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Nitrogen, weeds and water as yield-limiting factors in conventional, low-input, and organic tomato systems

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Abstract

The importance of nitrogen (N), weeds, and water as yield-limiting factors was evaluated over a 4-year period in tomato cropping systems under conventional, low-input, and organic management. The cropping systems studied were part of the Sustainable Agriculture Farming Systems (SAFS) Project at the University of California, Davis, a comparison of conventional and alternative farming systems in California's Sacramento Valley. Water applied, soil N levels, plant N uptake, weed abundance, and tomato yield were measured and compared among treatments. Tomato yields ranged from just under 55 to over 90 t ha^{-1} and significant treatment differences were observed in 2 of the 4 years. Multivariate analyses, used to sort out the effects of N, weeds, and water, indicated all three factors influenced yields in this study but their relative importance was dependent upon the management system. Results indicated that N availability was most important in limiting yields in the organic system and water availability was more important under conventional management. Although weed abundance was relatively high in the organic system in 2 years of the study, weed competition for N was not evident. Instead, relative N input levels and N immobilization by soil microflora appeared to explain N uptake and tomato yield variation. The findings indicate that organic and low-input tomato systems in this region can produce yields similar to those of conventional systems but that the factors limiting yield may be more difficult to manage.

Keywords: Organic agriculture; Low-input agriculture; Tomato; Nitrogen; Weeds; Water; California

1. Introduction

Modern industrial agriculture is dependent upon synthetic N fertilizers and pesticides for high crop productivity. In some areas, particularly arid and semi-arid regions, water supplied by irrigation systems is also a necessity. The purposes of these inputs are to ensure adequate nutrient and water availability to crops while suppressing potential competitors for the crops or added resources, primarily weeds, insects, and pathogens, in order to maximize yields. The effects of input reductions on crop yields have been fiercely debated (Loomis, 1984; Loomis and Connor,

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1992; Pimentel et al., 1993; Bender, 1994; Knutson et al., 1994; Vandermeer, 1995; Avery, 1997; Hitzhusen and Davis, 1997) and there is considerable interest in finding means to reduce fertilizer and pesticide dependence while maintaining crop yields.

Alternative approaches to agriculture, including organic and low-input practices, have emerged in response to concerns over environmental degradation, natural resource consumption, human health risks, and rural economic decline associated with industrial agriculture. Alternative agricultural systems are typically based on a blend of traditional practices and ecological principles which allow for the reduction or elimination of synthetic chemical inputs. Although the kinds of alternative systems range widely from those based on modern scientific knowledge to those integrating elements of spirituality, the underlying strategy is to manage agroecosystems in such a way that they more closely resemble unmanaged ecosystems in both structure and function (e.g. tighter nutrient cycling and greater biodiversity).

Ecological comparisons of conventional and alternative agricultural systems have found fundamental differences in biological, chemical, and physical characteristics which may directly or indirectly affect crop productivity and yield (Reganold et al., 1993; Drinkwater et al., 1995). Consequently, studies evaluating the effects of alternative farming systems on crop yields by simply reducing or eliminating industrial inputs in otherwise conventionally-managed systems may not accurately represent conditions occurring in alternatively-managed agroecosystems. Complex interactions and feedback among soil, crops, pests, and inputs necessitate empirical systems analysis.

This study is based on research from the Sustainable Agriculture Farming Systems (SAFS) project at the University of California, Davis, a long-term comparison of conventional and alternative farming systems (Temple et al., 1994). The objective was to assess the relative importance of N availability, weed competition, and water application on yields of processing tomato managed with conventional, low-input, and organic practices. Previous research at the SAFS site indicated that N deficiency was a problem under organic management because of inadequate mineral N from organic sources (Scow et al., 1994; Cavero et al., 1997). Other research at this site also indicated that among the major pest classes (arthropods, weeds, pathogens, and nematodes), weeds were the only group associated with crop yield reduction (Clark et al., 1998a). In this study, the effects of nitrogen, weeds, and water on crop yield were compared with multivariate analyses and the relative importance of these factors assessed within the context of agricultural management and sustainability.

2. Materials and methods

2.1. Study site

The SAFS project was established on an 11.3 ha site (380°32′N, 121°47′W; 18 m elevation) in 1988 to study agronomic, biological, and economic aspects of conventional and alternative farming systems in California's Sacramento Valley. The region has a Mediterranean climate with most rainfall occurring during the winter months (December–March) and relatively little during the growing season. Total annual rainfall is typically 400–500 mm and daytime temperatures during the growing season average 30–35°C. Soil at the site is classified as Reiff loam and Yolo silt loam.

The major crops of the region, based on area planted, are rice (*Oryza sativa* L.), wheat (*Triticum aestivum* L.), processing tomato (*Lycopersicon esculentuin* Mill.), corn (*Zea mays* L.), and safflower (*Carthamus tinctorius* L.). Furrow irrigation is used for most crop production, though winter cash crops, such as wheat, and cover crops can get most necessary moisture from precipitation.

The SAFS project consists of four experimental treatments that represent farming systems differing primarily in crop rotation and use of external inputs. The treatments include a conventionally-managed, 2-year rotation (CONV2) and 4-year rotations under conventional (CONV4), low-input (LOW), and organic (ORG) management. The CONV2 treatment is a tomato and wheat rotation. The three, 4-year rotations are processing tomato, safflower, corn and bean (*Phaseolus vulgaris* L.). In the CONV4 treatment beans are double-cropped with winter wheat and in the LOW and ORG treatments beans follow a winter-grown mixture of oats (*Avena sativa* L.) and purple vetch (*Vicia benghalensis* L.) which is either harvested for seed, cut as hay, or incorporated as green manure. Cover crops (legumes or legume–grass mixtures) are grown during the winter preceding all other cash crops in the LOW and ORG systems but not in the conventional systems. Wheat in both conventional rotations is planted in the autumn and harvested in the following summer.

There are four replications of each farming system treatment and all possible crop-rotation entry points are represented, resulting in a total of 56, 0.12 ha plots, arranged in a randomized-block, split-plot design. In each year, 16 plots are planted to tomato.

All farming system treatments use 'best farmer management practices' which are determined through consultation with farmers and farm advisors cooperating on the project (Temple et al., 1994). The CONV4 and CONV2 treatments are managed with practices typical of the surrounding area, which include the use of synthetic fertilizers and pesticides. Decisions to use pesticides in these treatments are based upon common practices in the area as well as University of California integrated pest management (1PM) guidelines. In the LOW system, fertilizer and pesticide inputs are reduced primarily by using legume cover crops to improve soil fertility and mechanical cultivation for weed management. The ORG system, managed according to the regulations of California Certified Organic Farmers (CCOF), uses no synthetic chemical pesticides or fertilizers. Instead, management includes the use of cover crops, composted animal manure, mechanical cultivation, and limited use of CCOF-approved products (CCOF, 1995). Management in all systems is therefore dynamic, responding to agronomic, economic, social, and environmental factors. In this study, tomato crop yields from 1994 to 1997 were related to N, weed, and water management in the four treatments.

2.2. Tomato management

During the 4 years of this study tomatoes in all farming systems were grown on 1.52 m wide beds and furrow-irrigated. Planting in the CONV2 and CONV4 systems was by direct seeding and the ORG and LOW systems used transplants to extend the cover crop growing season, thereby increasing nitrogen fixation, and provide some advantage over weeds (Table 1). Tomato plots were sprinkler-irrigated immediately following direct seeding or transplanting and furrow-irrigated throughout the rest of the season. Furrow irrigation was done on an 'as-needed' basis throughout the season in all treatments. Although the amount of irrigation water applied depended largely on evapotranspiration rates, water needs were determined by the farm manager by visual monitoring of the plants and soil. In general, 1–3 sprinkler irrigations and 8–9 furrow irrigations were conducted during the growing season. During each furrow irrigation, water was allowed to fill the furrows to the tops of the beds before being shut off. Thus, the amount of irrigation water applied also depended upon infiltration rates into the soil; faster infiltration rates led to more water being applied. Therefore, soil management had an indirect effect on water use. Generally, 40–100 mm of water were applied to a plot during a single furrow irrigation.

The CONV2 and CONV4 tomato systems received N as urea and/or ammonium nitrate at about 170 kg N ha^{-1} per year. Most of this was applied as a side-dressing 6–8 weeks after planting. In the LOW system, fertilizer use was reduced to about 95 kg N ha^{-1} per year by using legume cover crops. The ORG system did not receive synthetic fertilizer inputs. Instead, aged or composted poultry manure, applied at 7–9 t ha^{-1} (dry weight), and cover crops were used (Tables 1 and 2). Vetch (*Vicia* spp.) was used as the legume cover crop in the ORG and LOW systems, but weeds often comprised a relatively large proportion of the cover crop biomass before incorporation into the soil. Consequently, the amount of N in the aboveground biomass depended heavily on the relative abundance of vetch and weeds. The N supplied by the cover crops was therefore a combination of biologically-fixed N and residual mineral N taken up by the vetch and weeds. The N content of the cover crops in the ORG and LOW systems at the time of incorporation ranged from 2.2 to 3.9% (Table 3), supplying 67–148 kg N ha^{-1} per year (Table 2).

Weeds were managed in the CONV4 and CONV2 systems with herbicides, cultivation, and hand hoeing. The conventional systems received 1–3 herbicide applications and 3–4 cultivations each season. At least one herbicide application was used before tomato planting and additional applications were used after tomato plant establishment as necessary. Cultivation was accomplished using a rolling cultivator and tractor-mounted toolbar with sweeps and knives. Hand

Table 1
Summary of production practices in the four tomato production systems, 1994–1997

Practice	Organic	Low-input	Conventional
Cultivar	'Brigade'	'Brigade'	'Brigade'
Planting method	Transplanting	Transplanting	Direct seeding
N fertility management	Aged or composted poultry manure, legume over crops	Legume cover crops, urea, ammonium nitrate	Urea, ammonium nitrate
Weed management	Cultivation, hand hoeing	Cultivation, hand hoeing, reduced herbicide use	Herbicides, cultivation, hand hoeing

Table 2
Nitrogen inputs (kg ha^{-1}) to the organic, low-input, and conventional (2- and 4-year rotations) tomato systems from manure, cover crops, and synthetic fertilizer, 1994–1997

Year	Source	Organic	Low-input	Conventional
1994	Manure	114	0	0
	Cover crop[a]	108	108	0
	Fertilizer	0	104	172
	Total	222	212	172
1995	Manure	119	0	0
	Cover crop	81	67	0
	Fertilizer	0	104	183
	Total	200	171	183
1996	Manure	439	0	0
	Covercrop	116	136	0
	Fertilizer	0	73	136
	Total	555	209	136
1997	Manure	226	0	0
	Cover crop	148	81	0
	Fertilizer	0	97	179
	Total	374	178	179
	Average total	338	193	168

[a] N in aboveground biomass; includes vetch and weeds.

Table 3
Nitrogen and carbon content and C : N ratios of manure and cover crops used in the organic and low-input systems, 1994–1997

Year	Organic system					Low-input system	
	Manure		Cover crops		Total	Cover crops	
	%N	C/N	%N	C/N	C/N	%N	C/N
1994	3.7	5.4	2.2	18.2	11.6	2.2	18.1
1995	2.7	7.6	1.8	21.7	13.3	2.2	14.9
1996	2.3	15.4	2.5	15.8	15.5	3.7	10.8
1997	2.8	11.3	3.9	10.2	10.8	2.2	18.3

hoeing was used later in the season when cultivation was no longer possible or to remove weeds in the crop row which were not eliminated with cultivation. Weeds in the ORG and LOW systems were managed identically from 1994 to 1996 with cultivation and hand hoeing (Table 4). In 1997 an herbicide application was used before planting to reduce hand hoeing costs in the LOW system. Greater use of hand hoeing in the ORG system was economically justifiable because of the premium prices paid for organically-grown tomatoes.

Table 4
Weed management practices and their frequency of use in the organic, low-input, and conventional (2- and 4-year rotations) tomato systems, 1994–1997

Year	Practice	Organic	Low-input	Conventional
1994	Herbicide	0	0	1
	Cultivation	4	4	3
	Hand hoeing	3	3	2
1995	Herbicide	0	0	2
	Cultivation	4	4	4
	Hand hoeing	2	2	1
1996	Herbicide	0	0	2
	Cultivation	5	5	3
	Hand hoeing	1	1	
1997	Herbicide	0	1	3
	Cultivation	4	3	3
	Hand hoeing	4	1	2

2.3. Field measurements

Water applied, soil N levels, plant N uptake, weed abundance, and tomato yield were measured. Water use was monitored with flow meters on the irrigation pipes. In 1994 water use was recorded only at the treatment level; however, from 1995 to 1997 water use was recorded at the individual plot level. Total water applied included all irrigation water used during the growing season and any precipitation (which contributed 5% or less of the total water applied in any year).

Soil mineral N levels were measured in the upper 15 cm of soil, 5–7 times per season each year except in the CONV2, which was not monitored in 1996. At each sampling, 30 soil cores (2.5 cm diameter) were taken from each plot. The soil was mixed thoroughly in a bucket and sieved through a 2 mm mesh screen. An 8 g subsample was placed in a tube with 40 ml of 2 M KCl for extraction of NO_3^-; and NH_4^+. The sample tubes were taken to a laboratory, shaken for 1 h, and the contents filtered through Whatman #2. The samples were then submitted to the University of California's Division of Agriculture and Natural Resources (UC DANR) Analytical Laboratory for determination of NO_3^-; and NH_4^+ concentrations with a diffusion–conductivity analyzer (Carlson, 1978). In addition, 8 g of soil were also placed in 10 ml of deionized water and incubated under anaerobic conditions for 1 week at 38°C. The NH_4^+ generated during this period was extracted and analyzed as described above to provide a measurement of potentially-mineralizable N (PMN) (Bundy and Meisinger, 1994). Determination of PMN using anaerobic incubation is considered an indicator of the ability of a soil to supply N (Drinkwater et al., 1996). In each year, soil mineral N (NO_3^-–N and NH_4^+–N) and PMN data for each sampling date were pooled into one of three periods corresponding to three tomato growth stages: early season (plant emergence to first bloom), mid-season (first bloom to first fruit), and late season (first fruit to harvest).

Nitrogen uptake by the tomato plants was monitored with petiole samples taken at first bloom, first fruit, and first color (pink). Twenty plants per plot were sampled by removing the fourth leaf from the growing tip and stripping off all leaflets. The samples were dried at 60°C, ground to pass through a 40-mesh screen of a Wiley Mill, and submitted to the UC DANR Analytical Laboratory for determination of NO; concentration by acetic acid extraction (Johnson and Ulrich, 1959) and diffusion–conductivity analysis (Carlson, 1978).

Weed abundance was monitored with two methods: visual estimation of groundcover and measurement of weed biomass at tomato harvest. Visual estimates of weed groundcover were made monthly and recorded as the percentage of ground covered by weeds. For this analysis, weed percent groundcover in July was used as an indicator of weed pressure, as the tomato crop was not cultivated or sprayed with an herbicide after this time. Aboveground weed biomass at harvest was measured by cutting, drying, and weighing 4–8, 1 m^2-subsamples per plot about 1 week before tomato harvest.

Tomato yields were determined each year using commercial-scale harvesting equipment. The center one-half of each plot was harvested and weighed. Tomato fruit, plant tissue, and weed samples were collected and analyzed for total N by the UC DANR Analytical Laboratory using combustion gas analysis (Pella, 1990a, 1990b).

2.4. Data analysis

Tomato yield and N content, water applied, soil NO_3^-–N and NH_4^+–N, soil PMN (measured as NH_4^+–N,), tomato petiole NO_3^-–N, and weed abundance were compared among treatments graphically and with analysis of variance (ANOVA). The Student-Newman–Keuls test was used for mean separation when significant differences were detected ($P \leq 0.05$). In addition, the amount of water applied was compared with estimated potential seasonal evapotranspiration which was calculated from cumulative daily pan evapotranspiration measurements obtained from a weather station located 0.5 km from the SAFS field site. A seasonal crop coefficient of 0.75 was assumed for evapotranspiration estimates (Doorenbos and Kassam, 1979; Loomis and Connor, 1992). Soil and tissue N measurements were compared with total N inputs and, in the ORG and LOW systems, the C : N ratios of the inputs.

Due to the large number of variables and the presumed high degree of co-linearity between them, the data were then subjected to principal components analysis (PCA) to generate a new set of independent variables. The original variables used for this procedure included: total water applied, soil NO_3^-–N, soil NH_4^-–N, soil NO_3^-–N + soil NH_4^+–N (total mineral N), soil NO_3^-–N : soil NH_4^+–N ratio, soil PMN, petiole NO_3^-–N, weed biomass at harvest, and weed percent groundcover in July. All N-related variables were sub-divided further into the three plant growth stages to account for changes over the growing season. In total, 21 variables were entered into the analysis. The amount of variation explained by the PCs was assessed with the factor loadings of each measurement. Factor loadings > 0.50 were considered significant (Manly, 1994). The PCs were then subjected to stepwise multiple linear regression with tomato yield as the dependent variable. Although crop yield responses to N, weeds, and water are nonlinear when measured across the full range of possible conditions (Loomis and Connor, 1992; Tan, 1993; Liebman and Gallandt, 1997), yield responses in this study were assumed to be linear because all systems were managed for optimal yields and therefore subjected to rather narrow ranges of N and water availability and weed competition. All PCs with eigenvalues > 1 were entered into the stepwise regression procedure and 0.15 was used as the significance level for entry into the model (Everitt and Der, 1996). This analysis was performed on yield data pooled from the four treatments and on yield data for each individual treatment. The relative importance of N, weeds, and water in explaining yield variation in these five data sets was assessed based on the variation accounted for by the PCs in the linear regression equations and the factor loadings on those PCs. All statistical analyses were performed with SAS (SAS Institute Inc., Cary, NC) and SigmaStat (Jandel Scientific Software, San Rafael, CA).

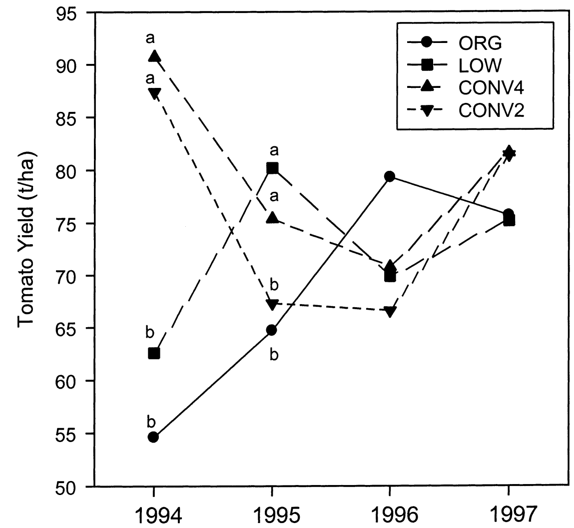

Fig. 1. Tomato fruit yields ($t\,ha^{-1}$ fresh weight) in the four management systems of the SAFS Project, Davis, CA, 1994–1997. Different letters within a year indicate statistically significant differences between systems (ANOVA, Student–Newman–Keuls test; $P < 0.05$).

3. Results

3.1. Treatment effects on yield, water, nitrogen, and weeds

Tomato yields ranged from just under 55 to over $90\,t\,ha^{-1}$ (Fig. 1). Significant treatment differences were observed in 1994 and 1995 but not in 1996 or 1997. In 1994, the CONV4 and CONV2 systems had substantially greater yields than the ORG and LOW treatments. This appeared to be partly the result of a virus (Tomato Infectious Chorosis Virus) transferred to the transplants in the greenhouse before planting. In 1995 tomato yields showed less variability across treatments, and yields in the LOW and CONV4 systems were significantly higher than those of the ORG and CONV2 systems. Yields in 1996 and 1997 averaged 70–80 $t\,ha^{-1}$ across the treatments. In comparison with the CONV2 system, average yields in the CONV4 system were 7% higher during the 4-year period. By contrast, yields in the ORG and LOW systems averaged 9 and 4% lower, respectively, than those of the CONV2 system.

The amount of water applied during the growing seasons ranged from 400 to over 1100 mm (Fig. 2).

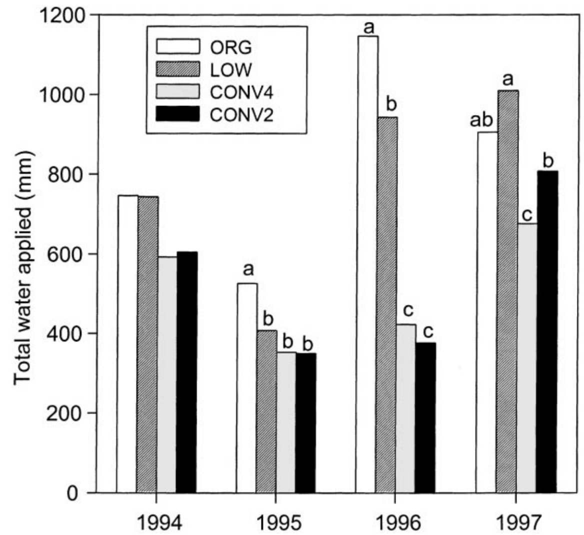

Fig. 2. Total water applied (irrigation + precipitation) in the four management systems of the SAFS Project, Davis, CA, 1994–1997. Different letters within a year indicate statistically significant differences between systems (ANOVA, Student–Newman–Keuls test; $P < 0.05$). Data for 1994 could not be analyzed statistically because data were only recorded at the treatment level.

Although the frequency of irrigation did not differ among treatments, greater amounts of water were applied to the ORG and LOW systems than the CONV4 and CONV2 systems because of greater infiltration rates. Treatment differences were greatest in 1996 when the total amounts of water applied to the ORG and LOW systems were over twice that applied to the CONV4 and CONV2 systems. Water applications in the CONV4 and CONV2 systems were less than potential seasonal evapotranspiration by 80–120 mm in 1995 and 1996 as a result of poor infiltration in the conventionally-managed soils. In 1997, the furrows of the CONV4 and CONV2 systems were ripped with a chisel plough early in the tomato production season to facilitate water infiltration, and water applied exceeded potential seasonal evapotranspiration in all treatments.

In 1994 and 1995, total N inputs were relatively similar among the four tomato systems (Table 2). In 1996, however, the manure application to the ORG system was increased dramatically in an effort to compensate for low soil mineral N levels observed in previous years, resulting in 2.5–4.0 times greater N input in comparison with the other treatments. The manure application to the ORG system in 1997 was reduced somewhat but still resulted in more than twice as much N being applied to the ORG as the conventional systems. Although some of the soil NO_3^-–N and NH_4^+–N patterns observed can be accounted for by N input levels, differences in cover crop and manure C : N ratios, as well as other identified factors, complicate interpretation in the LOW and ORG systems.

Soil NO_3^-–N levels over the four years ranged from less than 5 to nearly 50 mg kg^{-1}. Significant differences among treatments were uncommon and, because of the lack of consistent trends, few generalizations can be made (Fig. 3). The ORG and LOW systems tended to have similar or lower NO_3^-–N levels in comparison with the CONV4 and CONV2 systems from 1994 to 1996. The relatively low soil NO_3^-–N levels in the ORG system during this period, particularly in 1996, suggests that N immobilization occurred despite input C : N ratios of less than 20, the ratio generally considered to be the threshold for net mineralization (Table 3). In 1997, however, the ORG system had significantly higher early season NO_3^-–N levels compared with the other treatments (Fig. 3). In that

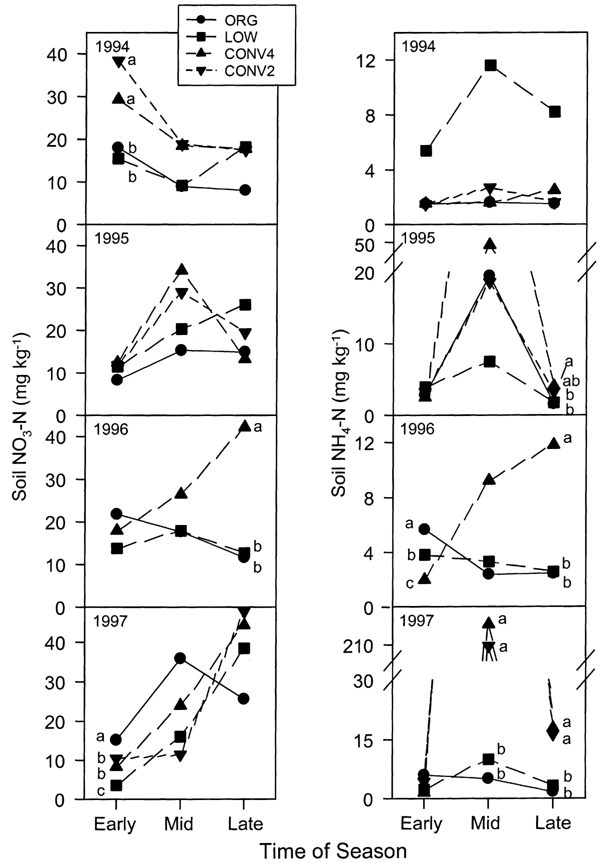

Fig. 3. Soil NO_3^-–N and NH_4^+–N levels during early season (plant emergence to first bloom), mid-season (first bloom to first fruit), and late season (first fruit to harvest) in the four management systems of the SAFS Project, Davis, CA, 1994–1997. Different letters within a year indicate statistically significant differences between systems (ANOVA, Student–Newman–Keuls test; $P < 0.05$).

year, the cover crop had a higher N content and lower C : N ratio in comparison with the previous 3 years and may have accounted for the higher soil NO_3^-–N levels.

Soil NH_4^+–N levels were even more variable than NO_3^-–N levels (Fig. 3). Early-season NH_4^+–N levels were similar across treatments in all years except 1996, when the ORG and LOW systems had higher levels than the CONV4 system. The fertilizer side-dressing of urea was apparent in the mid-season soil samples of 1995 and 1997. Except for 1994, intra-seasonal variability in NH_4^+–N levels was greater in the CONV4 and CONV2 than in the ORG and LOW systems. The differences in soil NH_4^+–N levels between the LOW

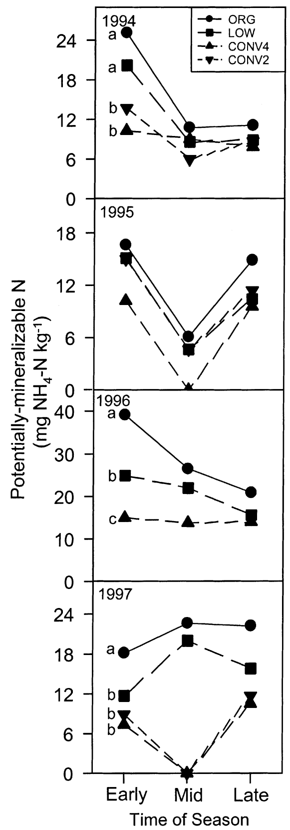

Fig. 4. Soil potentially-mineralizable N during early season (plant emergence to first bloom), mid-season (first bloom to first fruit), and late season (first fruit to harvest) in the four management systems of the SAFS Project, Davis, CA, 1994–1997. Different letters within a year indicate statistically significant differences between systems (ANOVA, Student–Newman–Keuls test; $P < 0.05$).

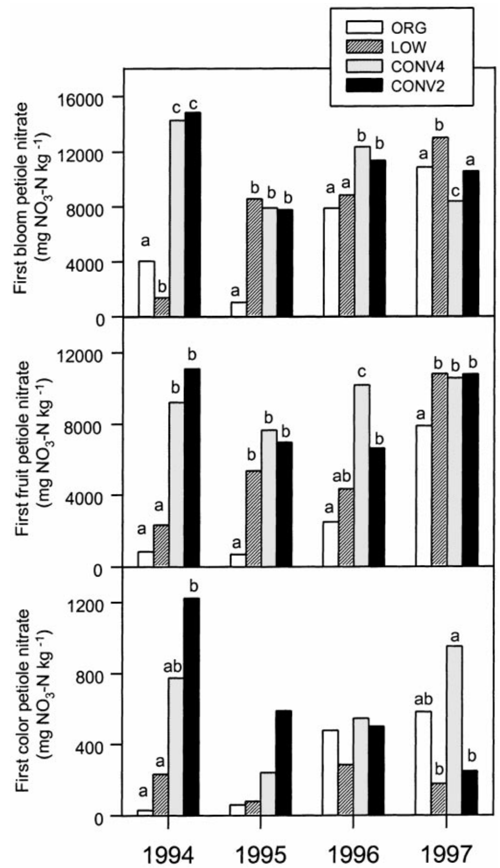

Fig. 5. Petiole NO_3^-–N levels at first bloom, first fruit, and first color (pink) in the four management systems of the SAFS Project, Davis, CA, 1994–1997. Different letters within a year indicate statistically significant differences between systems (ANOVA, Student–Newman–Keuls test; $P < 0.05$).

and ORG systems in 1994, although not statistically significant, are perplexing considering the cover crops had identical N contents and C : N ratios (Tables 2 and 3) and the manure added to the ORG system had a high N content and low C : N ratio as well.

Potentially-mineralizable N measurements appear to account for at least some of the apparent inconsistencies between N inputs and soil mineral N levels. Potentially-mineralizable N was consistently highest in the ORG system, intermediate in the LOW system, and lowest in the CONV4 and CONV2 systems, particularly early in the season (Fig. 4). Early season PMN in the ORG system ranged from 17 to 40 mg kg^{-1}. By contrast, early season PMN levels in the CONV4 and CONV2 systems were always less than 15 mg kg^{-1}. These patterns are consistent with the relative amounts of organic inputs added to the systems and highlight the importance of accumulating soil organic N to maintain N availability in the alternative treatments (Doran et al., 1988).

Petiole NO_3^-–N concentrations, particularly at first bloom and first fruit, were lowest in the ORG system and highest in the CONV4 and CONV2 systems (Fig. 5). Patterns observed in 1997 were the exception in that the ORG system resembled the CONV4 and CONV2 systems more closely. Petiole NO_3^-–N concentrations below 8000 mg kg^{-1} at first bloom are considered deficient for obtaining maximum yields based on data from conventional systems (Geraldson and Tyler, 1990). Thus, in 1994, the ORG and LOW

Table 5
Total N uptake by tomato fruit, tomato plants (fruit + stems), and tomato plants + weeds (kg ha^{-1}) in the organic, low-input, and conventional (2- and 4-year rotations) tomato systems, 1994–1997

Year	Organic	Low-input	Conventional (4)	Conventional (2)
Tomato fruit				
1994	67c	93b	145a	129a
1995	88b	123a	140a	119a
1996	103	93	88	98
1997	93b	103ab	129a	134a
Tomato plants				
1994	105b	133b	226a	208a
1995	120b	169a	200a	177a
1996	189	182	189	199
1997	143b	158ab	185a	186a
Tomato plants + weeds				
1994	108b	136b	230a	211a
1995	132b	180a	207a	182a
1996	220	216	198	203
1997	148b	161ab	191a	188a

systems, and in 1995, the ORG system, were NO_3^-–N deficient at first bloom according to this criterion. Although treatment differences were also observed at first bloom in 1996 and 1997, petiole NO_3^-–N concentrations were relatively similar across farming systems and near or above the recommended minimum level. Petiole NO_3^-–N concentrations at first fruit showed similar overall patterns to first bloom. First color petiole NO_3^-–N concentrations showed less variability among treatments; however, all treatments showed NO_3^-–N concentrations below the suggested deficiency threshold of 2000 mg kg^{-1} for this growth stage (Geraldson and Tyler, 1990).

Total N uptake by the tomato fruit and tomato plants (fruit + stems) was significantly greater in the conventional systems compared with the ORG system in 3 of the 4 years of the study (Table 5). In the LOW system, N uptake was variable but always equal to or greater than that in the ORG system.

According to weed groundcover estimates and biomass measurements at harvest, weed abundance was relatively low and similar across treatments in 1994 and 1997 (Fig. 6). In 1995 and 1996 considerable differences in weed abundance were measured across treatments. In these 2 years the ORG and LOW systems had the highest weed levels whereas the CONV2 had the lowest. Nitrogen uptake by weeds generally accounted for 5% or less of the total N in the aboveground plant biomass (Table 5). However, in 1995 and 1996, weeds accounted for 7–10 and 15% of the total N in the aboveground plant biomass, respectively, in the alternative systems.

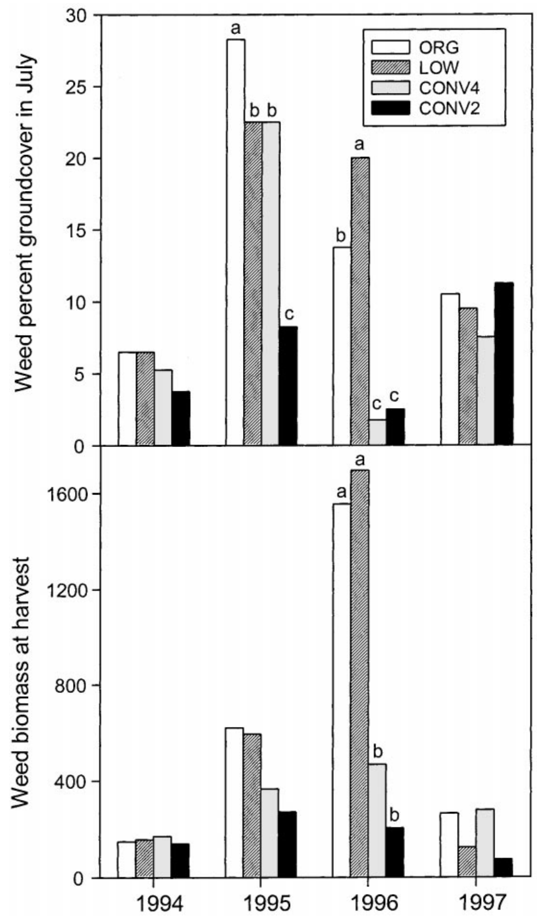

Fig. 6. Weed percent groundcover in July and weed biomass at harvest in the four management systems of the SAFS Project, Davis, CA, 1994–1997. Different letters within a year indicate statistically significant differences between systems (ANOVA, Student–Newman–Keuls test; $P < 0$ 05).

3.2. *Effects of water, nitrogen, and weeds on tomato yield*

A total of six PCs with eigenvalues ≥ 1 were generated. Together these accounted for 77% of the variability in the original data set of 21 variables and 60 observations (data set = 1260 values). Each of the first two PCs had significant loadings (≥0.50) from eight vari-

Table 6
Factor loadings, eigenvalues, and percentage of total variance for the first six principal components derived from 21 field measurements.

Variables		Principal components					
Measurement	Timing	PC1	PC2	PC3	PC4	PC5	PC6
Petiole NO_3–N	First bloom	0.22	0.71[a]	0.47	0.10	0.22	0.01
	First fruit	0.61[a]	0.55[a]	0.38	0.01	0.23	−0.05
	First fruit	0.17	0.62[a]	−0.01	0.26	0.14	0.02
Soil NO_3–N	Early season	−0.33	0.80[a]	−0.23	0.32	−0.01	0.06
	Mid-season	0.09	0.08	0.11	0.04	0.67[a]	0.53[a]
	Late season	0.78[a]	0.03	0.51[a]	0.02	−0.17	0.03
Soil NH_4–N	Early season	−0.27	−0.26	0.22	0.37	0.18	−0.07
	Mid-season	0.79[a]	−0.21	−0.26	0.38	0.19	−0.21
	Late season	0.79[a]	−0.08	0.11	0.25	−0.40	0.23
Soil NO_3–N+NH_4–N	Early season	−0.47	0.67[a]	−0.29	0.29	−0.06	0.15
	Mid-season	0.74[a]	−0.19	−0.34	0.33	0.38	0.04
	Late season	0.60[a]	0.14	0.30	−0.04	−0.40	0.47
Soil NO_3–N/NH_4–N	Early season	−0.05	0.88[a]	−0.33	−0.01	−0.09	−0.07
	Mid-season	−0.46	0.51[a]	0.13	0.04	0.10	0.00
	Late season	−0.30	0.16	0.39	−0.46	0.33	−0.27
Potentially-mineralizable N	Early season	−0.68[a]	−0.23	0.00	0.48	−0.21	0.12
	Mid-season	−0.68[a]	0.10	0.46	−0.23	−0.18	0.29
	Late season	−0.25	−0.27	0.52[a]	0.39	0.19	−0.08
Water applied	Total season	−0.30	−0.20	0.45	0.58[a]	−0.11	−0.40
Weed biomass	At harvest	−0.47	−0.31	0.00	0.42	0.05	0.40
Weed groundcover	In July	−0.24	−0.58[a]	−0.11	−0.21	0.35	0.27
Eigen value		5.28	4.14	2.10	1.91	1.50	1.21
% of total variance		25	20	10	9	7	7

[a]Factor loadings ≥ 0.50 and considered statistically significant.

ables (Table 6). Principal component (PC)1 received high positive loadings from first fruit petiole NO_3^-–N and mid- and late season soil N measurements and negative loadings from early and mid-season PMN levels. Principal component 2 received high positive loadings from all petiole NO_3^-–N measurements and several soil N measurements and a negative loading from weed percent groundcover. The other four PCs had significant loadings from only 1–2 variables. Two variables, weed biomass at harvest and late season soil $NO_3^- : NH_4^+$–N ratio, did not have significant loadings on any of the PCs, though the negative loading of weed biomass on PC1 was nearly significant.

The final stepwise regression model generated to predict tomato yields across all treatments used the first five PCs and accounted for 51% of yield variation (Table 7). Most of this variation was accounted for by PC2 and PC5, indicating that high petiole NO_3^-–N levels, high early to mid-season soil NO_3^-–N levels, and low weed groundcover resulted in high tomato yields. The regression models

Table 7
Results of stepwise regression analyses using principal components (PCs) as independent variables to predict tomato yield in all tomato systems combined and the organic, low-input, and conventional (2- and 4-year rotations) systems separately.

Treatment	Variable	Coefficient	*P*	r^2
All	PC2	5.5	0.0001	0.25
	PCS	4.1	0.0007	0.39
	PCi	2.4	0.03	0.44
	PC4	2.1	0.05	0.47
	PC3	1.9	0.07	0.51
Organic	PC3	7.2	0.0002	0.48
	PC6	8.1	0.004	0.73
Low-input	PCS	6.1	0.003	0.42
	PC2.	19.5	0.01	0.67
Conventional (4)	PC2	5.8	0.03	0.26
	PC6	−3.1	0.04	0.46
	PCS	2.9	0.06	0.60
Conventional (2)	PC4	7.3	0.04	0.28
	PC2	3.8	0.05	0.53

generated for the individual treatments accounted for more yield variability than the model produced for all treatments combined. In the ORG system, a model using PC3 and PC6 accounted for 73 % of yield variation. High positive loadings on these PCs indicate that high late-season PMN and mid- to late season soil NO_3^-–N levels were associated with high yields in the ORG system. Interestingly, weed abundance variables had low loadings on these PCs even though weed abundance was relatively high in this treatment in 2 of the 4 years studied. In the LOW system, PC5 and PC2 accounted for 67% of yield variation, indicating that high yields were associated with high petiole NO_3^-–N levels throughout the season, high early to mid-season soil NO_3^-–N levels, and low weed abundance. Principal component 2 was also a significant variable in the regression models for the CONV4 and CONV2 systems. In addition, the model for the CONV4 system included PC5 and PC6 and accounted for 60% of yield variation. In the CONV2 system, PC4 accounted for most yield variation in the model, indicating that the amount of water applied was the most important factor predicting yields. The model including PC4 and PC2 accounted for 53% of yield variation in the CONV2 system (Table 7).

4. Discussion

The effects of organic and low-input farming methods on crop yields have obvious and important implications for the adoption of these methods by farmers, governmental support for research, development, and extension, and the supply and security of food at local, regional, and global scales if such practices become more widely used. Researchers considering the effects of widesread adoption of organic and low-input methods on food production have come to varied conclusions ranging from little or no yield reduction to catastrophic crop losses (Loomis and Connor, 1992; Pimentel et al., 1993; Bender, 1994; Knutson et al., 1994). Based on 205 comparisons from the literature, mainly from northern Europe and North America, Stanhill (1990) found that the productivity of organic crop and animal production systems averaged about 10% less than comparable conventional systems. Although this generalized finding is important and insightful, systems comparisons for specific regions and crops are necessary because of geographic differences in farming practices, soils, climate, pest pressures, and other factors. Recent studies in Maryland (Abdul-Baki et al., 1996), Pennsylvania (Steffen et al., 1995), South Dakota (Smolik et al., 1993, 1995), California (Drinkwater et al., 1995), and New Zealand (Reganold et al., 1993), for example, have shown that alternative systems can perform as well agronomically as conventional systems. However, other studies indicate that the use of low-input and organic production methods can lead to unpredictable, and sometimes substantial, reductions in crop yield (Lockeretz et al., 1981; Liebhardt et al., 1989; Nelson and King, 1996).

The present results indicate that organic and low-input production of processing tomato can produce yields comparable with those of conventional production systems but that the potential yield-limiting factors are different from those of conventional systems and may be more difficult to manage, at least if synthetic chemical inputs are completely eliminated. The wide range of values in the variables measured and the statistical significance of the first six PCs in explaining yield variation illustrate the complexity of the interactions among variables and their effects on yield. Although this limits ability to generalize from the results, several interesting patterns do emerge which indicate considerable differences in ecological processes at the system level.

The multiple regression models explaining yield in the LOW, CONV4, and CONV2 systems included PC2, indicating the importance of high N uptake and low weed abundance. The regression model for the ORG system did not include PC2; instead, it included PC3 and PC6, indicating that high mid- to late season soil NO_3^-–N and PMN levels were associated with greater yields in the ORG system. This suggests the importance of soil biological activity for supplying adequate mineral N for crop uptake.

The availability of N is commonly cited as a yield-limiting factor in organic and low-input production. Insufficient decay of added organic inputs or immobilization of N by the microbial community can result in unpredictable N release patterns and insufficient N uptake by the crop for obtaining maximum yields (Doran et al., 1987; Karlen and Doran, 1991; Nelson and King, 1996). By contrast, some studies have shown that N supplied by organic sources, including cover crops and/or composts, can provide adequate N fertility and produce crop yields comparable to those with conventional chemical inputs (Stivers and Shennan, 1991; Sullivan et al., 1991; Steffen et al., 1995). This study demonstrates the possibility for both outcomes and indicates that in order to ensure adequate N availability for obtaining yields comparable to conventional methods, total N inputs should be sufficiently high to accommodate the possibility of slow decay rates and/or immobilization. Although this may suggest that N losses to leaching or denitrification would be higher with the use of large amounts of organic inputs, research findings, including those from the SAFS site, indicate the contrary (Fraser et al., 1988; Nelson and King, 1996; Clark et al., 1998b). Instead, the additional N, when associated with high C inputs, contributes to the building of soil organic matter (Sommerfeldt et al., 1988; Wander et al., 1994; Agbenin and Goladi, 1997) which provides long-term fertility benefits. Eventually, soil organic matter levels should stabilize and N input requirements decline. The higher yields in the ORG system during the latter 2 years of the study may be an indication that such stabilization was occurring.

In contrast to the ORG system, yield limitation in the CONV2 system appeared to be related most to insufficient water availability. In 1995 and 1996, the two years with the lowest yields in the CONV2 system, estimated potential evapotranspiration exceeded the amount of water applied. This would not necessarily lead to a water deficit for the tomato crop if there was sufficient water stored in the soil from the previous winter. However, there was also slightly greater weed biomass in the CONV2 system in those two years that could have resulted in even greater competition for this already limited resource. Water availability was probably less problematic in the CONV4 system because of the slightly higher soil organic matter levels in that soil (Clark et al., 1998b) which would likely result in improved infiltration rates and water-holding capacity.

As expected, the LOW system showed characteristics of both the conventional and ORG systems. If data from 1994, the year with the virus-infected transplants, are excluded, the soil and plant N dynamics had greater similarity with the conventional systems but water and weed measurements more closely resembled the ORG system. During this 3-year period, tomato yields in the LOW system were comparable to the CONV4 system. The inclusion of PC2 in the regression equation and the observed patterns in soil and plant N data, especially in the latter 2 years, suggest that N processes affecting yield in the LOW system were more similar to those of the conventional systems than the ORG system. However, the use of cover crops in the LOW system appeared to prevent the occurrence of water infiltration problems observed in the conventional systems. Future research should focus on elucidating soil, plant and soil N dynamics in organic and low-input systems, developing N management tools for such systems, and assessing their economics at farm, community, and regional scales.

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