27.2	2.2	52.2	0	0	0	0	0
Frisee[f]	23	1.3	17	12	1479	101	2.90	2.80	32.0	6.0	57.5	95	13	11	5	4
Green leaf[i]	5	1.1	7	6	940	64	1.85	1.78	40.0	10.0	73.3	169	26	14	50	0
Parsley[j]	76	0.3	32	13	2162	148	4.25	4.10	27.9	1.0	53.6	0	0	0	0	0
Radicchio[k]	14	2.3	9	14	780	53	1.53	1.48	33.8	2.1	67.6	79	13	9	7	2
Red leaf[i]	3	1.0	15	11	940	64	1.85	1.78	40.0	8.3	75.0	141	18	11	47	0
Romaine[i]	13	2.5	13	7	1350	89	2.56	2.47	32.3[c]	4.6	78.1	129	24	15	16	17

Means include all varieties of each taxon. Mildew refers to the specific products to control powdery and downy mildews (see text).

[a] Lettuce (*Lactuca sativa* (L.)), chard (*Beta vulgaris* L. ssp. *cicla* (L.) Koch), mizuna mustard (*Brassica rapa* (L.)), arugula (*Eruca vesicaria* (L.) Cav. ssp. *sativa* (P. Mill.) Thellung), frisee (*Cichorium endivia* (L.) (Crispum Group)), and radicchio (*Cichorium intybus* (L.) (Rubifolium Group)).

[b] *Brassica oleracea* L. var. italica Plenck.

[c] Below critical value.

[d] *Apium graveolens* (L.).

[e] *Coriandrum sativum* (L.).

[f] *Cichorium endivia* (L.) (Crispum Group).

[g] *Cichorium endivia* (L.) (Latifolium Group).

[h] *Foeniculum vulgare* Mill.

[i] *Lactuca sativa* (L.).

[j] *Petroselinum crispum* (P. Mill.) Nyman ex A.W. Hill.

[k] *Cichorium intybus* (L.) (Rubifolium Group)).

All weeds in the 1250 cm^2 plot were counted. They were also identified to species (Hickman, 1993).

For the crop and soil monitoring data set, 504 soil samples were taken between 10 June 2000 and 3 March 2003. Soil was sub-sampled in the laboratory, and analyzed for gravimetric soil moisture content, and KCl-extractable nitrate (NO_3^--N) and ammonium (NH_4^+-N) colorimetrically using modifications of Miranda et al. (2001) and Forster (1995), respectively. A 7-day anaerobic incubation was used to determine potentially mineralizable nitrogen (PMN) (Waring and Bremner, 1964). Roots were separated from 100 g of fresh soil, rinsed, cleared and stained for determination of mycorrhizal colonization. The roots were cleared in 10% KOH at room temperature, rinsed with water, neutralized with 1N HCl, and stained in 0.06% Trypan blue in lactoglycerol for 1 h, rinsed in DI water, and stored in lactic acid:glycerol (1:1, v/v) (modified from Phillips and Hayman, 1970). Arbuscular mycorrhizal (AM) colonization was determined by the magnified intersects method (McGonigle et al., 1990). Samples from 2003 unfortunately were lost. Microbial biomass carbon (MBC) was determined using the fumigation–extraction technique, then total MBC was calculated by multiplying the flush of C by 2.64 (Vance et al., 1987).

For the soil properties data set, soil sub-samples were air dried and composited by transect (27 samples) and sent to the Division of Agriculture and Natural Resources (DANR) Analytical Laboratory at the University of California at Davis (http://danranlab.ucdavis.edu/). Total soil N and C were measured by the combustion gas analyzer method (Pella, 1990). Electrical conductivity (EC) (Rhoades, 1982), and particle size distribution (Sheldrick and Wang, 1993) were also measured. Olsen P, a measure of extractable phosphate (PO_4^{3-}), was based on alkaline extraction (Olsen and Sommers, 1982). Soluble potassium was determined in a saturated paste extract by emission spectrometry (Knudsen et al., 1982; Soltanpour et al., 1982).

Dried plant samples were sub-sampled and ground. Sub-samples were sent to the DANR Lab for analysis of total N, using a Nitrogen Gas Analyzer with an induction furnace and thermal conductivity (LECO FP-528, St. Joseph, MI), and total phosphorus (P) and potassium (K) by microwave acid digestion and dissolution of sample followed by quantitative determination by atomic absorption spectrometry (AAS) or inductively coupled plasma-atomic emission spectrometry (ICP-AES) (Meyer and Keliher, 1992).

2.3. Statistical analysis

Much of the statistical analysis was based on comparisons by growing season, since there were substantial differences in weather, crops, and management during the year. A growing season was defined as a 3-month period with generally similar weather: spring (March 1–May 31), summer (June 1–August 31), fall (September 1–November 30) and winter (December 1–February 28). These analyses used the monitoring data from the 81 sampling plots for the 3 years. The number of samples in the crop and soil monitoring data set varied from season to season and year to year. Note that in winter and in spring, the sampling occurred just before cover crop incorporation, and there were very few incidences when crops were harvested. Shannon's diversity index (Margalef, 1958) was used to describe seasonal changes in crop taxa. We use taxon/taxa to refer to distinctions from the species- to the cultivar-level.

Analysis of variance (ANOVA) was used to test for year to year changes in relative yield, and soil biological activity, as well as by growing season during the transition period (JMP 6, SAS Inc., 2006). Mycorrhizal colonization data was transformed before analysis using the arcsine of the square root of the proportion. Tukey–Kramer's honestly significant difference was used to compare differences between means.

Log-linear models were used to test for differences in the categorical data for presence/absence of shoot damage by insects or disease, or for root disease. Multiple factor contingency tables were employed to differentiate the effects of year, growing season, and crop taxa (Dammer and Heyer, 1997). Log-linear models were first used to test for independence of crop damage by year or by sampling season. Conditional log-linear models that were run for dependencies between year, season and variety were not significant, nor were models that included interactions between year and season or season and crop taxa. By failing to reject the null hypotheses that included these interactions between these factors, unconditional log-linear models were run separately either for year, season by year, or crop taxa by season. Proportions that were significantly different among seasons were contrasted with a procedure similar to a Tukey test for significance after transforming using a modification of the Freeman and Tukey (1950) transformation, $p' = (1/2)[\arcsin\sqrt{(x/n+1)} + \arcsin\sqrt{(X+1)/(n+1)}]$ (Zar, 1974).

Multivariate statistics were then used to better understand the driving factors that would explain the differences identified in the ANOVA and log-linear analyses. Recursive regression trees were used to explore the relationship between management and relative yield, and damage to crops from insects, and disease for all crop taxa excluding cover crops. Recursive partitioning function (RPART) in the freely available R statistical software (http://www.r-project.org/) was used for the following CART analyses: a continuous variable (relative yields), a nominal variable (presence of plant damage from either disease indicated by yes or no) and an ordinal variable (degree of severity from insect damage, ranked as none, mild, or severe) (Breiman et al., 1984; Moore et al., 1991). A total of 32 different parameters that were recorded during the 3 years of monitoring were used in the analysis, including the data in Table 2, soils data (e.g., NO_3^--N, NH_4^+-N, PMN, soil moisture, MBC, and AM colonization), management data (e.g., organic fertilizer or pesticides applied) and weather data (e.g., average rainfall, average solar radiation, average temperature, average relative humidity). For each CART

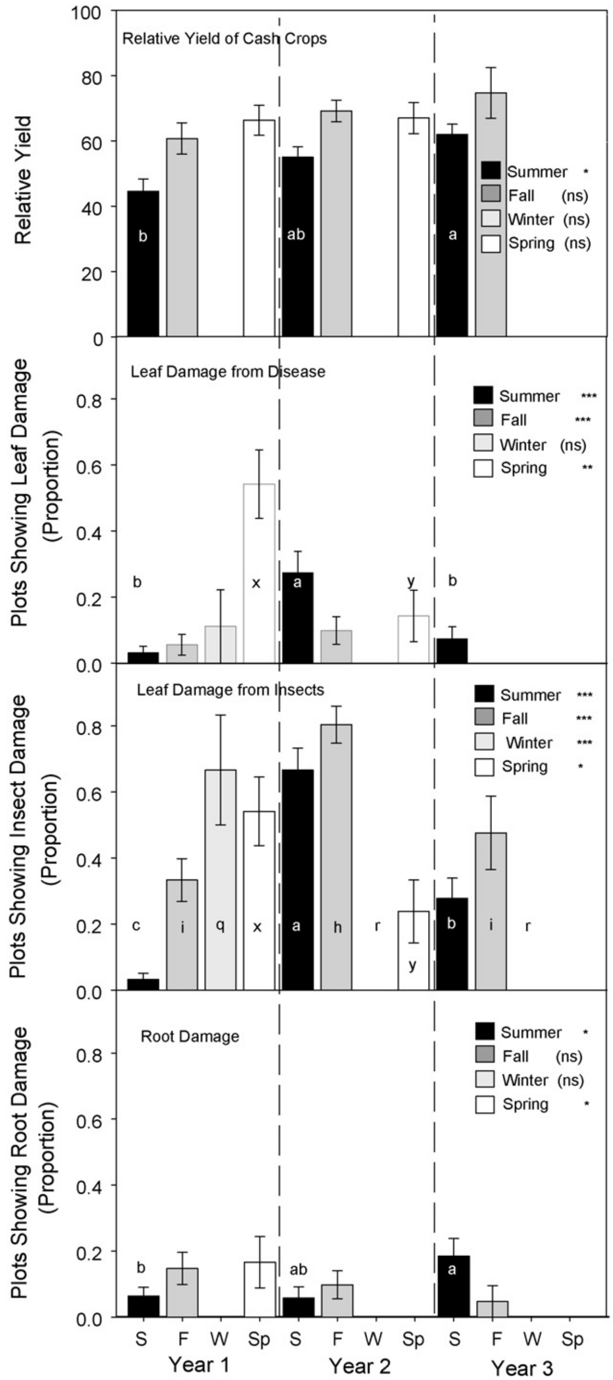

Fig. 2. Crop performance indicators during the transition to organic production. Results were compared by growing season. ANOVA was used to analyze relative yields, which was the ratio between a sample mean and the maximum observed for a specific taxon. Log-linear tests were used to analyze presence/absence results for crop damage (see text). Different letters indicate significant differences at $^*P < 0.05$, $^{**}P < 0.01$, $^{***}P < 0.001$. Mean ± S.E.

analysis, the sample size depended on the completeness of the data set; samples with any missing values were not used in the analysis.

To examine the differences in soil properties between time 0 to year 3, ANOVA was used to compare the mean values of the three transects in each of the nine management blocks. Canonical correspondence analysis (CANOCO Version 4.5, 2006) was then used to explore how the soil properties changed in these different blocks. The direct effects (standardized partial regression coefficients) of each explanatory variable on changes in soil properties, and the indirect effects of each independent variable on other independent variables (e.g., clay content and compost application rates) were partitioned in the CANOCO analysis.

3. Results

3.1. Crop performance and pest damage

Crop performance increased over the 3-year period (Fig. 2) based on relative yields. During the most intensively cropped season, which was the summer, there was a significant increase in relative yields from 45% in the first year to 62% in year 3. Relative yield was highest in the green and red leaf lettuces, which averaged 96% and 85%, respectively, and lowest in parsley and romaine lettuce, at 52% and 45%, respectively. Nearly all crops were sold and marketed during the 3-year transition, indicating adequate

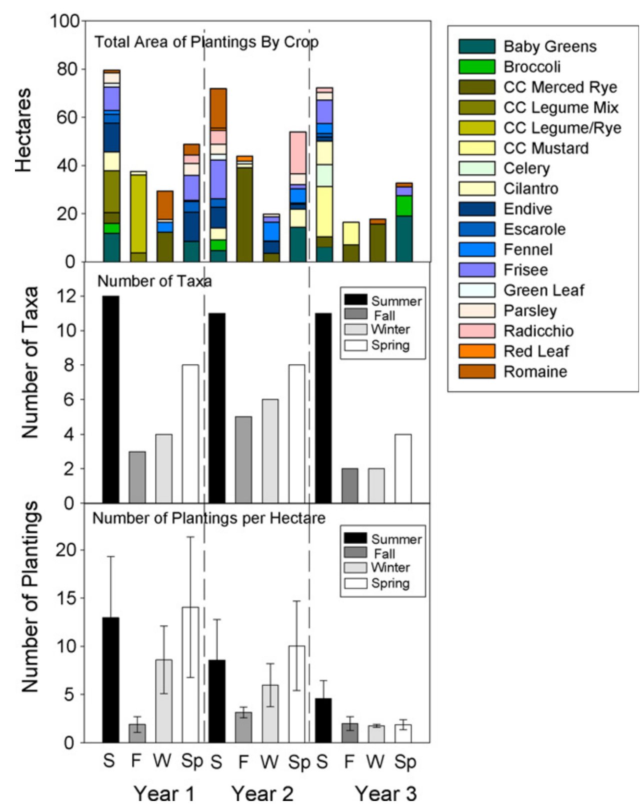

Fig. 3. Crop plantings on the two ranches during the organic transition. Size of plantings by crop is shown for the season in which plantings were made, and is summed for the entire 86.2 ha of the two ranches. The number of taxa refers to the total planted in a given season. The number of plantings (ha^{-1}) made in a given season is also shown (mean ± S.E.).

Table 3
Summary of damage to each crop taxon from insect pests, leaf disease, and root disease

Crop name	Variety	Insect damage (% (*n*))					Leaf damage (% (*n*))					Root damage (% (*n*))				
		Summer	Fall	Winter	Spring	3-Year total	Summer	Fall	Winter	Spring	3-Year total	Summer	Fall	Winter	Spring	3-Year total
Baby greens	Mesculin mix	11 (36)			44 (9)	18 (45)	8 (36)			0 (9)	7 (45)	0 (36)			0 (9)	0 (45)
	Baby mix	0 (18)				0 (18)	0 (18)				0 (18)	33 (18)				33 (18)
Broccoli	Greenbelt		100 (5)			100 (5)		0 (5)			0 (5)		0 (5)			0 (5)
	Patriot		0 (3)			0 (3)		0 (3)			0 (3)		0 (3)			0 (3)
Cover crop	Merced rye		0 (6)	0 (50)	0 (18)	0 (74)		0 (6)	0 (50)	0 (18)	0 (74)		0 (6)	0 (50)	0 (18)	0 (74)
	Legume mix	0 (3)	100 (9)			75 (12)	0 (3)	0 (9)			0 (12)	0 (3)	0 (9)			0 (12)
	Legume mix/rye		14 (21)	67 (9)		30 (30)		14 (21)	11 (9)		13 (30)		24 (21)	0 (9)		17 (30)
	Mustard		0 (3)			0 (3)		0 (3)			0 (3)		0 (3)			0 (3)
Celery	340	0 (3)				0 (3)	0 (3)				0 (3)	0 (3)				0 (3)
	414	0 (6)	75 (8)			42.9(14)	0 (6)	0 (8)			0 (14)	0 (6)	0 (8)			0 (14)
Cilantro	LS014	17 (6)	17 (6)			16.7(12)	0 (6)	0 (6)			0 (12)	0 (6)	0 (6)			0 (12)
	Leisure	0 (6)	0 (3)		0 (3)	0 (12)	0 (6)	0 (3)		0 (3)	0 (12)	0 (6)	0 (3)		0 (3)	0 (12)
Endive	Markant	92 (12)	75 (12)		67 (3)	81 (27)	33 (12)	0 (12)		33 (3)	19 (27)	0 (12)	8 (12)		0 (3)	4 (27)
Escarole	Full heart	11 (9)	0 (3)		0 (3)	7 (15)	22 (9)	0 (3)		0 (3)	13 (15)	0 (9)	0 (3)		0 (3)	0 (15)
Fennel	Orion	0 (7)			0 (9)	0 (16)	0 (7)			0 (9)	0 (16)	0 (7)			0 (9)	0 (16)
	Santo	0 (2)				0 (2)	0 (2)				0 (2)	0 (2)				0 (2)
	Victorio	0 (3)				0 (3)	67 (3)				67 (3)	67 (3)				67 (3)
Frisee	Frenzy	0 (2)				0 (2)	0 (2)				0 (2)	0 (2)				0 (2)
	Tosca	75 (12)	100 (9)			86 (21)	33 (12)	0 (9)			19 (21)	25 (12)	11 (9)			19 (21)
Green leaf	Shining star		100 (3)			100 (3)		0 (3)			0 (3)		100 (3)			100 (3)
Italian parsley	Green forest	21 (43)	100 (6)		50 (12)	34 (61)	2 (43)	0 (6)		75 (12)	16 (61)	7 (43)	50 (6)		8 (12)	11 (61)
	Italian dark	0 (5)	25 (12)			18 (17)	0 (5)	0 (12)			0 (17)	0 (5)	0 (12)			0 (17)
Radicchio	Giovanna	83 (6)	100 (9)			93 (15)	50 (6)	22 (9)			33 (15)	0 (6)	0 (9)			0 (15)
	Leonardo	80 (15)				80 (15)	13 (15)				13 (15)	33 (15)				33 (15)
Red leaf	Red tide		67 (6)			67 (6)		50 (6)			50 (6)		17 (6)			17 (16)
Romaine	Hearts delight				100 (6)	100 (6)				100 (6)	100 (6)				50 (6)	50 (6)
	X^2	104***	105***	27***	43***	258***	39**	24	4*	54***	94***	43***	37**	0	15*	95**
	d.f.	17	16	1	7	25	17	16	1	7	25	17	16	0	7	25

Log-linear tests were used to analyze presence/absence results for crop damage (see text). Significant differences in percentages are indicated by: *$P < 0.05$; **$P < 0.01$; ***$P < 0.001$.

yield and quality to meet conventional standards. Less than 10 crop plantings were not harvested and disced, and the main reasons were disease (e.g., downy mildew on romaine), insects (e.g., lettuce aphid (*Nasonovia ribisnigri*) on romaine), and lack of market demand (endive and escarole).

When average nutrient contents of each crop were compared with reported stringent critical deficiency values for macronutrients (N, P and K) using the most-recently matured whole leaf plus petiole (MRM leaf) analysis (Hochmuth et al., 1991; Hartz et al., 2007), most were well above the critical value (Table 2). No critical values are available for cilantro, fennel, frisee, parsley, or radicchio, so it was impossible to evaluate their nutrient status. Means for two cash crops fell slightly below the critical value for N (endive and romaine at 32.5 and 32.3 mg N g^{-1} dry weight, respectively), both with a critical value of 35.0 mg N g^{-1} dry weight. Broccoli shoots were 2.0 mg P g^{-1} dry weight on average, which was below the MRM critical value of 3.0 mg P g^{-1} dry weight. Both endive and escarole shoots averaged 1.3 mg P g^{-1} dry weight, while their MRM critical value was 4.0 mg P g^{-1} dry weight. All crops had more than sufficient K, except baby greens, for which the mean was just above the critical value.

Insect damage, measured by presence/absence, increased from an average of 3% ($n = 114$) during the summer of the first year to 66% ($n = 51$) in the second summer, but then decreased in the summer of the third year to 28% ($n = 54$) (Fig. 2). Insect damage in the fall increased from year 1 to year 2, from 33% ($n = 54$) to 80% ($n = 51$), and decreased to 47% ($n = 21$) in the fall of year 3. In the spring, insect damage decreased from year 1 (54% ($n = 24$)) to year 2 (24% ($n = 21$)). There was no data for the spring of year 3 because no vegetables were harvestable when sampling ended in March 2003. For winter cover crops, insect damage occurred on 75% of the legume mix samples, and 30% of the legume mix/Merced rye samples (data now shown) which was used initially, but was not observed on Merced rye or brassicaceous cover crops, which were by far the most commonly used cover crops and used in years 2 and 3 (Fig. 3). The crops that were most damaged were broccoli, endive, frisee, green leaf, radicchio, and romaine, while the crops with the least damage were cilantro, escarole, baby greens and parsley (Table 3).

The lettuce aphid was the most important pest, especially in year 2 on romaine. Leaf miners, mainly pea leafminer (*Liriomyza huidobrensis*), caused minor damage, especially on the leafy greens, and were most abundant in year 2. There were a number of different insects frequently observed over the study period. Pests included corn earworms (*Helicoverpa zea*), cucumber beetles (*Acalymmna trivittatus* and *Diabrotica* spp.), and false cinch bugs (*Nysius raphanus*). Beneficial insects included green lacewings (*Chrysoperla* spp.), leaf hoppers (*Circulifer tenellus*), and syrphid flies (*Syrphus* spp.), assasin bugs (*Zelus renardii*), predatory thrips (*Aeolothrips fasciatus*), lady bugs (*Hippodamia convergens*), spiders (*Erigone* spp. and *Cheiracanthium* spp.), and minute pirate bugs (*Orius* spp.)

For the two spring seasons, incidences of symptoms of leaf disease declined from 54% of the samples ($n = 24$) in year 1 to 14% ($n = 21$) of the samples in year 2 as determined by the log likelihood statistic (Fig. 2). There was an increase in leaf disease symptoms from the summer of year 1, where 3% ($n = 114$) of the samples were infected, to the summer of year 2, where 27% ($n = 51$) of the samples showed disease symptoms followed in the summer of year 3 by a decrease to 7% ($n = 54$). Red leaf and romaine lettuces had more incidences of leaf diseases than any of the other crops (Table 3).

The occurrence of root disease symptoms (presence/absence) increased during the summer seasons from 6% of

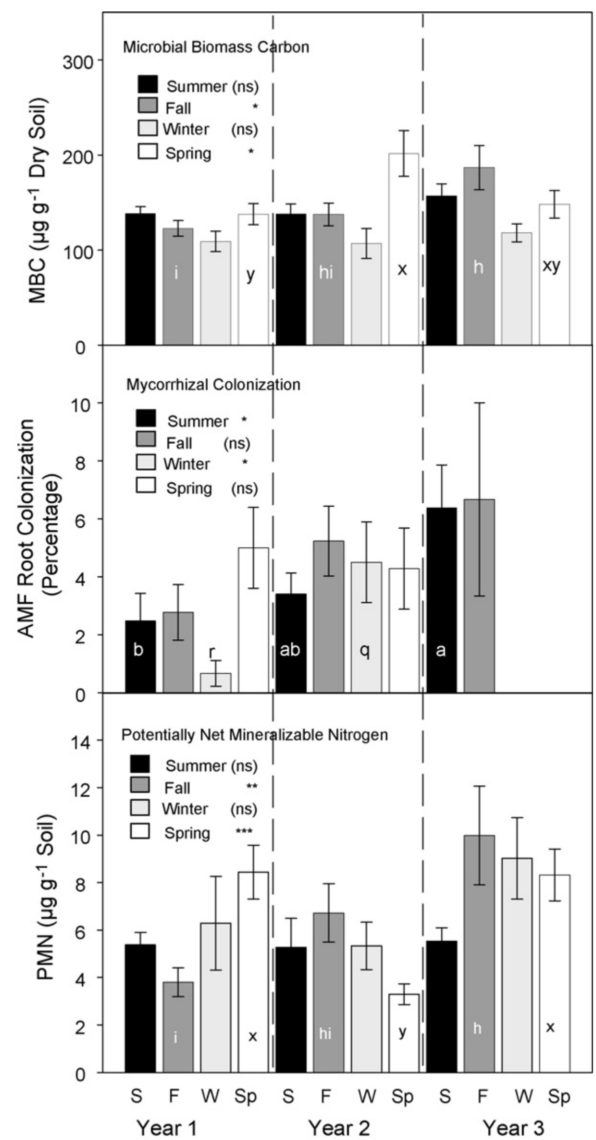

Fig. 4. Changes in biological indicators of soil activity during the organic transition. Results were compared by growing season using ANOVA. Different letters indicate significant differences at $^{*}P < 0.05$, $^{**}P < 0.01$, $^{***}P < 0.001$. Mean ± S.E.

samples in the first ($n = 114$) and second years ($n = 51$) to 18% in year 3 ($n = 54$) (Fig. 2). Root disease occurrence, however, decreased significantly for the spring crops, from 17% ($n = 24$) to 0% ($n = 21$). There were no significant differences in root disease for fall and winter crops. Green leaf lettuce was the only crop that was more susceptible to root disease than the others (Table 3).

The most important foliar disease was downy mildew of lettuce on romaine, especially in late summer plantings. In year 2, three romaine plantings were disced before harvesting due to downy mildew. Lettuce drop (*Sclerotinia minor*) was the most prevalent root disease, and very little corky root of lettuce (*Rhizomonas suberifaciens*) was observed. Diseases that were commonly observed were big vein of lettuce (Mirafiori lettuce virus) vectored by a soil fungus (*Olpidium brassicae*) (Lot et al., 2002), and powdery mildew (*Erysiphe cichoracearum*) on several crops. Occasionally seen were Sclerotinia white mold (*S. sclerotiorum*) on fennel, and *Botrytis* spp. on fennel and romaine.

3.2. Weeds

The frequency of weeds was greatly influenced by weed control, which was achieved by cultivation, hand hoeing, and removal of plants from the field. Thus it is difficult to assess whether weed and weed seed densities actually changed during the course of the study. One indicator of weed density was the percentage of sampled plots that contained weeds. For the Storm Ranch, in 2000, 2001, and 2002, respectively, 27%, 39% and 16% of the sampled plots contained weeds. For Daugherty Ranch, this was 4%, 11%, and 18%, respectively. There was no consistent pattern observed in the frequency and biomass of weeds, except for high abundance in the legume cover crop, i.e., mean weed aboveground biomass was 1.1 g 1250 cm^{-2} (i.e., approximately 88 kg ha^{-1}, although measurements did not include the furrow) compared to <0.4 g 1250 cm^{-2} for all other crops and cover crops. For example, the crops at the Storm Ranch showed the following mean frequencies of weed occurrence: baby greens (46%), cilantro (37%), escarole/endive/frisee (52%), fennel (58%), leaf lettuce (21%), radicchio (8%), romaine (67%), parsley/Italian parsley (14%), and cover crop (40%). The main species were groundsel (*Senecio vulgaris* (L.)) and shepherd's purse (*Capsella bursa-pastoris* (L.)). Purslane (*Portulaca oleracea* (L.)) was less abundant, but it was a problem due to its vegetative propagation, especially on Storm Ranch Blocks 1 and 2.

Hoeing and thinning costs are another indicator of weed severity, since they reflect the effort involved in removing weeds. For the Storm Ranch, in 2000, 2001, and 2002, hoeing and thinning costs were 1922, 2529, and 2014 USD ha^{-1}, respectively. For Daugherty Ranch, this was 1446, 1084, and 1530 USD ha^{-1}, respectively.

3.3. Biological indicators of soil activity and inorganic N

Over the 3-year transition period there was a trend towards greater soil biological activity (Fig. 4). Soil MBC at the 0–15 cm depth increased significantly during the most biologically active times of the year, which is the mild wet

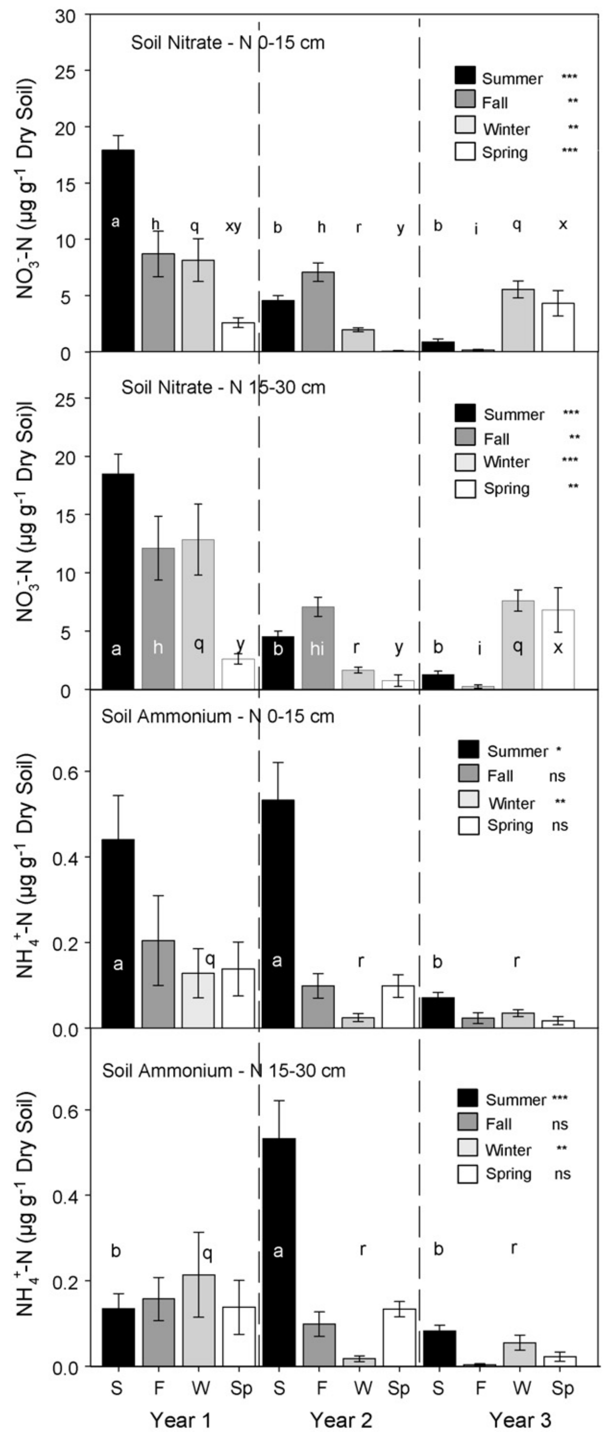

Fig. 5. Changes soil NO_3^--N and NH_4^+-N concentrations at 0–15 and 15–30 cm depths during the organic transition. Results were compared by growing season using ANOVA. Different letters indicate significant differences at $^*P < 0.05$, $^{**}P < 0.01$, $^{***}P < 0.001$. Mean ± S.E.

fall and spring, over the 3-year period. For the fall season, average values of MBC increased from 123 μg C g^{-1} dry soil in year 1, to 187 μg C g^{-1} dry soil in year 3 ($P = 0.02$), but there was no difference in year 2 (137 μg C g^{-1} dry soil). Spring values increased from 138 μg C g^{-1} dry soil in year 1 to 201 μg C g^{-1} dry soil in year 2, but decreased to 148 μg C g^{-1} dry soil in the spring of year 3 ($P = 0.02$), when samples were taken before, rather than after cover crop incorporation.

Arbuscular mycorrhizal colonization of the summer cash crops and winter cover crops increased with time while spring and fall crops remained unchanged (Fig. 4). Mean colonization of summer crops in year 1 was only 2.8% of the root length, but this more than doubled to 6.8% by year 3. The colonization of winter cover crops increased more than fourfold from 0.7% in year 1 to 4.5% in year 2, and no data are available for 2003.

Potentially mineralizable N (0–15 cm depth) in the soil increased in the fall from 3.8 μg N g^{-1} dry soil in year 1 to 10.0 μg N g^{-1} dry soil in the fall of year 3 (Fig. 4). In the spring, mean values decreased from 8.4 μg N g^{-1} dry soil in the first year to 3.3 μg N g^{-1} dry soil in the second year, but then increased to 8.3 μg N g^{-1} dry soil in the third year ($P < 0.001$). There were no significant differences in the summer and winter seasons from year to year.

Nitrate concentrations at the soil surface (0–15 cm) generally declined over the study period (Fig. 5). This annual decline was particularly pronounced for the summer seasons, when the concentration decreased by an average of 13.5 μg N g^{-1} dry soil from the summer of year 1 to the summer of year 2 with no subsequent difference between years 2 and 3. Similarly, fall values showed a decline between years 2 and 3, at which point, the mean was only 0.2 μg N g^{-1} dry soil. The winter and spring seasons, however, declined from year 1 to 2 but then increased slightly in year 3. The same general pattern was observed for deeper (15–30 cm) NO_3^--N concentrations.

Ammonium (NH_4^+-N) concentrations were generally low at both soil depths (Fig. 5). Fall and spring seasons showed no changes in NH_4^+-N concentration throughout the transition at either depth. There was a decrease in NH_4^+-N during the winter seasons after the first year at both depths, and in the summer, a decline occurred after the second year in the 0–15 cm depth. In contrast, summer NH_4^+-N concentrations for the deeper (15–30 cm) layer more than doubled in year 2 to 0.5 μg N g^{-1} dry soil, then declined to only 0.1 μg N g^{-1} dry soil in the third year.

3.4. Management

Maintaining a diversity of crops was a purposeful strategy used by the grower. Overall, 13 cash crops and four cover crops, each represented by one or more cultivars were planted during the study period (a total of 26 crop taxa). The large blocks were divided into much smaller sections that were planted at different times with different species (Fig. 3). Planting sizes varied throughout the transition, but on average, the crops were planted in 1.8 ha strips, ranging from 0.16 ha plantings of escarole to 8.7 ha of a cover crop, with larger plantings in the fall and winter when cover crops were prevalent. The cash crops with the greatest total area on the two ranches were baby greens, frisee, and endive, at 65, 53 and 41 ha, respectively. In summer and fall, the number of species and the Shannon's diversity index (not shown) remained similar throughout the transition period. In winter and spring of the third year, however, diversity decreased as there were fewer types of cover crops planted in the fall, and late rains delayed incorporation and spring planting of vegetable crops.

Cover crop management changed through time. In the first year, most plantings were legume mix or legume mix/

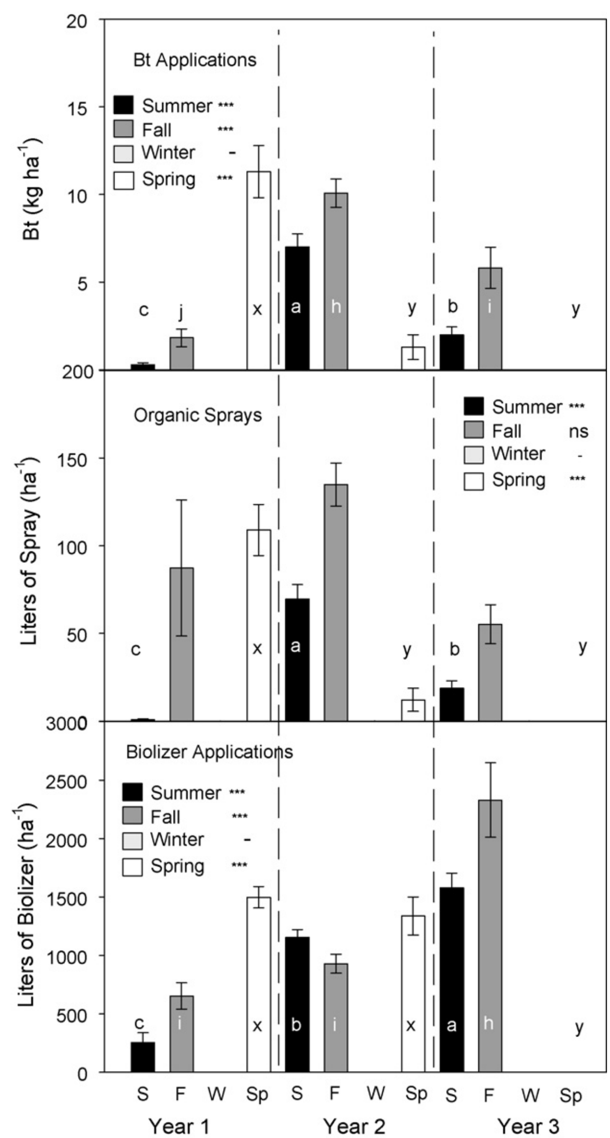

Fig. 6. Management of organic pesticides and soluble fertilizer (Biolizer) during the organic transition. Results were compared by growing season using ANOVA. Different letters indicate significant differences at $^*P < 0.05$, $^{**}P < 0.01$, $^{***}P < 0.001$. Mean ± S.E.

Merced rye mix (Fig. 3). Due to insect damage and high weed densities in the legume mix cover crops, the grower switched mainly to Merced rye in the second year. In the third year, brassicaceous cover crops were planted on a total of 20.8 ha. The cover crops in the third year were not disced until April. The Merced rye had produced seed before discing, and created a costly weed problem in fields of baby greens during the following summer (R. Yokota, pers. comm.).

Crop choices favored taxa that were short-term, e.g., baby greens, and had lower pest susceptibility, e.g., cilantro, parsley and escarole, especially in the first year. Recognizing that aphids and leaf miner populations typically are most abundant in late summer, some plantings were delayed until September, and not all of the land was planted with crops in mid-summer.

Crop fertilization rates increased significantly through time (Fig. 6). Applications of the soluble Biolizer fertilizer

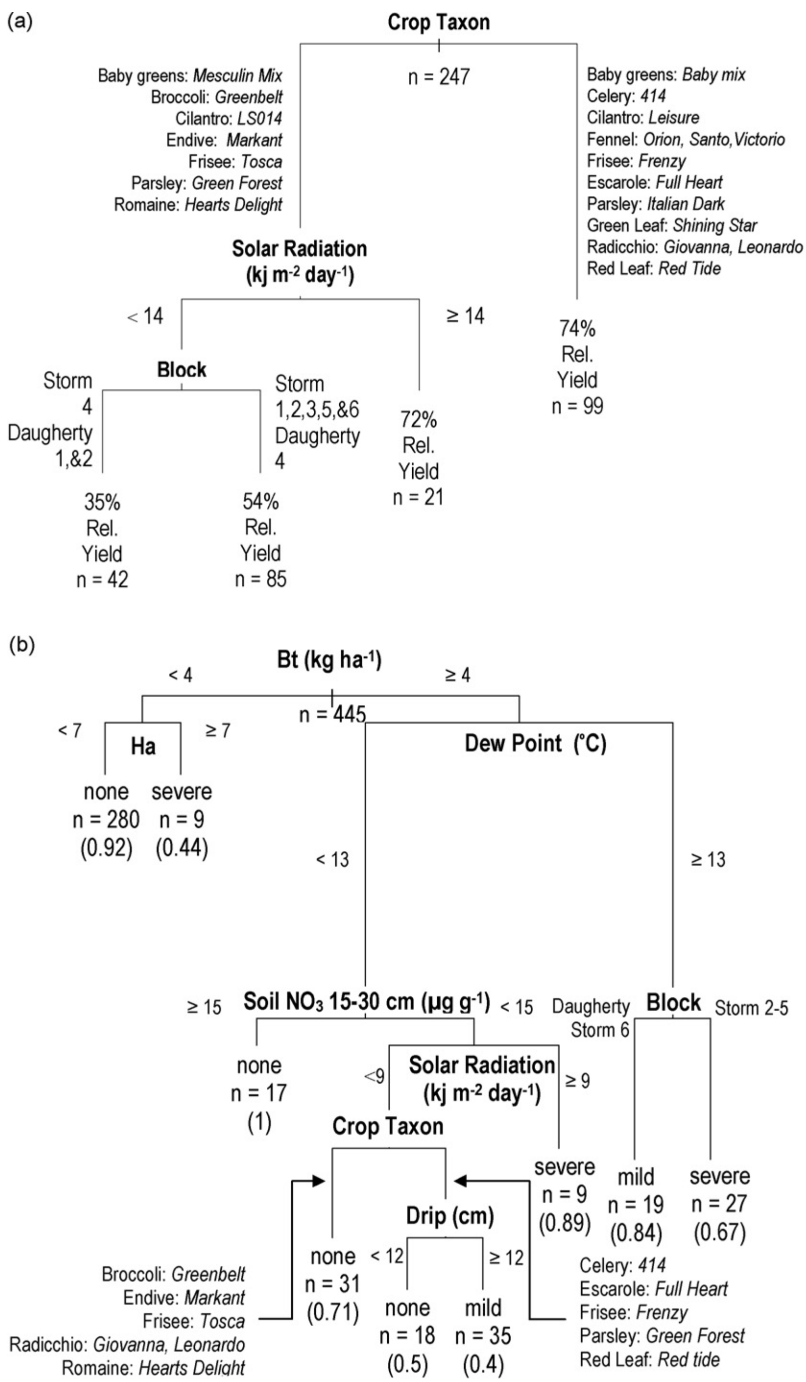

Fig. 7. Classification and regression trees for (a) relative yields of crops, which was the ratio between a sample mean and the maximum observed for a specific taxon and (b) level of insect damage per sample (none, mild or severe). For each split of the tree, the right side indicates the higher value for numerical variables, while categorical variables are listed on each side of the split. For each end point, the mean and number of samples are shown.

through the drip tape increased in the summer and fall seasons but decreased in the spring season over the study period. There were no Biolizer applications during the winter. Mean application rates per crop during the summer were initially 253 L ha^{-1}, i.e., 18 kg N ha^{-1}, increasing in year 2 to 1155 L ha^{-1} and in year 3 to 1580 L ha^{-1}. In the fall season, the crops received 653 L ha^{-1} in year 1, 928 L ha^{-1} in year 2 and 192 L ha^{-1} in year 3. Spring season crops received 1498 L ha^{-1} in year 1, 1336 L ha^{-1} in year 2, and our sampling did not include any spring crops in the third year. All of the Daugherty Ranch and Storm Ranch Block 1 received lower compost application rates, <8.8 Mg ha^{-1} $year^{-1}$, while the other blocks received between 9.2 and 12.7 ha^{-1} $year^{-1}$ (Table 1).

Initially, large quantities of organically certified pesticides were applied in response to crops when outbreaks were imminent or had already occurred, which is much the same strategy as used in conventional agricultural systems. For example, PCAs applied chemicals specific to the target organism as it appeared on the crop. The use of these pesticides declined after the grower found them relatively ineffective at controlling outbreaks (Figs. 2 and 6). In the spring season of the first year, a mean of 109.0 L ha^{-1} of certified organic pesticides were applied, but this declined to 12.1 L ha^{-1} in the second year, and nothing the third (Fig. 6). During the summer season, mean application rates varied from 0.8 L ha^{-1} in year 1, to 69.6 L ha^{-1} in year 2, to 18.7 L ha^{-1} in year 3. The highest application rates were in the fall of year 2 at 134.8 L ha^{-1} but this was not statistically different from application rates in the fall of year 1.

Bt was used in response to pest pressure from various lepidopteran larvae, as well as a preventative application measure. In the fall and summer seasons, application rates increased from year 1 to year 2, and then decreased in year 3 (Fig. 6). In the fall season, applications were 1.9 kg ha^{-1} in year 1, 10.1 kg ha^{-1} in year 2, and then decreased to 5.8 kg ha^{-1} in year 3. Summer applications of Bt were 0.3 kg ha^{-1} in year 1, 7.0 kg ha^{-1} in year 2, and 2.0 kg ha^{-1} in year 3. Spring season applications decreased from 11.3 kg ha^{-1} in year 1 to 1.3 kg ha^{-1}in year 2 ($P < 0.0001$).

3.5. Linking management and crop responses

Recursive regression trees were used to explore the relationships among relative yields of crop taxa (excluding cover crops) and management. CART was run with all 32 variables but the tree was constructed using only seven variables after pruning to a cross-validation error of 0.75. Most of the variation in relative yield can be explained by crop selection as indicated by the relative length of the vertical bars in Fig. 7a. The red leaf and green leaf lettuces had higher relative yields than romaine. Cultivars also showed different levels of performance, e.g., for baby greens, cilantro, frisee, and parsley. The crop taxa to the right of the initial split had relative yields of 74% ($n = 99$). The crop taxa on the left split on solar radiation; for crops receiving ≥14 kJ m^{-2} day^{-1}, relative yield was 72% ($n = 21$). For lower radiation values, the tree split on management block. For those crops grown at Daugherty Ranch Blocks 1 and 2 and Storm Ranch Block 4, relative yields were 35% ($n = 42$), while those grown at Daugherty 4, Storm 1, 2, 3, 5, and 6, were 54% ($n = 85$).

CART was also used to explain the variation in severity of insect damage to crops (Fig. 7b). The tree was developed using 445 samples (59 samples were not used due to incomplete data) and 38 variables. This tree was pruned to a cross-validation error of 0.2, producing eight nodes. The tree split first on Bt application rate, a factor that explained a relatively small amount of the overall variance as indicated by the short length of the vertical line. Note that the average application rate during the transition was 3 kg ha^{-1}. The majority of the samples (289) received Bt applications <4 kg ha^{-1}, and based on the next split of the tree, no insect damage occurred in most of these crops. The exception was a very few instances when large plantings >7 ha suffered severe damage; these were all legume mix cover crops with damage from leaf miners and aphids. To the right side of the tree are crops that received ≥4 kg ha^{-1}, and for which the tree split on dew point. Higher dew point (>13 °C) and thus higher relative humidity, was the main factor that contributed to insect damage, as shown by its long vertical line. Under these moister conditions, the central portion of the Storm Ranch (Blocks 2–5) was more likely to experience

Table 4
Mean initial values for soil parameters in the 0–15 layer, taken in June, 2000

Soil parameters	Daugherty Ranch		Storm Ranch	
	Time 0	Year 3	Time 0	Year 3
C (mg g^{-1})	17.62 ± 1.37	16.59 ± 1.1	18.13 ± 0.73	19.66 ± 0.6
N (mg g^{-1})	1.89 ± 0.10	1.69 ± 0.1	1.74 ± 0.05	1.74 ± 0.0
Olsen P (mg kg^{-1})	134.79 ± 5.58	88.69 ± 5.5	72.37 ± 1.54	65.68 ± 2.1
K (mg L^{-1})	24.09 ± 2.67	17.80 ± 1.2	27.44 ± 1.49	24.80 ± 1.3
EC (μS cm^{-1})	462.00 ± 31.95	385.56 ± 11.6	521.53 ± 23.67	407.58 ± 8.6
pH	7.31 ± 0.10	7.77 ± 0.1	7.89 ± 0.04	8.06 ± 0.0
Sand (%)	–	18.06 ± 1.7	–	30.22 ± 2.3
Silt (%)	–	54.56 ± 0.5	–	46.19 ± 1.4
Clay (%)	–	27.39 ± 1.6	–	23.58 ± 0.9

Nine samples were composited per management block ($n = 9$ and 18 for the Daugherty and Storm Ranches, respectively).

severe insect damage than the Daugherty Ranch or the edge of the Storm Ranch (Block 6). For crops grown during a period when the dew point was <13 °C ($n = 110$), a complex set of factors influenced insect damage (Fig. 7b). Lower dew point, high solar radiation, and higher drip irrigation were factors that increased pest damage especially for certain taxa, based on the subsequent splits of the tree. The role of soil NO_3^--N at 15–30 cm depth is more difficult to explain, and it may be an associated rather than causal factor, as samples taken in year 1 were much higher in NO_3^--N, and this coincided with a long period of low insect damage (Fig. 2).

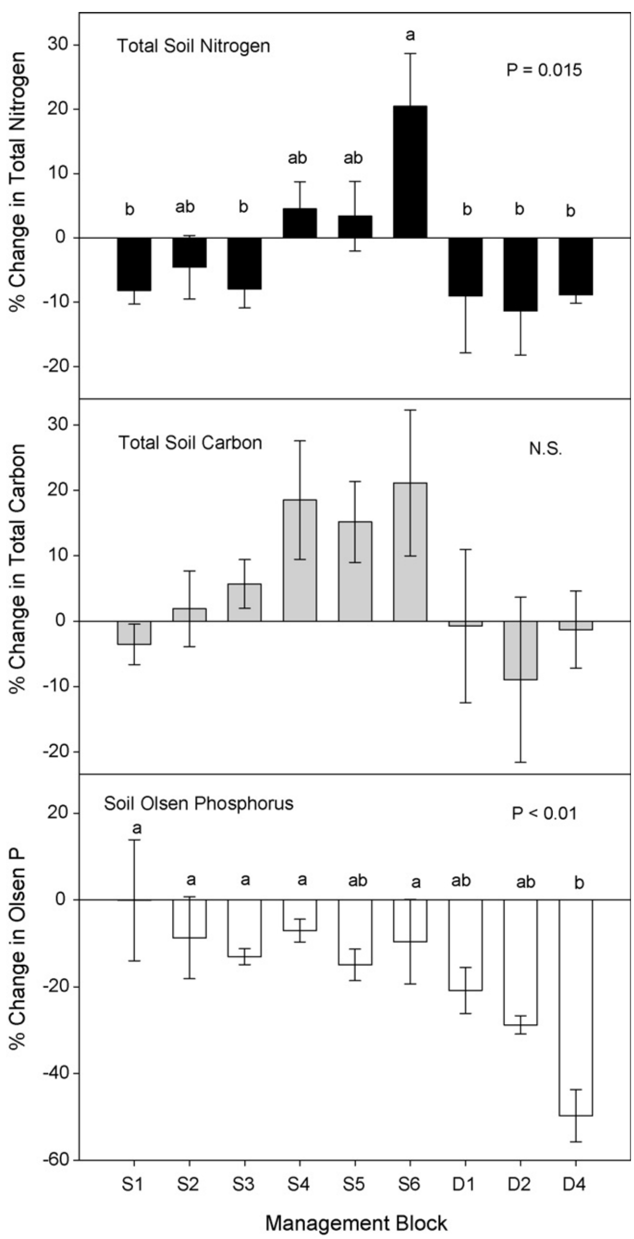

Fig. 8. Percent change in total soil C and N, and Olsen P by management block after 2.75 years of organic transition ((year 3 values − time 0 values)/time 0 values). ANOVA tested for differences among management blocks on the two ranches. Different letters indicate significant differences at $P < 0.05$. Mean ± S.E.

3.6. Changes in soil properties

The initial values of soil properties at the 0–15 cm depth are shown in Table 4. For total soil C or N, there were no differences between the mean values of the two ranches at the onset and the end of the transition period (data not shown). Across both ranches, mean Olsen P decreased from 93.3 to 73.4 mg P kg^{-1} soil ($P < 0.001$), soluble potassium from 26.3 to 22.5 mg K kg^{-1} soil ($P = 0.0012$), EC from 502 to 400 μS cm^{-1} ($P < 0.0001$), while pH increased from 7.69 to 7.96 ($P < 0.0001$). Table 4 shows means values for each ranch separately.

The magnitude of the changes in soil properties depended on the management block (Fig. 8). Total soil N in Block 6 at the Storm Ranch increased by 20% from 1.47 to 1.77 mg N g^{-1} soil, while other management blocks decreased between 8% and 11%. The changes in total soil C were not significantly different among blocks. For only Storm Blocks 4 and 6, total soil C increased between time 0 and year 3 (t-tests, $P = 0.04$). Soil Olsen P at the Daugherty Ranch decreased as much as 50% from the beginning to the end of the transition period. Block 4 at the Daugherty Ranch decreased from a mean of 147.8 to 73.4 mg P kg^{-1} soil, while Olsen P in the Storm Ranch management blocks remained relatively constant.

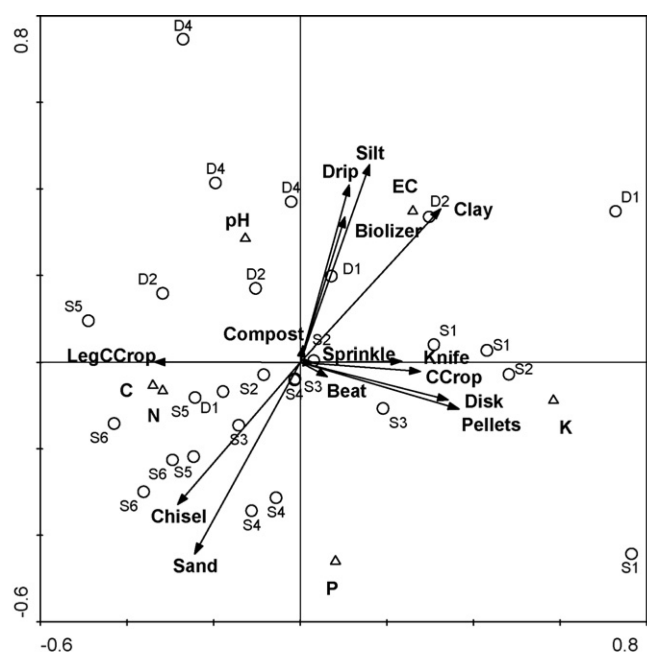

Fig. 9. Biplot for the canonical correspondence analysis (CCA) of the relationship between management practices and changes in soil properties. The dependent variables used for the analysis were the percentage change from the initial (June 2000) to final (March 2003) samples of soil properties at the 0–15 cm depth (Fig. 8). The cumulative variance explained by axis one and two are 67% and 92%, respectively. This model was tested using a Monte Carlo of 499 permutations and was significant for all axes ($P = 0.002$). D and S refer to Daugherty and Storm Ranches, and the associated number refers to each management block. LegCCrop refers to either of the legume mix cover crops and CCrop refers to a non-leguminous cover crop, i.e., Merced rye or brassicaceous taxa.

3.7. Linking changes in soil properties to management

Canonical correspondence analysis (CCA) was used to explore the relationship between management practices and changes in soil properties. The dependent variables used for the analysis were the percentage change from the initial (June 2000) to final (March 2003) samples of total soil C, total soil N, Olsen P, EC, pH and soluble K from the 0–15 cm depth. Independent variables included four types of nutrient applications, two methods of irrigation, four categories of tillage, and three intrinsic soil properties (sand, silt and clay contents) (Table 4). The nutrient applications were the cumulative amount of cover crop biomass (g dry weight 1250 cm^{-2}) that was designated as LegCCrop (legume mixes) and CCrop (non-legume), compost (Mg ha^{-1}), Biolizer fertilizer (L ha^{-1}), and chicken manure pellets (kg ha^{-1}) inputs over the study period in each management block. Tillage categories were defined as *chisel* (includes all deep tillage operations), *disc* (all types of root zone tillage), *knifing* (surface tillage for weed control), and *beating* (all crop pre-incorporation operations).

In the CCA, the first three axes account for nearly all of the cumulative variance (for axis one, two, and three, respectively, 67%, 92% and 97.5%) (Fig. 9). This model was tested using a Monte Carlo of 499 permutations and was significant for all axes ($P = 0.002$). Along the first axis there is a clear separation of higher total soil C and N on the left side of the biplot and higher soil K on the right side, which is associated with higher amounts of chicken manure pellets, more surface tillage (*knifing* or *disc*) and non-leguminous cover crops. On the second axis, the biplot shows higher soil P on the lower side, and pH and EC on the upper side. The CCA biplot implies that changes in pH and EC are driven largely by higher silt, Biolizer fertilizer and amounts of drip irrigation. Higher Biolizer inputs and drip irrigation amounts are strongly associated with silt content, and with certain blocks at the Daugherty Ranch. The Daugherty Ranch received higher Biolizer inputs than the Storm Ranch (Table 1).

Distinct clusters of management blocks can be seen on the biplot as well (Fig. 9). Almost all of the blocks at the Daugherty Ranch are in the upper quadrants associated with higher pH and EC, and lower P. Storm Ranch Blocks 1 and 2 are associated with higher K, while Blocks 5 and 6 are associated with higher total soil C and N.

4. Discussion

The transition from conventional to organic production was successful at a large-scale even in a region dominated by conventional agriculture. Tanimura and Antle, Inc. used some of the principles of organic farming (e.g., crop diversity, crop rotation, organic matter management) at an industrial scale. But they also showed a heavy reliance on substitution-based organic management, specifically, fertigation with soluble nutrients, initially heavy applications of organic pesticides, and use of off-farm-derived inputs such as compost and manure. Management practices over the transition period showed a distinct learning curve in relation to both nutrients, i.e., increased soluble fertilizer additions, and pest management, i.e., decreased use of organic pesticides. Overall, management resulted in improved soil biological indicators, generally adequate plant available N with reduced soil NO_3^--N, and a gradual increase in relative yields with time. These results demonstrate that some of the strategies that were developed by small-scale organic producers can be applied to larger-scale production to achieve a more sustainable agricultural intensification, which has far reaching implications as the demand for organic production increases.

4.1. Crop taxa and performance

High diversity in crop taxa was maintained during each summer of the transition period. One goal was to ecologically diversify the farm in order to minimize pest outbreaks, and to allow different crop rotations that would facilitate cover cropping each year. Organic farming has widely adopted the concept that biological diversity provides ecological functions, such as pest control and soil fertility, that reduce the need for synthetic, off-farm inputs (Pimentel et al., 2005). Although ecologists still debate the processes and situations in which such biodiversity functions occur (Swift et al., 2004; Balvanera et al., 2006) many organic growers heed the concept often in a trial-and-error fashion. For example, the legume mix/Merced rye cover crop mixtures in the fall/winter of the first year had high weed densities and insect damage, and in the second year, the grower switched to the faster-growing, more weed-supressive Merced-Rye, when it was apparent that crops had adequate N supply even with low soil NO_3^--N concentrations.

Merely adding more species to most agroecosystems has little effect on function, given the redundancy in many groups of taxa (Swift et al., 2004). Instead, agricultural biodiversity is most likely to enhance ecosystem functioning when a unique or complementary effect is added to an ecosystem, e.g., supporting more parasitoids or insect enemies with specific roles in controlling pests (Altieri and Nicholls, 2003; Tscharntke et al., 2005), or including a plant functional group, such as a legume or a cover crop/trap crop, that increases N inputs and/or cycling (Drinkwater et al., 1998; Jackson et al., 2004). Although these types of relationships are difficult to measure, especially across an entire farmscape, many organic growers manipulate plant species richness and evenness within the constraints of managing supply for market demand, as one of the main sets of allowable tools for farm management (Fuller et al., 2005; Zehnder et al., 2007).

A second goal of managing crop diversity was risk management. The grower specifically planted crops that he thought would be less susceptible to insect pests or disease, such as baby lettuces that have a short growth period, or cilantro or fennel for which his experience showed low susceptibility to insect pressure. Three of the typically conventionally grown, cool-season taxa, cauliflower, crisp-head lettuce, and spinach, were not grown during the transition period, mainly because they presented more difficult problems for fertility (cauliflower (Xiao et al., 1998)), and pest control, especially downy mildews, *Bremia lactucae* on crisphead lettuce (Grube and Ochoa, 2005) and *Peronospora farinosa* f. sp. *spinaciae* on spinach (Irish et al., 2003).

Small plantings of many different crops would preclude a massive failure, e.g., from pests or low fertility, especially during a transition period when growing conditions are relatively unknown. As the CART analysis showed, some crops and varieties were more likely to have higher relative yields than others and this was spatially variable, i.e., lower yielding taxa did worse in three of the management blocks. The contingency tables also showed clear differences in damage between crops, and those that had high incidences of insect damage particularly in year 2, were not grown again, while others had consistently low incidence of insect damage throughout the transition (Table 1). Planting more taxa alleviates the risk that might have occurred if only the low-yielding taxa had inadvertently been planted. For non-crop species, higher plant diversity decreases the temporal variance in productivity (Tilman et al., 2006) supporting the theoretical concept that biodiversity can safeguard against high variance in productivity (Yachi and Loreau, 1999). For crops, there is clearly a benefit to larger planting sizes in terms of economy of scale and simplicity of management, especially when the specific benefit of diversity is not obvious. These tradeoffs appeared to change through time, as the number of plantings per hectare decreased by half in year 3 compared to year 1. Overall, planting many taxa, including different varieties of the same species, in small plantings at staggered intervals, appears to have been an effective way to avoid risks from low yields or crop failure initially and allowed the grower to then select a smaller, less diverse, but successful crop mix.

Compliance with market demands was the third goal of maintaining high crop diversity. Small, staggered plantings can compensate for changes in short-term market demands, especially for unusual, non-mainstream crops, since during the transition period, the crops were marketed as conventional produce. For example, endive was disced into the soil at least twice due to lack of market demand. By developing organic production strategies for unusual specialty crops and herbs, e.g., escarole, frisee, and cilantro, the company chose to broaden its base of total products, since organic markets have high demand for these crops, yielding greater stability.

4.2. Pests

These results showed no consistent increase in pest problems in terms of insects, disease, or weeds through the organic transition period. The pests were the same species as are found in local conventional production; there were no new species. The majority (69%) of the production crop samples were either undamaged or only mildly damaged by insects, e.g. the leaf miner tracks on leaves. Few symptoms of leaf and root disease were seen, and 87% and 90% of the samples were visually undamaged, respectively. Our analysis showed that weeds were controlled effectively through mechanical cultivation and other cultural practices (e.g. pre-germination of weeds) particularly hand weeding, although this difficult job raises issues related to human labor (see below). In the Salinas Valley, where pesticide applications are frequent and conventional cool-season vegetables are managed to deal with continual threats by both insects and disease (Wu et al., 2005), we know of no comparable studies that address the frequency of pest and disease incidence across a conventional farmscape on this time frame, as a basis for comparison.

The dew point was the climatic variable, of the nine used, that explained the largest amount of the variation in insect damage (Sehgal et al., 2006) in the CART analysis. The dew point is the temperature which air must cool at a constant barometric pressure for water vapor to condense. A mean daily dew point of $>13\ ^{\circ}C$, which corresponded to a mean relative humidity of 94% at the nearest weather station, indicates very moist air. Relative humidity has been linked to insect survival and to migration patterns in other types of agricultural systems (Berlinger et al., 1996; Boulard et al., 2002; Diaz and Fereres, 2005), and thus may explain the higher insect damage at higher dew points. During periods of high humidity, the CART analysis showed that management blocks that were more completely bordered by residential areas or conventional production, i.e., Storm Ranch Block 6, and the Daugherty Ranch (Fig. 1), had lower incidence of pest damage than those in the central area of the Storm Ranch (Blocks 2–5). The dew point was measured at a weather station several kilometers away, but even so, the $>13\ ^{\circ}C$ dew point may be an estimate of threshold value at which to expect higher pest damage on these ranches.

Solar radiation also was associated with higher damage from insect pests, based on the CART analysis, but only in nine instances, and only when dew point was $<13\ ^{\circ}C$. During periods of higher solar radiation, higher temperatures would cause insects to be more active, inflicting greater damage to crops (Bale et al., 2002).

Management factors were shown to be less important for insect damage in the CART analysis. Higher irrigation increases herbivory in grapes (Daane and Williams, 2003) and soybean (Lambert and Heatherly, 1995), while in other crops the relationship is not as clear, such as with barley where specific insect pests increased with water stress while other pests decreased (Oswald and Brewer, 1997). Nitrogen availability might have been expected to increase herbivory (Mattson, 1980; Letourneau, 1997), but any association between low soil NO_3^--N and higher pest damage is likely coincidental, as described above.

Bt applications, a common tool to deal with lepidopterous larval herbivory in organic systems (Zehnder et al., 2007), were used intensively in the middle of the transition period. This was a period of high insect damage, suggesting little impact of the applications, but impossible to evaluate with our sampling regime. According to the grower, the use of Bt and other organic insecticides was determined to be relatively ineffective, and after the second year, they minimized these applications. Other organic sprays were heavily used at this time as well, but also declined after local extension workers discovered that beneficial syrphid flies decreased and aphids increased after applications (R. Yokota, personal communication). A complex of syrphid species are involved in suppressing lettuce aphid (*N. ribisnigri*) and other aphid pests of organic lettuce in the Salinas Valley (Smith and Chaney, 2007).

Downy mildew of lettuce, the most important foliar problem in both organic and conventional production, was not effectively controlled by sprays. The CART analysis indicated that greater precipitation was a key distinguishing factor for leaf disease damage in this study (data not shown). For root disease damage, a CART analysis showed that high relative humidity was also a main explanatory variable (data not shown) for positive incidences. In both CART analyses, few other factors had discernible effects, suggesting that either humid weather appeared to explain much of the variation in disease, or that different diseases responded in opposing ways to the set of factors that were included.

Weeds were the most stable and predictable pests, as indicated by generally similar frequency and biomass across crops and years. The exception was the high weed density in the legume mix cover crop, which probably resulted from slow legume growth in the fall, and was less evident in the legume mix/Merced rye mix cover crop which shaded the soil surface more quickly (Brennan and Smith, 2005; Riesinger and Hyvonen, 2006). Weeds are tolerated more easily in the larger crops such as lettuces and endive than in baby greens, where weeds need to be removed prior to mechanical harvest. Although weeds were effectively controlled throughout the transition, it is well documented that the switch from chemical-based weed control to hand hoeing and increased tillage can increase cost of production substantially (Clark et al., 1998; Abu-Hamdeh and Abu-Qudais, 2001; Tourte et al., 2004), and weed control typically requires high management effort by organic farmers (Park and Lohr, 2005).

4.3. Soil quality

During the 3-year transition period, soil quality (NRCS, 2007) generally increased, based on trends toward increasing MBC, greater mycorrhizal root colonization, and the provision of a generally adequate supply of macronutrients to crops with less potential loss of NO_3^--N and P, due to lower soil concentrations.

Only a slight increase in total soil C and N would be expected in 3 years, compared to a much larger relative increase for labile C pools such as MBC (Jackson et al., 2004). More time is required for intensively managed soils in California to sequester total C with similar inputs of organic matter (Six et al., 2002; Kong et al., 2005). Some blocks (Storm Ranch Blocks 4–6), tended to show higher increases in total soil C and N. These blocks also had the coarsest soil texture and some of the lowest initial values for total soil C and N (data not shown) which suggests that these soils were most responsive to the higher inputs of organic matter *via* compost and cover crops, despite their lower clay content (Plante et al., 2006). The increase in total C in Storm Ranch Blocks 5 and 6 may have been driven by the legume cover crop in the first year, and others have shown that soil C storage increases linearly with legume inputs (Kuo et al., 1997).

Higher MBC, potentially mineralizable N, and AM colonization matches other results that have shown increased biological activity in organic farming (Drinkwater et al., 1995; Mader et al., 2002) or transitional systems (Martini et al., 2004). Potentially mineralizable N showed a more steady increase through time than did microbial biomass C, possibly because incorporated organic matter inputs had C:N ratios <20, favoring net N mineralization (Silgram and Shepherd, 1999). Cover crops typically had C:N ratios ≤ 20, based on their N content and previous studies (Wyland et al., 1996; Lundquist et al., 1999; Jackson, 2000), the compost C:N averaged 18 (Jackson et al., 2004), and the C:N of the chicken manure is typically 10 (Khalil et al., 2005).

The low NO_3^--N concentrations, and high NH_4^+-N/NO_3^--N ratios suggest soil processes that increased the cycling of organic N through microbial N transformations and efficient plant N uptake. Gross rates of N mineralization and nitrification were approximately two times higher in organic than conventional tomato systems in California's Central Valley (Burger et al., 2005), despite similar concentrations of NH_4^+-N and NO_3^--N. Although the Biolizer fertilizer, which includes NH_4^+-N and both water-soluble and -insoluble organic N, was applied at much lower rates than the applications of inorganic N fertilizer (150–350 kg N ha^{-1} $crop^{-1}$) in conventional Salinas Valley production systems, it was applied through drip to the zone of highest root length density (Mmolawa and Or, 2000). This is more efficient than the usual practice of banding fertilizer and applying furrow or sprinkler irrigation, which distributes NO_3^--N into soil zones with lower root length density (Jackson and Bloom, 1990). Low NO_3^--N at 0–30 cm depth however suggests that leaching to deeper layers may have been minimal, unlike conventional fields (Jackson et al., 1994).

The decrease in Olsen P is most likely due to cessation of preplant applications of phosphate (PO_4^{3-}), e.g., 336 kg ha^{-1} of 5:25:25 fertilizer per crop, i.e., 36 kg P ha^{-1}, 1, were applied conventionally on the Daugherty Ranch (Jackson et al., 2004), compared to the combined inputs from Biolizer and pelleted chicken manure of 11 kg P ha^{-1} per crop. The initial mean level of Olsen P (94 mg kg^{-1} soil at 0–15 cm depth) across the ranches exceeds the recommended environmental limits (Sharpley et al., 2001), as do many soils under conventional production in the Salinas Valley (Johnstone et al., 2005) (Bray P was similar at 116 mg kg^{-1} soil (data not shown)). Other studies have shown that organic and conventional systems either had similar runoff and leaching losses of PO_4^{3-} (Sileika and Guzys, 2003), or that conventional systems were lower than either green manure- or animal manure-based organic systems (Aronsson et al., 2007). Despite the high levels of soil available P at these two ranches, the shoot tissue content was below MRM critical values in three crops (broccoli, endive and escarole), suggesting that OM interactions (Varinderpal-Singh et al., 2006) or some other factor, limited crop P uptake.

The addition of different materials may have ensured a gradual nutrient supply, as well as decreased the P applied simply to provide N, as can occur when manure is the main or only fertilizer source (Schoenau and Davis, 2006). Based on the CCA, the main factor affecting EC was the level of Biolizer application rather than pelletized manure (2.5–2–2.5), which instead was associated with higher soil K. The combination of soluble fertilizer, manure, and more recalcitrant inputs of compost and green manures clearly met plant requirements and increased soil quality, a nutrient management strategy that may be applicable to both conventional and organic producers at various scales.

4.4. Management implications

Tanimura and Antle, Inc. utilized many of the biologically based management strategies outlined in the National Organic Program (USDA, 2007): compost applications, cover crops, crop rotations and diversified plantings. They also employed capital-intensive operations that meet the organic standards, such as installation of drip irrigation, recovery, and recycling of the drip tape each season. The organic-soluble nutrients that are applied through subsurface drip lines are more expensive than the equivalent amount of N supplied as manure. Hand hoeing was an expensive but effective way to control weeds, although even the legislated long-handled hoes can cause worker stress. Organically approved pesticides were at times applied heavily, with little apparent efficacy. Neither the financial costs nor the profits were provided by the grower, so the actual tradeoffs between alternative management strategies cannot be calculated. Immediate financial returns of a specific ranch are not the only consideration. By expanding the product base, the company could meet the growing demand of markets that sell both conventional and organic produce, and thereby increase total sales and profits. In addition, worker safety poses fewer risks, compared to their conventional production, since there is no exposure to toxic pesticides.

This research raises several questions for which processes are not well-understood, but which would facilitate organic transition:

- Why do some varieties of certain crops perform better than others?
- Why is high soil P availability associated with marginally adequate P content in some crops, and how can soil P be decreased to avoid environmental losses?
- How can spatial heterogeneity in soils and microclimate be compensated for by management inputs and planting design?
- How can planting sizes be planned for increasing ecological functions, e.g., for cash crop rotations, cover crops, and pest control, and also maintain an economy of scale that increases profits?
- What are the criteria for product success in terms of yield, pest damage, and nutrition, and how do short-term market demands change these criteria?

4.5. Research approach

In terms of approach, choosing an additional set of rough survey variables, or using a preliminary subset of data, would have been valuable. The large numbers of samples could not be processed rapidly enough to give information to the grower within the growing season. Many people were involved in the project, such as company personnel, farm advisers, extension specialists, and students. The sampling for the project gradually became more centralized, but this took time to develop. Adaptive management clearly occurred during the transition period, but would have been facilitated by more rapid data analysis and transfer. Switching from synthetic to biologically based nutrient management often will cause a decline in yields until SOM accumulates, or until the grower learns to manage the new system appropriately (Macrae et al., 1990). This was not the case here. We cannot evaluate the economic success of the transition, but the company has expanded its land in organic production, indicating that it is financially profitable.

5. Conclusion

Organic production, as practiced here, may have the potential to sustainably intensify agriculture on a much larger scale. This study demonstrates the feasibility of large-scale operations to transition to organic practices using methodologies traditionally employed by small-scale organic farmers such as cover cropping, crop rotations, small planting sizes, and diversity of plantings to increase soil quality and minimize pest pressure. Of course, there are many tradeoffs for agricultural production, environmental quality, and social well-being that cannot be assessed here. Most evident are the positive implications for environmental quality if organic agriculture were adopted on a larger scale. In Monterey County in 2005, 3821 Mg of organically approved and conventional synthetic pesticides were applied to 631,749 ha of farmland (CDPR, 2007) and much of the waterways and groundwater in the Salinas Valley are contaminated with either synthetic pesticides (Anderson et al., 2003) or nitrate (Vengosh et al., 2002). From 2003 to 2006, the area of farmland in organic production in Monterey County increased from 5447 to 7024 ha, a constant percentage of the county's farmland (6%). The farmgate value of this production increased from 4% to 6% of the total during that same period (Agricultural Commissioner, 2006). If more land was converted from conventional farmland, there would be substantial reduction in synthetic pesticide use. Even if the area of organic farms does not greatly increase, many of the practices employed in this transition to organic production are transferable to conventional production, and if adopted, could set the stage for greater sustainability of agricultural production.

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