Agriculture, Ecosystems and Environment 68 (1998) 51–71

Agriculture Ecosystems & Environment

Agronomic, economic, and environmental comparison of pest management in conventional and alternative tomato and corn systems in northern California

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Received 7 May 1997; accepted 2 September 1997

Abstract

The effectiveness, economic efficiency, and environmental impact of pest management practices was compared in conventional, low-input, and organic processing tomato and field corn systems in northern California. Pests, including arthropods, weeds, pathogens, and nematodes, were monitored over an 8-year period. Although both crops responded agronomically to the production-system treatments, arthropods, pathogens, and nematodes were found to play a relatively small role in influencing yields. In contrast, weed abundance was negatively correlated with tomato and corn yields and appeared to partially account for lower yields in the alternative systems compared to the conventional systems. Lower pesticide use in the organic and low-input systems resulted in considerably less potential environmental impact but the economic feasibility of reducing pesticide use differed dramatically between the two crops. The performances of the organic and low-input systems indicate that pesticide use could be reduced by 50% or more in corn with little or no yield reduction. Furthermore, the substitution of mechanical cultivation for herbicide applications in corn could reduce pest management costs. By contrast, pesticide reductions in tomato would be economically costly due to the dependence on hand hoeing as a substitution for herbicides. Based on the performance of the low-input and organic tomato systems, a 50% pesticide reduction would increase average pest management costs by 50%. © 1998 Elsevier Science B.V.

Keywords: Tomato; Corn; Pest management; Organic agriculture; Low-input agriculture; Pesticide use; Environmental impact; Economic impact

1. Introduction

Reducing pesticide use is a widely acknowledged strategy for improving agricultural sustainability. In

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PII S0167-8809(97)00130-8

fact, reduction in pesticide use has become a government-mandated policy in some countries and provinces (Jansma et al., 1993; Pettersson, 1993; Surgeoner and Roberts, 1993; Matteson, 1995). Although there is no national policy for pesticide reduction in the United States, the federal government has set a goal to bring 75% of agricultural land under integrated pest management (IPM) by the year 2000 (Benbrook et al., 1996). In addition, voluntary pesticide reduction programs have been initiated at the state and regional levels by government institutions and non-governmental organizations (Matteson, 1995). Despite the use of approximately 320 million kg of pesticides annually, current pre-harvest crop losses to pests (including arthropods, weeds, diseases, and nematodes) in the United States are estimated to be about 37% of the maximum potential yield. Although an estimated 10% additional loss would be incurred if no pesticides were used, specific crop losses would range widely; being negligible for some crops and disastrous for others (Pimentel et al., 1993a).

In conventional agriculture, the decision to use a pesticide is generally based on its effectiveness against particular pests, application costs, the economic value of the crop, and the relative risks to the crop of using the pesticide (phytotoxicity, resistance, etc.) versus not using it (pest outbreak, damage, yield reduction) (van der Werf, 1996). With high-value crops growers may be more inclined to use pesticides as ‘insurance’ even when pest populations are below economically damaging levels. Moreover, farmers may be directly or indirectly encouraged to apply pesticides by fieldmen working for agrochemical distributors or by strict cosmetic standards set by wholesalers, processors, or distributors (Pimentel et al., 1993b; Olkowski and Olkowski, 1996). The potential environment and health hazards associated with pesticide use are considered less often than direct economic benefit or risk reduction by those who make pesticide use decisions (Pimentel et al., 1993c). By contrast, a principal aim of low-input and organic agriculture is to avoid environmental degradation and health risks by reducing or eliminating the use of synthetic chemical pesticides.

Clearly, there is a need to have precise information on the productivity benefits from pesticides as well as the economic and environmental consequences of pesticide use reductions. Estimating crop loss solely based on data from control treatments in pesticide trials is misleading because the controls differ from the conventionally-managed treatments only by the absence of a single pesticide or class of pesticides, with all other management aspects remaining constant. In reality, however, farmers using fewer or no synthetic chemical inputs generally substitute alternative management methods for pesticides. Furthermore, non-chemical or low-chemical systems may differ from conventionally-managed systems in a wide array of ecological characteristics which may influence pests directly or indirectly (Drinkwater et al., 1995).

In a review of conventional and alternative pest management practices for major crops in the USA, Pimentel et al. (1993a) concluded that, with some additional cost, pesticide use could be reduced substantially in tomato and corn production. They estimated that herbicide use in corn could be reduced by 50% if herbicide applications were replaced with mechanical cultivation and crop rotation, and that insecticide use could be reduced by 80% with crop rotation and resistant varieties. Although they found no increase in weed management costs, the costs of insect management were calculated to increase by greater than 60% where corn is grown continuously (although this is not the case in California where corn is always grown in rotation). Potential herbicide reductions in tomato were estimated to be 80% by using mechanical cultivation and wiper-application technology. In addition, conventional insecticide use could be reduced by 80% with pest scouting and using *Bacillus thuringiensis* (Bt) and other biological control agents. Fungicide use could be reduced by 50% with forecasting and scouting. Estimated cost increases for these pesticide reductions for weed, insect, and disease management were 30%, 0%, and 10% respectively. Other analyses have come to a wide range of conclusions concerning the feasibility of pesticide reduction in tomato (Knutson et al., 1994; Walgenbach and Estes, 1992; Trumble and Alvarado-Rodriquez, 1993; Trumble et al., 1994; Brumfield et al., 1995; Sellen et al., 1995). Most of these studies, however, provide little insight for pesticide reduction in northern California either because of differences in climate, pest species, pest pressures, experimental methods, and cosmetic requirements of fresh-market production. Antle and Park (1986) assessed the economic viability of scouting for tomato fruit-damaging insects in the northern California and concluded that this practice reduced average insecticide use by over 20% and slightly increased profits by reducing fruit damage.

This paper compares pest abundance, economic costs, and the environmental impact of conventional systems using synthetic pesticides with alternative systems using non-chemical and organically acceptable pest management practices. The Sustainable Agriculture Farming Systems (SAFS) project, an interdisciplinary, experiment station-based study of conventional, low-input, and organic farming systems (Temple et al., 1994), provided a unique opportunity to assess the consequences of alternative pest management practices on yield, pest abundance, and pest management costs at the field and farm scale. The two crops evaluated in this study, field corn, *Zea mays* L., and processing tomato, *Lycopersicon lycopersicum* (L.) Karst. ex Farw., differ dramatically in conventional pest management practices. Corn production accounts for over half of herbicide use in the USA with over 90% of cropland being treated annually. Insecticides are used on 41% of corn area but fungicides are rarely used. Yield losses to weeds, insects, and pathogens are estimated to be 10%, 12%, and 10% respectively (Pimentel et al., 1993a). By contrast, processing tomato is treated with herbicides, insecticides, and fungicides on 99%, 88%, and 64% of planted land, respectively (Davis et al., 1996). The specific objectives were to: (1) compare pest abundance levels in the systems and identify which pests or pest classes were associated with relative yield reductions; (2) assess the relative pest management costs in alternative and conventional systems; and (3) compare the relative environmental impact of pesticide use in the systems.

2. Methods

2.1. System descriptions

The Sacramento Valley has a Mediterranean climate with most rainfall occurring during the winter months (December–March) and relatively little during the growing season. Furrow irrigation is used for most crop production. Total annual rainfall is typically 400–500 mm and daytime temperatures average 30–35°C during the growing season. The Sustainable Agriculture Farming Systems (SAFS) Project is located at the Agronomy Farm of the University of California at Davis (38°32′N, 121°47′W, 18 m elevation), on an 8.1 ha site on soil classified as Reiff loam (coarse–loamy, mixed, non-acid, thermic Mollic Xerofluvents; 36% sand, 45% silt, and 19% clay).

The study consists of two conventional and two alternative systems which differ primarily in crop rotation and use of external inputs (Fig. 1). These include 4-year rotations under conventional (Conv-4), low-input, and organic management and a conventionally-managed, 2-year rotation (Conv-2). The three systems with 4-year rotations include processing tomato, safflower, bean, and corn. In the Conv-4 treatment, beans are double-cropped with a winter wheat crop and in the low-input and organic treatments, beans typically follow a bi-culture of oats and vetch which serves as either a cover crop or cash crop. The Conv-2 treatment is a tomato and wheat rotation. All crops and rotation entry points are represented each year. The 56 plots, each 0.12 ha, are arranged in a randomized block, split-plot design with four replications.

Tomatoes in all farming systems were grown on 1.52 m-wide beds and furrow-irrigated throughout this study. Planting in all systems was by direct seeding from 1989 to 1991. However, tomato seedlings were transplanted into the low-input and organic systems from 1992 to 1996 in order to allow greater cover crop growth in the spring, thereby increasing nitrogen fixation. Tomato seedlings were sprinkler-irrigated immediately following transplanting and furrow-irrigated throughout the rest of the season. The conventional tomato systems typically received nitrogen as urea and/or ammonium nitrate at 140 kg N ha^{-1} yr^{-1}. This rate was reduced by about one-half in the low-input system by using leguminous cover crops. The organic tomato system received aged or composted poultry manure at 4–5 t ha^{-1} (dry weight). Corn was planted on 0.76 m-wide beds and furrow-irrigated in all farming systems. The Conv-4 corn system received about 190 kg N ha^{-1} yr^{-1} as urea and/or ammonium nitrate; the low-input system received about one-half this amount.

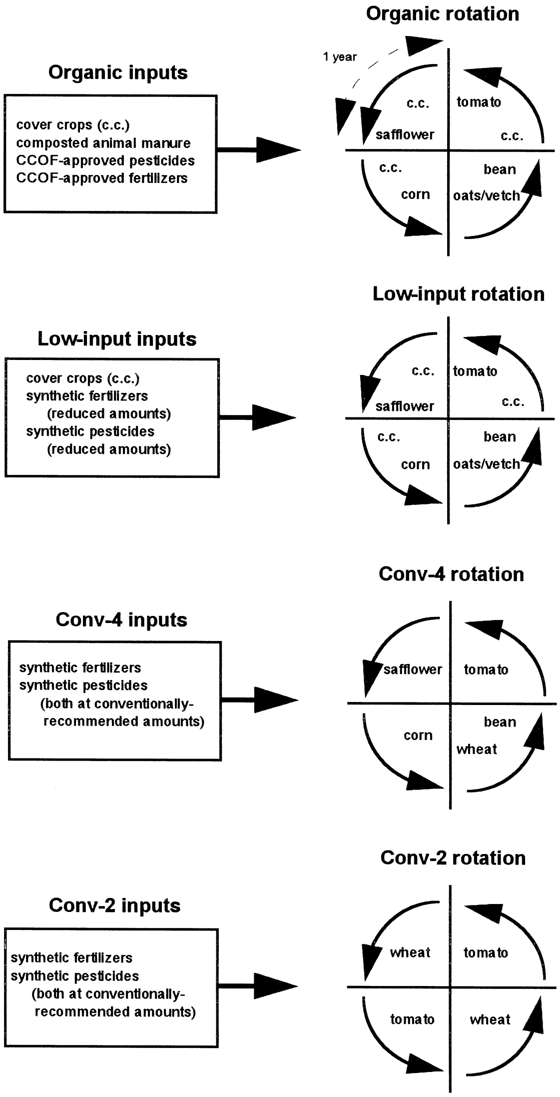

Fig. 1. Conceptual diagram showing the inputs and rotations of the four farming system treatments of the SAFS project, Davis, CA, 1989–1996.

Poultry manure was applied to the organic corn system at 5–7 t ha^{-1} (dry weight).

During the 8-year period, all systems used 'best farmer management practices' which were determined through consultation with project investigators, University of California Cooperative Extension farm advisors, and area farmers cooperating on the project. Thus, management decisions on crop variety selection, agronomic practices, and pest management were made as needed based upon market demand, weather, pest pressures, and current practices in the region. All farming systems utilized a combination of preventive and therapeutic pest management tactics (Table 1). The Conv-4 and Conv-2 treatments were managed with practices typical of the surrounding area, which included the use of synthetic chemical pesticides and fertilizers. In the low-input system, fertilizer and pesticide inputs were reduced primarily by using vetch (*Vicia* spp.) and vetch/oat (*Avena sativa* L.) cover crops to improve soil fertility and mechanical cultivation for weed management. The organic treatment was managed according to the regulations of California Certified Organic Farmers (CCOF, 1995). Thus, no synthetic chemical pesticides or fertilizers were used. Management included the use of vetch and vetch/oat cover crops, aged or composted animal manure, mechanical cultivation, and limited use of CCOF-approved products including Bt, sulfur, and insecticidal soap. Decisions to use therapeutic pest management were made based upon a combination of University of California guidelines (e.g., University of California, 1996), expert advice from participating investigators and farm advisors, and professional opinions of participating farmers. This paper analyzes pest abundance and management data collected in these tomato and corn systems from 1989–1996 (Table 2).

2.2. Pest abundance and association with yield

Arthropod pests, weeds, plant pathogens, and plant-parasitic nematodes were monitored in all systems for varying number of years (Table 2) using sampling methods described below. Pest abundance was compared among treatments in each year with a two-way Analysis of Variance (ANOVA) followed by the Student–Newman–Keuls test when $P \leq 0.05$. Non-normal data were transformed to achieve normality and ratings were analyzed with the non-parametric Kruskal–Wallis test.

Tomato and corn yields were determined each year using commercial-scale machinery and small-scale hand harvests. Machine harvests consisted of the yield from the center one-third of each plot. Hand harvest data were usually used to verify machine harvest data, but occasionally used for compar-

Table 1
Pest management practices used in tomato and corn production under the four farming system treatments of the SAFS project, Davis, CA, 1989–1996

Crop	Practice	Organic	Low-input	Conv-4	Conv-2
Tomato	Synthetic chemical insecticides		+	+	+
	Microbial insecticides	+	+		
	Insecticidal soap	+			
	Sulfur	+	+	+	+
	Synthetic chemical herbicides			+	+
	Four-year rotation	+	+	+	
	Mechanical cultivation	+	+	+	+
	Hand hoeing	+	+	+	+
	Synthetic chemical fungicides		+	+	+
Corn	Synthetic chemical insecticides			+	NA[a]
	Synthetic chemical herbicides		+	+	NA
	Four-year rotation	+	+	+	
	Mechanical cultivation	+	+	+	NA

[a]Not applicable.

isons when problems were noted in the machine harvest. The association between yield and pest abundance measurements was assessed with Pearson correlation analysis. Statistical analyses were performed on SigmaStat (Jandel Scientific, San Rafael, CA) and SuperANOVA. (Abacus Concepts, Berkeley, CA).

2.2.1. Arthropod pests

Arthropod pests were monitored on an alternating, bi-weekly basis such that one-half of the plots were sampled each week during the growing season. In tomato, potato aphid (*Macrosiphum euphorbiae* Thomas), tomato fruitworm (*Helicoverpa zea* Boddie), and beet armyworm (*Spodoptera exigua*

Table 2
Tomato and corn pests systematically monitored in the four farming system treatments of the Sustainable Agriculture Farming Systems (SAFS) Project, Davis, CA, 1989–1996

Crop	Pest group	Common name	Scientific name	Years monitored
Tomato	Arthropods	Potato aphid	*M. euphorbiae* Thomas	1989–1995
		Tomato fruitworm	*H. zea* Boddie	1989–1995
		Beet armyworm	*S. exigua* Hübner	1989–1995
	Weeds	Total weed cover[a]	NA[b]	1990–1996
		Total weed biomass[a]	NA	1990–1992, 1994–1996
	Diseases	Corky root	*P. lycopersici* Gerlach	1995–1996
		Pythium root rot	*Pythium* spp.	1995–1996
		Phytophthora root rot	*Phytophthora* spp.	1995–1996
		Rhizoctonia root rot	*R. solani* (Kühn)	1995–1996
		Fusarium wilt	*Fusarium* spp.	1995–1996
		Knobby root	Unidentified	1995–1996
	Nematodes	Root-knot nematode	*Meloidogyne* spp.	1988, 1990–1995
		Root-lesion nematode	*Pratylenchus* spp.	1988, 1990–1996
Corn	Arthropods	Aphids	*Aphididae* spp.	1989–1995
		Spider mites	*Tetranychus* spp.	1989–1995
		Corn earworm	*H. zea* (Boddie)	1989–1995
	Weeds	Total weed cover[a]	NA	1990–1996
		Total weed biomass[a]	NA	1990–1996
	Nematodes	Root knot nematode	*Meloidogyne* spp.	1988, 1990–1995
		Root lesion nematode	*Pratylenchus* spp.	1988, 1990–1995

[a]Dominant weed species noted in text.
[b]Not applicable for total weed cover and total weed biomass.

Hübner) were quantitatively monitored (Table 2). Potato aphid sampling consisted of picking the leaf below the highest open flower on a plant and recording the presence or absence of aphids, with 30 leaves being sampled per plot. Tomato fruitworms and beet armyworms were monitored by picking 50 fruit per plot at random and examining each for damage. In addition, the number of tomato fruitworm eggs and percent parasitism by native *Trichogramma* spp. wasps were determined by sampling the leaf below the highest open flower on a plant with 30 leaves being sampled per plot (Zalom et al., 1986; Hoffmann et al., 1990). These numbers were compared to established threshold values (University of California, 1996) to determine if insecticide applications were necessary. The levels of some pests, including russet mites (*Aculops lycopersici* Massee), flea beetles (*Epitrix* spp.), lygus bugs (*Lygus* spp.), and stink bugs (Pentatomidae) were monitored with qualitative observations during scouting. At harvest, 200 tomato fruit were collected from each plot and evaluated for infestation by tomato fruitworm and beet armyworm and, in years when populations were present during the season, for stink bug damage. In corn, aphids (Aphididae), spider mites (*Tetranychus* spp.), and corn earworm (*H. zea*) were quantitatively monitored (Table 2). Aphid and spider mite abundance was based on presence/absence sampling on the lowest non-senescing leaf of 40 plants per plot. Corn earworm was monitored by examining 40 ears per plot and recording the number of ears infested. All data presented are means at peak abundance for each year.

2.2.2. Weeds

Weeds were monitored using two methods (Table 2). Visual estimates of weed percent groundcover were made monthly with dominant species noted. For this analysis, weed percent groundcover in July was used as an indicator of weed pressure, as crops were not cultivated after this time. In addition, above-ground weed biomass at harvest was measured by cutting, drying, and weighing several subsamples per plot. In corn, three subsamples, each measuring 1 m^2, were taken per plot from 1990–1996. In tomato, eight, 1 m^2-sub-samples were taken per plot during the same period, except in 1993 when weed biomass was not measured.

2.2.3. Plant pathogens

Foliar plant pathogens were observed only occasionally; no systematic surveys were conducted to quantify foliar diseases. Tomato root pathogen severity was quantitatively assessed in 1995 and 1996 (Table 2). Several days before fruit harvest, four plants from each of five center rows in each plot were uprooted with a shovel. Roots were rinsed and rated for typical lesions of corky root (*Pyrenochaeta lycopersici* Gerlach), Fusarium root rot (primarily *Fusarium* species producing red pigments in culture), Rhizoctonia root rot (*Rhizoctonia solani* Kühn), Pythium root rot (*Pythium ultimum* Trow and *P. aphanidermatum* Fitzp.), and Phytophthora root rot (*Phytophthora parasitica* Dast.). Scoring scales varied according to the symptoms observed: for corky root, the numbers of dark brown bands with transversal fissures were counted on the tap root and main lateral roots of each root system with 30 lesions being equivalent to about 100% infection; for Fusarium root rot, the number of roots larger than 1 mm diameter with dry reddish brown roots tips were counted; for Rhizoctonia root rot, the number of oval-shaped, dark brown and sunken lesions were counted on the tap root and large lateral roots of each plant; for Pythium root rot, the number of small feeder roots (> 1 mm diameter) with soft, brown tips were counted; and for Phytophthora root rot, the number of large lateral roots (including the tap root) that were dark brown, starting from the root tip. To confirm the presence of suspected pathogens, six 1–2 cm long root pieces per plant (20 plants per plot) were surface sterilized and placed onto agar plates with semi-selective media: water agar for *Rhizoctonia*; acid potato dextrose agar for *Fusarium* and *Macrophomina*; pimaricin–ampicillin–rifampicin–pentachloronitrobenzene agar for *Pythium* and *Phytophthora*; and corky root medium agar for *Pyrenochaeta* (Singleton et al., 1992).

2.2.3.1. Plant parasitic nematodes in bulk soil. Nematodes were sampled in 1988, before the establishment of the SAFS experiment, and once annually in each plot from 1990 to 1995 (Table 2). Thirty soil cores (15 cm deep, 2.5 cm diameter) were taken from each plot in the autumn of each year, except in 1990 and 1991 when samples were taken in the spring. The cores were composited and hand mixed.

A 400 cm^3 subsample was removed and subjected to elutriation and sugar centrifugation (Byrd et al., 1976). The total number of nematodes was counted and the first 200 were identified to genus, or species when possible, with a compound microscope at 400 × magnification. The total number of nematodes of all taxa were estimated from the proportion of the 200 identified specimens (Ferris et al., 1996).

Two plant-parasitic nematode taxa were quantified: root-knot nematode (*Meloidogyne* spp.) and root-lesion nematode (*Pratylenchus* spp.). Root-knot nematodes are a relatively common pest of tomato but do not cause significant damage to corn. Root-lesion nematodes can damage corn, but the common species found at this site, *P. thornei* Sher and Allen, is not reported to reproduce in tomato.

2.2.3.2. Plant parasitic nematodes in tomato rhizosphere. The same roots used for disease ratings were also scored for root-knot nematode (*Meloidogyne* spp.) injury and knobby root (cause unidentified) as the extent of galling and knobby root tips, respectively, on a 0–10 scale for each root system. Nematodes were extracted from roots by the mist-chamber method (Ayoub, 1980) and examined for the presence of plant-parasitic nematodes. Nematodes were extracted from the rhizosphere soil by the elutriation and sugar centrifugation method or by the Baermann funnel method for large nematodes, for which the funnel was lined with cheese cloth (Ayoub, 1980).

2.3. Economic performance

Pest management costs and crop yields were recorded from 1989 to 1996. Pest management costs were estimated using the Budget Planner computer program (Klonsky and Cary, 1990; Klonsky and Livingston, 1994). This program generates costs, returns, and profits and simulates the economic performance of a hypothetical 810 ha farm. The actual costs of material inputs and labor, based upon prices representative from the region, were used; however, the economics of field operations were derived from standardized costs. This approach produced realistic budgets by accounting for the disproportionately large amount of time needed to manage small, experimental plots. Pest management costs, categorized by pest class (arthropods, weeds, pathogens, and nematodes) were compared among systems as a percentage of total production costs and using the Conv-4 treatment as a standard (100%).

2.4. Pesticide use and environmental impact

Total pesticide use was compared among systems using the total amount of active ingredient applied per ha (kg/ha) and the number of years in which pesticide applications were used over the 8-year period. In addition, use of specific pesticide types (chemical insecticides, microbial insecticides, chemical herbicides, etc.) was compared. In order to assess the potential environmental impact of pesticide use in each of the cropping systems the environmental impact quotient (EIQ) system developed by Kovach et al. (1992) was used. The EIQ for each pesticide is derived from the following 11 environmental factors, which are categorized into farm worker, consumer, and ecological components: dermal toxicity, chronic toxicity, systemicity, fish toxicity, leaching potential, surface loss potential, bird toxicity, soil half-life, bee toxicity, beneficial arthropod toxicity, and plant surface half-life. Using an algebraic equation, which gives equal weight to the three components but weighs the 11 factors according to their presumed relative importance, a single EIQ value is generated which increases with greater negative environmental impact. An EIQ field use rating is then calculated for each pesticide by multiplying the EIQ by the amount of active ingredient (kg/ha) applied. The total environmental impact is calculated as the sum of the EIQ field use ratings for all pesticides applied. The relative environmental impact of the cropping systems was compared in this study using the total amount of active ingredient of each pesticide applied over the 8 years. One potential criticism of this method is that it does not consider the environmental impact of the pesticide alternatives, such as cultivation. Although more comprehensive models for such assessment are being developed, their increased complexity and number of assumptions can make them difficult to use and interpret (Levitan et al., 1995; Pease et al., 1996).

3. Results

3.1. Arthropod pests

Arthropod pest abundance showed considerable inter-year variability, particularly for the three corn pests (Fig. 2), however no statistically significant differences among treatments was observed. This is not particularly surprising considering the small size of the plots relative to the potential mobility of the insects studied.

The three tomato pests tended to be more problematic during the first several years of the study compared to latter years (Fig. 2D–E) probably be-

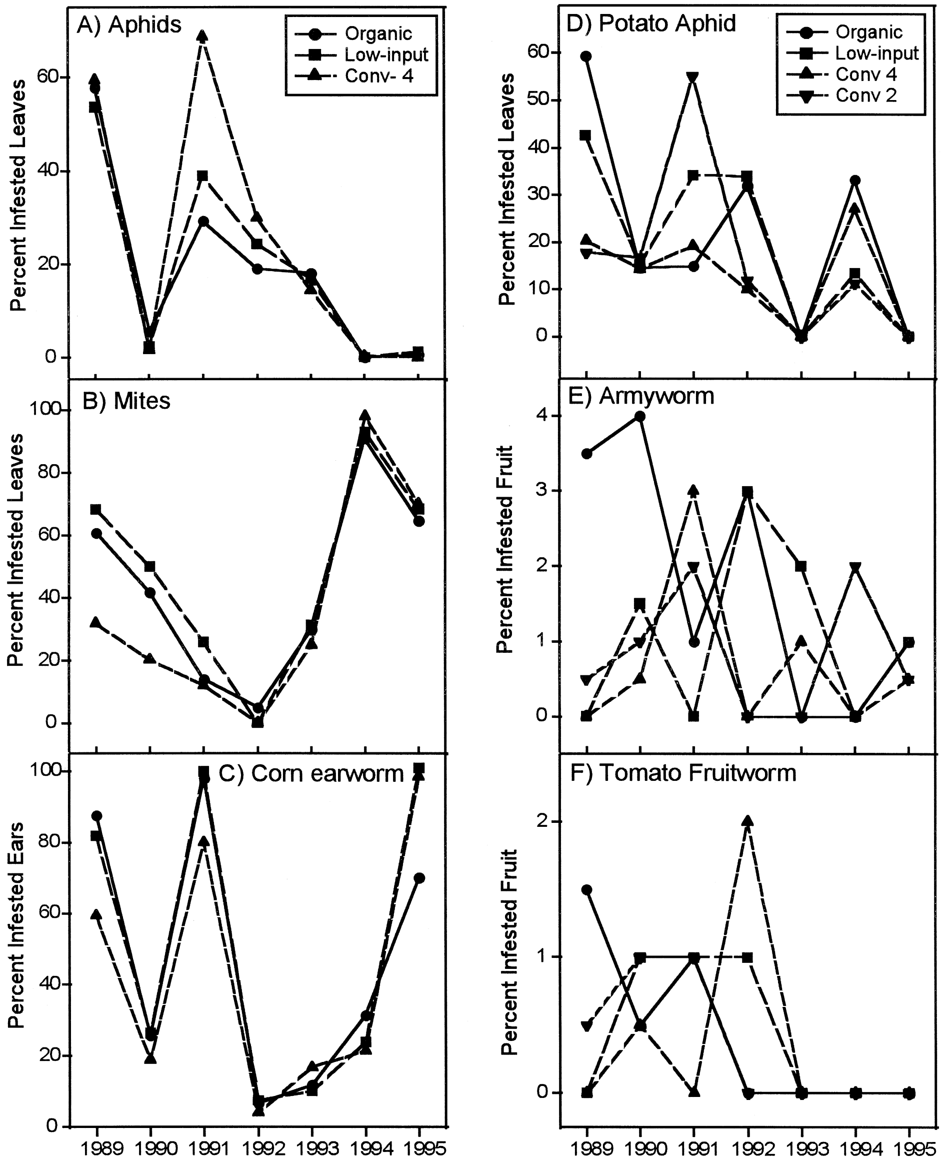

Fig. 2. Arthropod pest abundance in the corn (A–C) and tomato (D–F) crops in the four farming system treatments of the SAFS project, Davis, CA, 1989–1995. Means are calculated from abundance at peak of infestation. No significant treatment differences were found using Analysis of Variance, $\alpha = 0.05$.

cause of the late planting dates which expose the fruit to higher insect pest populations. Tomato fruitworm was not found in any of the treatments from 1993 to 1995. Insecticides were applied to control potato aphid, armyworm, and/or tomato fruitworm in the conventional and low-input tomato systems during the first 3 years of the study (1989–1991). In the organic system, insecticidal soap was applied to control potato aphids in 1989 and Bt was applied for tomato fruitworm in 1991. The greater aphid numbers in the organic system in 1989 (Fig. 2D) reflect the somewhat more effective control achieved with synthetic chemical insecticides compared to the soap treatment. Similarly, slightly higher armyworm and tomato fruitworm abundance in the organic system in 1989 and 1990 apparently resulted from not using therapeutic control measures in that treatment. Other pests which were occasionally problematic in tomato included russet mites, stink bugs, and lygus bugs. Based on qualitative observations, sulfur was deemed necessary to control russet mites in all treatments during the first 3 years of the study (1989–1991) and synthetic insecticides were applied in the conventional systems to control stink bugs in 1992 and lygus bugs in 1994. Insect-infested fruit at harvest was at acceptable levels (below the 2% grade standard) in all treatments throughout the study (Fig. 3).

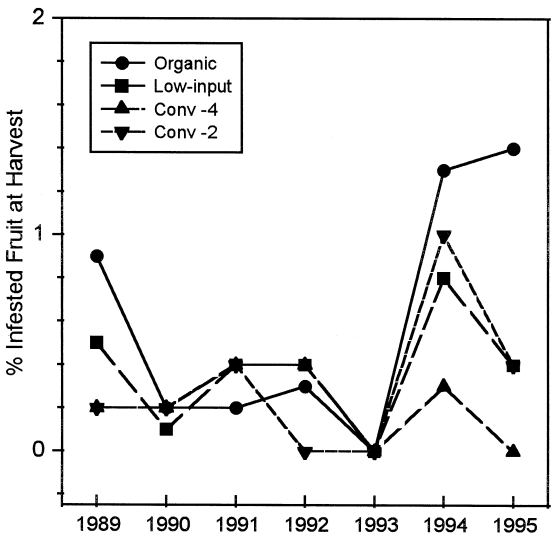

Fig. 3. Percent of tomato fruit at harvest infested with tomato fruitworm and/or beet armyworm in the four farming system treatments of the SAFS project, Davis, CA, 1989–1995.

Fruit injury at harvest from stink bug, cosmetic damage which is generally considered unimportant for paste processing but significant if the tomatoes are intended for whole peel or diced processing, was substantially greater in the organic and low-input systems compared to the conventional systems in 1992 (data not shown; see Lanini et al., 1994).

Among the corn pests monitored, only spider mites necessitated chemical control, which was applied in 1989 and 1990 in the Conv-4 system. The organic and low-input systems were left untreated. Therapeutic control for spider mites may also have been warranted in 1994 and 1995 (Fig. 2C); however, due to the difficulty and cost of spraying relatively mature corn plants, treatments were not applied. Other pests presented periodic problems in corn. In 1992, feeding by seedcorn maggot (*Delia platura* Meigen) resulted in damage to 25% of corn seedlings in the organic and low-input system. This pest is known to be problematic under conditions with high organic matter and moist surface residue, characteristics typical of cover-cropped agroecosystems after incorporation (Hammond, 1995). Nevertheless, yield reductions in those systems, relative to the Conv-4 systems, were not apparent (Friedman et al., 1997).

3.2. Weeds

Weed abundance in tomato, measured as percent groundcover in July, tended to be higher in the alternative compared to the conventional systems throughout most of the study (Fig. 4A). Only during 1993 and 1994 were significant differences not detected. In corn, the organic system had significantly greater weed cover, compared to the low-input and Conv-4 systems from 1990 to 1993, but showed similar or lower weed cover from 1994 to 1996 (Fig. 4B). Redroot pigweed (*Amaranthus retroflexus* L.) was a common weed in both crops and all systems. However, barnyard grass (*Echinochloa crus-galli* P. Beauv.), purslane (*Portulaca oleracea* L.), and common lambsquarters (*Chenopodium album* L.) were more problematic in the alternative systems, while black nightshade (*Solanum nigrum* L.) was more common in the conventional systems.

Weed biomass at harvest in tomato was significantly greater in the alternative systems compared to

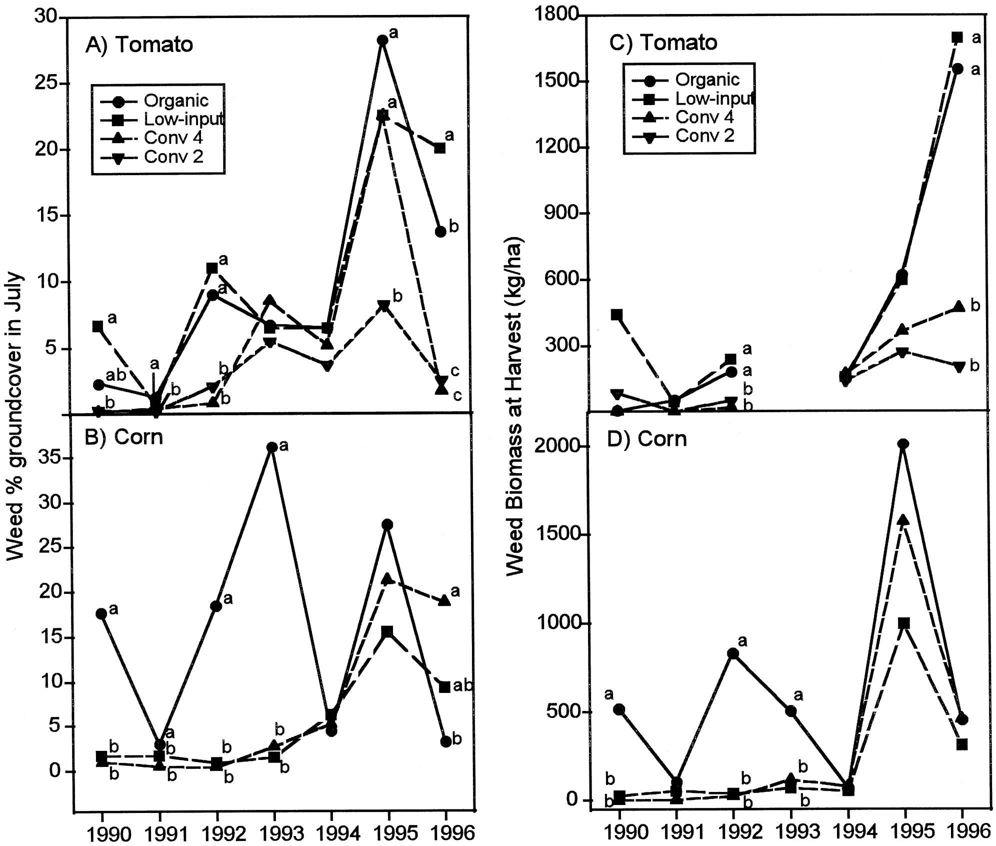

Fig. 4. Weed abundance in the four farming system treatments of the SAFS project measured as percent groundcover in July (A, B) and biomass at harvest (C, D) in tomato (A, C) and corn (B, D), Davis, CA, 1990–1996. Different letters indicate significant treatment differences using Analysis of Variance followed by the Student–Newman–Keuls test, $P \leq 0.05$.

the conventional systems in 1992 and 1996 (Fig. 4C). Over the 6-year period in which weed biomass was measured in tomato, there was a relatively close correlation between weed cover in July and biomass at harvest ($r = 0.61$, $P < 0.001$). Weed biomass in corn was significantly greater in the organic compared to the low-input and Conv-4 systems in three of the 7 years measured (Fig. 4D). Weed biomass patterns in corn also showed close similarity to weed cover patterns, however, the correlation between these measurements was somewhat weaker than that in tomato ($r = 0.23$; $P = 0.04$).

3.3. Plant pathogens

The following foliar pathogens were observed over the years: corn smut (*Ustilago maydis* Cda.), tomato black mold (*Alternaria alternata* Keissl. f. sp. lycopersici Grogan), and tomato bacterial spot (*Xanthomonas campestris* pv. vesicatoria Dye (Lanini et al., 1994). The incidence of corn smut varied over the years and no consistent differences were observed among treatments. Black mold and bacterial spot were only observed in those fall and spring with substantial rainfall, respectively. Again, there were no apparent differences among treatments.

Tomato root diseases were generally more severe in 1995 than 1996 (Fig. 5). In 1995, root diseases were quite severe in the Conv-2 system. In particular, severities of corky root, Pythium root rot, and Fusarium root rot were significantly higher in the Conv-2 system compared to the other systems (Fig. 5A, B and E). Other root diseases were not very

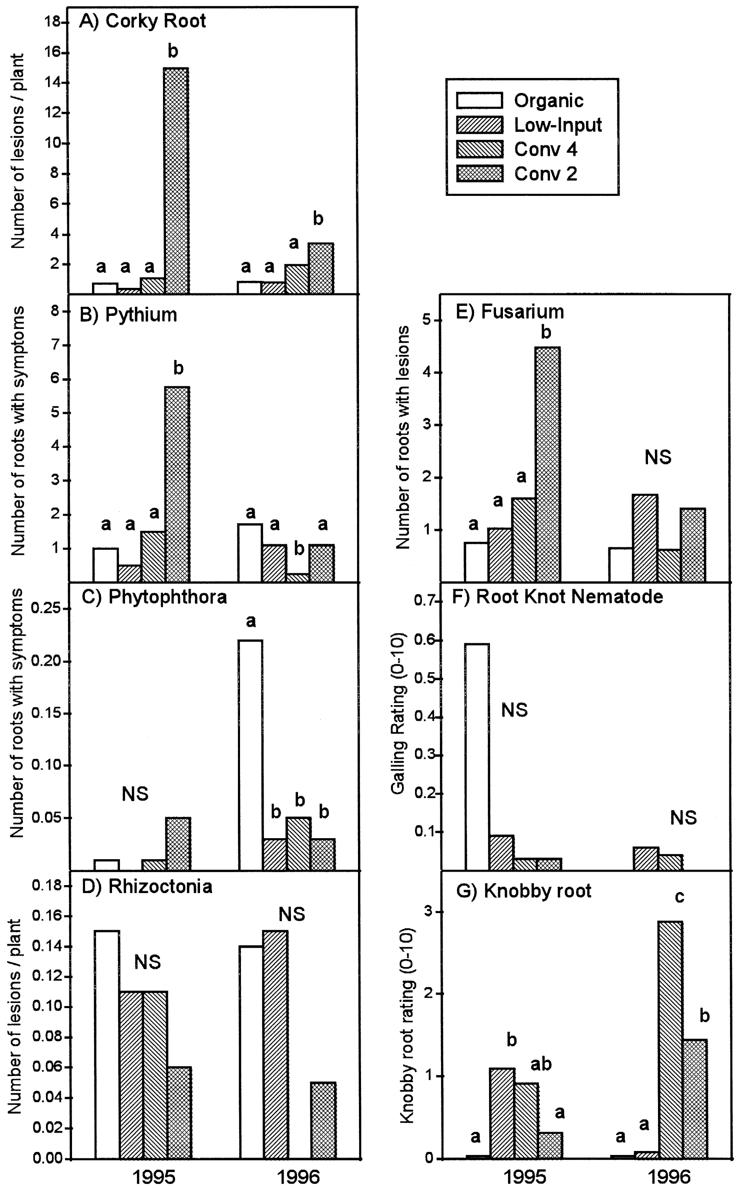

Fig. 5. Disease severity scores on tomato roots at harvest in the four farming system treatments of the SAFS project, Davis, CA, 1995–1996. Different letters indicate significant treatment differences using Analysis of Variance followed by the Student–Newman–Keuls test, $P \leq 0.05$.

prevalent. A new disease manifested by knobby root tips was observed but the cause was not determined. Knobby root was generally less severe in the organic compared to other systems (Fig. 5G). In 1996, knobby root was significantly more severe in both conventional systems than in the alternative treatments, particularly in the Conv-4 treatment. The knobby root tips may have prevented infection by *Pythium* spp. which was significantly less in the Conv-4 system than in the other systems. Differences in corky root severity in 1996 were similar to those in 1995 albeit less pronounced (Fig. 5A). Phytophthora root rot was exceptional in being more severe in the organic system than in the other systems in 1996 (Fig. 5C).

Isolation of plant pathogenic fungi from tomato roots confirmed the presence of most pathogens suspected to be present based on root symptoms. *P. lycopersici* was isolated from roots with corky root in 1995. *R. solani* was isolated in both years. *Pythium* sp. was isolated in 1995, and *P. ultimum* and *P. aphanidermatum* were identified in 1996. All *Phytophthora* colonies isolated were *P. parasitica*. The isolated *Fusarium* colonies were mainly purple and red in both years, but were not identified to species. However, most colonies looked like *F. oxysporum* (probably *F. oxysporum* f. sp. radicis lycospersici) known to cause Fusarium crown rot on tomatoes (Watterson, 1985). In addition to these pathogens, *Macrophomina* sp. was frequently isolated in 1996.

3.3.1. Plant parasitic nematodes in bulk soil

In 1988, root-knot nematodes were nearly absent from all plots that were planted to tomato in 1989. However, because of one plot with a density of over 14,000 l^{-1} of soil, the mean density of root knot nematodes across all plots was 1256 l^{-1} of soil. In 1990, root-knot nematode densities in all plots were relatively low and similar across treatments and crops. Over the course of the experiment root-knot nematode abundance was variable but showed a gradual increase in all treatments and both crops. Population levels increased at a somewhat greater rate in tomato compared to corn (Fig. 6). Significant treatment effects were found only in 1994, when

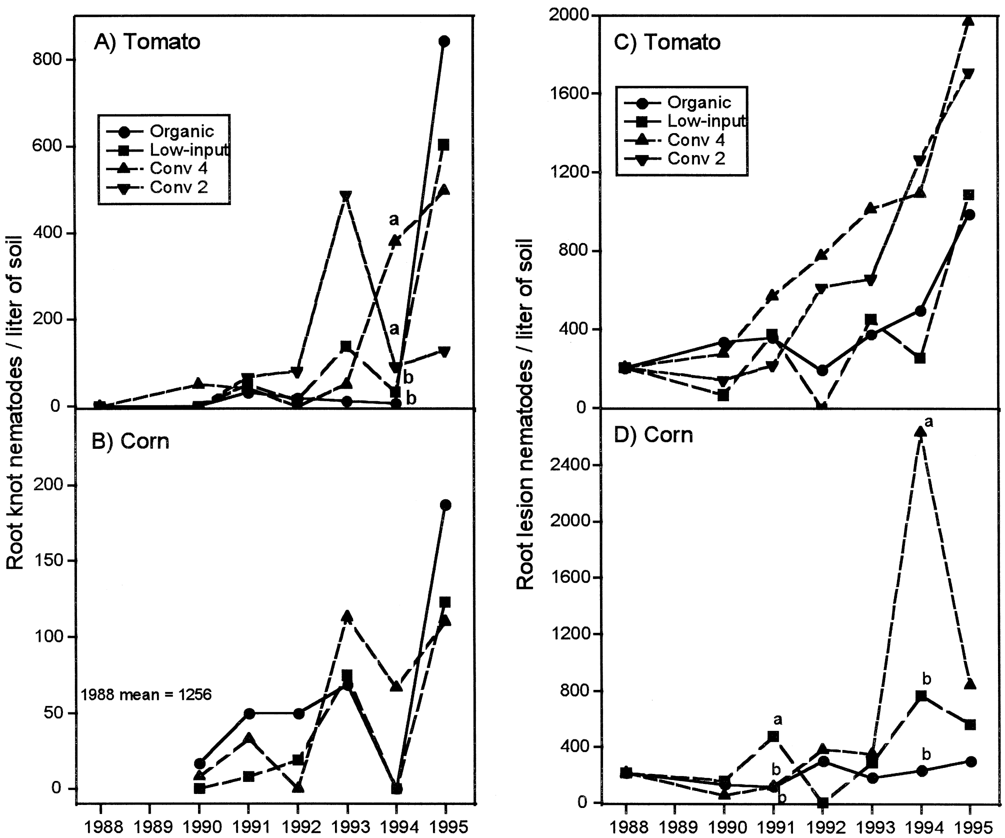

Fig. 6. Root-knot nematode (A, B) and root-lesion nematode (C, D) densities in soils with tomato (A, C) and corn (B, D), in the four farming system treatments of the SAFS project, Davis, CA, 1988–1995. Different letters indicate significant treatment differences using Analysis of Variance followed by the Student–Newman–Keuls test, $P \leq 0.05$.

levels in tomato were greater in the two conventional systems compared to the alternative systems (Fig. 6A).

Root-lesion nematodes tended to be more abundant than root-knot nematodes in soils of both crops. In tomato, root-lesion nematode abundance generally increased in all treatments from 1990 to 1996, but showed slightly more rapid and pronounced population growth in the conventional treatments (Fig. 6C). Nevertheless, no statistically significant differences among treatments were found. By contrast, root-lesion nematode abundance in corn plots remained relatively stable in all treatments with the exception of the Conv-4 system in 1994. Densities were significantly greater in the low-input compared to the other two systems in 1991 and in the Conv-4 compared to the other two systems in 1994. The significant treatment effects observed in 1991 may not have been a result of differences in corn management because samples were taken only seven weeks after planting. However, no major differences in the management of the previous safflower or vetch crops in the organic and low-input systems appears to account for the differences in root-lesion nematode densities. The organic corn system generally had the lowest root-lesion nematode densities throughout the study (Fig. 6D).

3.3.2. Plant-parasitic nematodes in rhizosphere

Root galling, typical of root-knot nematode symptoms, was observed only occasionally; there were no significant differences among treatments (Fig. 5F). Root-knot nematodes were extracted from roots with root-knot symptoms and identified as *Meloidogyne javanica* Treub. in 1995. Rhizosphere samples from plants with knobby roots were examined for *Xiphinema* sp. but these nematodes were not observed and therefore probably not the cause of the observed symptoms. However, rhizosphere samples

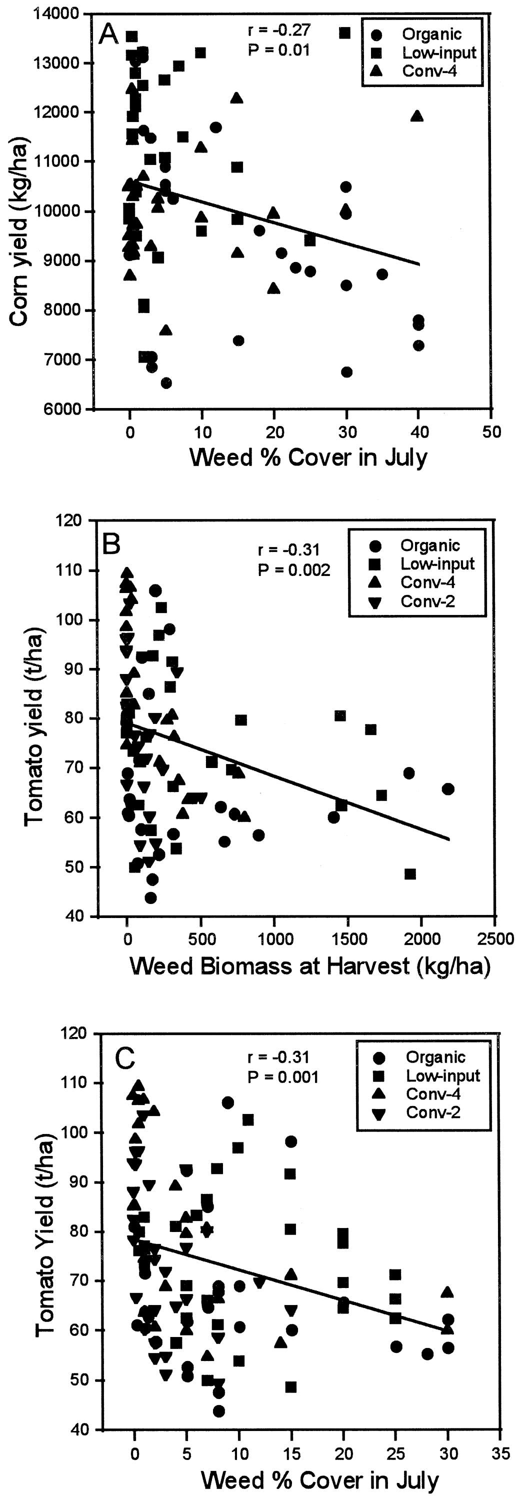

Fig. 7. Correlation between weed percent cover in July and corn yield ($r = -0.27$, $P = 0.01$) (A), weed biomass at harvest and tomato yield ($r = -0.31$, $P = 0.002$) (B), and weed percent cover in July and tomato yield ($r = -0.31$, $P = 0.001$) (C), SAFS project, Davis, CA, 1990–1996.

contained low to moderate numbers of root lesion nematodes (about 20 l^{-1} of soil in 1995 and 415 l^{-1} of soil in 1996) and stunt nematodes, *Tylenchorhynchus* sp. (230 l^{-1} of soil in 1995).

3.4. Pest effects on crop yields

Tomato yields in the organic, low-input and Conv-2 systems averaged 17%, 6%, and 7% less than the Conv-4 system over the 8-year period. In corn, however, yields in the organic system averaged only 5% less and yields in the low-input system were 11% greater than those of the Conv-4 system. Significant treatment effects were detected in 5 of the 8 years of the study in both crops (data not shown). Among the 21 pest variables analyzed, only weed abundance showed significant correlations with crop yield. Weed percent cover was negatively correlated with corn yield ($r = -0.27$; $P = 0.01$) and tomato yield ($r = -0.31$; $P = 0.001$), and weed biomass at harvest was negatively correlated with tomato yield ($r = -0.31$; $P = 0.002$) (Fig. 7). Moreover, most data points with high weed cover and/or biomass and low crop yield were from the organic and low-input systems suggesting that weed competition was at least partially responsible for reduced crop yields in those systems (Fig. 7). However, the low correlation coefficients and wide range in crop yields at low weed-cover values indicate that other factors influenced relative yields as well. Interestingly, weed biomass at harvest was not correlated with corn yield. This lack of correlation and the relatively weak correlation between weed cover and biomass in corn indicates that these two weed sampling methods provided considerably different indications of weed pressure.

3.5. Pesticide use

Sulfur and synthetic chemical herbicides accounted for most of the pesticide active ingredient applied to the tomato systems over the 8 years (Table 3). Sulfur, used to control russet mites, was applied equally across treatments. All sulfur was applied during the first 3 years of the study and totalled about 20 kg ha^{-1} in each system. By contrast, most synthetic herbicide was applied to the conventional systems. Herbicides were used in the conventional tomato systems in all 8 years of the study, while they were used in only 2 years in the low-input system (Table 4). Similarly, most synthetic insecticides and fungicides were applied in the conventional systems, though they were used less often than herbicides. The total amount of synthetic pesticide used in the low-input system was $\approx 15\%$ of that used in the conventional systems (Table 3). No synthetic pesticides were used in the organic system. Instead, insecticidal soap and Bt were each applied to the organic tomato system in 1 year of the study to control potato aphids and tomato fruitworm, re-

Table 3
Total amount of pesticide active ingredient applied (kg ha^{-1}) and the environmental impact value calculated as the sum of the Environmental Impact Quotients (EIQ) for each pesticide used in the tomato and corn cropping systems over eight years (1989–1996)

Crop	Pesticide	Organic	Low-input	Conv-4	Conv-2
Tomato	Synthetic chemical insecticides	0	1.12	4.48	4.48
	Microbial insecticides	0.03	0.03	0	0
	Insecticidal soap	0.78	0	0	0
	Sulfur	20.16	20.16	20.16	20.16
	Synthetic chemical herbicides	0	0	12.75	13.56
	Synthetic chemical fungicides	0	2.52	5.17	5.17
	Total pesticides	20.97	23.83	42.56	43.37
	Environmental impact value	932.94	1120.09	1894.71	1787.90
Corn	Synthetic chemical insecticides	0	0	4.09	NA[a]
	Synthetic chemical herbicides	0	5.60	16.91	NA
	Total pesticides	0	5.60	21.00	NA
	Environmental impact value	0	275.13	618.88	NA

[a] Not applicable.

Table 4
Number of years (out of eight) in which herbicides, insecticides/acaricides, and fungicides were used in the tomato and corn cropping systems of the SAFS project, Davis, CA, 1989–1996

Crop	Pesticide group	Number of years pesticide group used			
		Organic	Low-input	Conv-4	Conv-2
Tomato	Herbicide	0	0	8	8
	Insecticide /acaricide	3	3	5	5
	Fungicide	0	1	1	1
Corn	Herbicide	0	4	7	NA[a]
	Insecticide /acaricide	0	0	2	NA
	Fungicide	0	0	0	NA

[a] Not applicable.

spectively. Increased cultivation and hand weeding were substituted for the herbicides. Fungicide was applied preventively only in the first year of the study in anticipation of a predicted early fall rain.

The total amount of pesticide used in corn was substantially less than in tomato largely because of the absence of sulfur. Synthetic herbicides, which were used in the Conv-4 and low-input systems in 7 and 4 years of the study, respectively (Table 4), accounted for most pesticide active ingredient applied (Table 3). Total herbicide use in the low-input system was about 30% of that in the Conv-4 system. However, because no insecticides were used in the low-input system, total pesticide use in the low-input system was only about 20% of that in the Conv-4 system. No pesticides were used in the organic corn system.

3.6. Pesticide environmental impact

The potential environmental impact of pesticide use, measured as the sum of the EIQ field use ratings, was substantially greater in the tomato compared to the corn systems for all treatments (Table 3). For tomato, the environmental impact of the organic system was about one-half that of the conventional systems and slightly less than the low-input system (Table 3). Sulfur contributed the most to the environmental effect of all tomato systems. However, in the conventional systems, the occasional use of several compounds with high EIQ values, such as dimethoate, esfenvalerate, and mancozeb, and the regular use of compounds with low to moderate EIQ values, such as glyphosate and trifluralin, contributed significantly to the total environmental impact as well. The slightly higher environmental impact value in the low-input compared to the organic system was due mostly to the use of endosulfan in 1989 for aphids.

In corn, the environmental effect of pesticide use was highest in the Conv-4 system and lowest in the organic system (Fig. 8B). In fact, the environmental

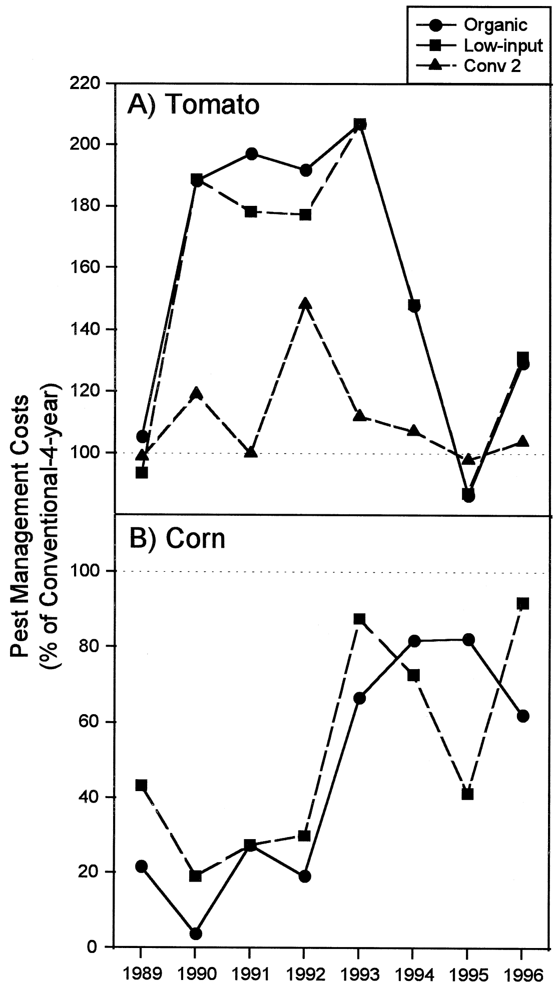

Fig. 8. Relative pest management costs in the tomato (A) and corn (B) systems of the organic, low-input, and Conv-2 treatments presented as a percentage of pest management costs in the Conv-4 system, SAFS project, Davis, CA, 1989–1996.

Table 5
Average pest management costs for tomato and corn in the four farming system treatments as a percentage of total operational costs, SAFS project, Davis, CA, 1989–1996

Crop	Pest group	Management cost (percentage of total operational costs)			
		Organic	Low-input	Conv-4	Conv-2
Tomato	Weeds	23.0	24.7	22.2	23.4
	Insects/mites	1.4	0.7	2.9	2.5
	Diseases	0.4	0.5	0.2	0.6
	Total	24.8	25.9	25.3	25.5
Corn	Weeds	3.6	5.2	11.5	NA[a]
	Insects/mites	0	0	1.7	NA
	Diseases	0	0	0	NA
	Total	3.6	5.2	13.2	NA

[a] Not applicable.

impact value of the organic systems was 0 because no pesticides were applied. The frequent use of glyphosate and occasional use of propargite largely accounted for the environmental impact value of the Conv-4 system. In the low-input system, the use of 2,4-D contributed most to the environmental impact value.

3.7. Pest management costs

Comparisons of total pest management costs in the alternative systems relative to the Conv-4 system illustrate dramatically different patterns between the tomato and corn crops. In tomato, pest management costs in the alternative systems averaged 51–57% greater than Conv-4 system costs over the 8 years (Fig. 8A). Weed management costs contributed the most to total pest management costs in all tomato systems and, as a proportion of total production costs, were nearly identical across treatments (Table 5). However, in absolute costs, weed management was considerably more expensive in the alternative systems because of greater reliance on hand hoeing. In fact, hand hoeing was largely responsible for the differences in costs between the alternative and conventional tomato systems. The lower costs in the alternative tomato systems from 1994 to 1996 relative to the prior 4-year period (1990–1993) were due to increases in hand hoeing costs in the Conv-4 system rather than cost reductions in the alternative systems (Fig. 8A).

Pest management costs in the alternative corn systems were lower, averaging 48–54% less than costs in the Conv-4 system throughout the study (Fig. 8B). However, in absolute costs, treatment differences were much smaller in corn than in tomato because pest management comprised a relatively small portion of corn production expenses, and corn was only about one-third as costly to produce as tomato. Nevertheless, cultivation was more cost effective than herbicide use in managing weeds and brought pest management costs down to 5% or less of total production expenses in the alternative systems (Table 5). The higher relative pest management costs in the alternative corn systems during the second rotation cycle (1993–1996) compared to the first (1989–1992) resulted from the use of two cultivations per season in the second rotation and only one cultivation during first rotation (Fig. 8B).

4. Discussion

The experimental treatments in this study provided relatively realistic examples of agricultural systems with widely differing pesticide inputs. All of the systems used pesticides to some degree, but in the low-input and organic systems pesticide use was reduced by 50% or more by substituting non-chemical tactics and tolerating higher pest densities. Although some differences in pest densities among treatments were observed, with the exception of weeds there was little evidence that pest abundance was an important factor in influencing crop yields. In fact, the findings of this study indicate that pests had relatively little influence on tomato or corn yields in comparison to other studies. However, because the alternative systems differed from the conventional systems in fertility management as well as in pest management, yield differences would likely not be attributable solely to pest abundance or pesticide use. Previous research at the SAFS experiment indicated that nitrogen availability was an important factor in explaining tomato and corn yield variability among treatments (Scow et al., 1994; Cavero et al., 1997; Friedman et al., 1997). Furthermore, fertility and pest management practices may interact, making separation of associated effects on productivity difficult to decipher. However, this study may support the explanation that lower relative yields in the alternative systems were related to nitrogen availability in that weed competition may have been partially responsible for the nitrogen limitation.

Although significant treatment differences were found in the levels of a range of pests, either consistently or occasionally, only weed abundance was found to be associated consistently over the years with reduced crop yields. Weed percent groundcover in July was negatively correlated with corn and tomato yields and weed biomass at harvest was negatively correlated with tomato yield. These correlations, along with crop yield data, indicate that weed competition was partially responsible for reduced crop yields in the alternative systems relative to the conventional systems at least in some years. Furthermore, these findings suggest that dependence solely on mechanical weed control, including cultivation and hand hoeing, is somewhat less reliable than using a combination of mechanical and chemical control. For example, in the low-input corn system, cultivation was the primary means of weed management, though herbicides were used in 4 of the 8 years. The level of weed control achieved with this approach was clearly as effective as that in the Conv-4 system which used three times more herbicide. Nevertheless, weed management in the organic corn system should not be entirely discounted. Although weed abundance was often substantially greater in that system compared to the others, yield loss to weed competition was less than 5% relative to the Conv-4 system even though no herbicides were used.

The lack of significant treatment and yield effects for arthropod pests was not particularly surprising considering the spatial scale and layout of the experimental site. The size of the plots was relatively small in comparison to the scale at which arthropod outbreaks occur. Furthermore, the infrequent need for therapeutic arthropod control measures was possibly a consequence of the high degree of vegetative diversity created by the randomized patchwork of crops. Spatial diversity is well known to influence the abundance of arthropod pests and their natural enemies, with greater diversity usually being associated with reduced pest levels (Altieri, 1994; Marino and Landis, 1996). Thus, the entomological findings of this study should be interpreted with the most caution because they are likely to be the least representative of pest levels in farmers' fields.

Planting date probably played some role in influencing arthropod pests in tomato. Earlier tomato planting dates in the later years of the experiment apparently contributed to lower tomato fruit injury among all treatments. In general, later tomato plantings require insecticidal treatment more frequently than earlier plantings (e.g., Antle and Park, 1986; University of California, 1990).

Foliar plant pathogens were seldom severe enough to warrant fungicide applications. This can be ascribed to the relatively dry California climate. Thus, no consistent difference were observed among farming systems. Foliar diseases on tomatoes and other vegetables would be expected to be more severe in organic farming systems in more humid climates.

Soil-borne pathogens in tomato showed some significant differences between treatments but only a few were consistent over the 2 years of sampling. Differences in corky root, and root rots caused by *Fusarium* spp. and *Pythium* spp. appeared to be influenced most by the length of the rotation. These diseases tended to be more common in the Conv-2 system compared to the other systems, all of which had 4-year rotations. General reductions in soil-borne pathogens and root disease severity in organic and low-input compared to conventional systems can be ascribed to longer rotations, regular applications of organic amendments, or abstinence from or reductions in pesticide use (van Bruggen, 1995). However, the exact mechanisms of root disease suppression in organic and low-input systems are not well understood. It is generally assumed that organic amendments reduce root diseases by increasing the level of microbial activity, resulting in increased competition and/or antagonism in the rhizosphere. Enhanced activity of the microfauna can also contribute to disease suppression by increased grazing of fungal plant pathogens in soil. Finally, a reduction in mycorrhizal infection of roots in conventionally compared to organically-managed soils may also contribute to the increase in root diseases observed in conventionally-managed soils. In this study, rotation length appeared to be the most important factor influencing disease severity. Although it is well known that diseases are more effectively managed with longer rotations, the economic returns from tomato production encourage growers to plant this crop more often. Increased disease severity in this analysis was not associated with detectable yield loss. Nevertheless, the findings suggest that the risks of future yield loss to soil-borne pathogens are greater with the 2-year rotation compared to the 4-year rotation.

Root-knot nematode and root-lesion nematode tended to increase in all treatments and crops over the course of this study. However, neither of these pests reached what would be considered economically damaging levels; hence no therapeutic treatments were directed at them. Statistically significant differences in root-knot nematode densities were found only in 1994. In that year, higher densities were found in the conventional compared to the alternative tomato systems, suggesting that the soil management practices used in the alternative systems may have directly or indirectly suppressed this pest, compared to the conventional systems. Nevertheless, the increasing nematode densities in all systems suggest that the continued use of susceptible tomato cultivars, which are selected based upon market demand, may create future pest management problems and should be reconsidered in light of the potential economic and environmental costs of their continued use, including yield loss and/or the need for nematicide applications. This situation illustrates the conflicts which can arise between integrating pest management practices and fulfilling the requirements of processors or buyers.

The root-lesion nematode species (*P. thornei*) is a potential pest of corn but is not known to affect tomato. Significant treatment differences were found in 2 years of the study and in one of those years (1994) root-lesion nematode reached relatively high densities in the Conv-4 system. Although corn yields in that system were significantly lower than yields in the organic and low-input systems (data not shown), there is no evidence to suggest that nematode damage was responsible for the differences. In general, plant-parasitic nematode densities have been low and have not required management intervention to reduce their numbers. However, the gradual increase in the densities of these pests in all of the treatments, but particularly in the Conv-2 system, may result in the need for future control measures.

With the exception of weeds, the different pest management systems represented in this study did not result in dramatically different pest levels in either crop. Weeds were more problematic in the organic system because of the non-use of herbicides, but other pests either did not differ between treatments or tended to be more abundant, though not at economically-damaging levels, in one or both of the conventional systems. The estimated economic costs and environmental effects of the different pest management approaches, however, varied tremendously with farming system and crop.

The use of non-chemical weed management in tomato, cultivation and hand hoeing, resulted in substantially increased pest management costs for the low-input and organic systems primarily because of the high labor costs for hand hoeing. For the organic system, this is not necessarily a problem because of the premium prices received for organically-grown products (Klonsky and Livingston, 1994). In a sense, consumers paying for organic premiums are absorbing some of the environmental costs of agriculture because farmers are compensated for reducing the environmental effects of pesticide use. But without premium prices, such increased costs may not be justifiable in a system in which weed management expenses account for over 20% of total operational costs.

The situation with corn is quite different than that of tomato, however, because the economic costs of the alternative systems were less than conventional pest management practices. Cultivation generally proved to be more cost-effective than herbicide use but the modest use of herbicides did improve yields, as evidenced in the low-input system. These findings suggest the low-input pest management system, which depends primarily on cultivation and uses herbicides occasionally, may be the best approach to optimize agronomic, economic, and environmental concerns in corn production.

5. Conclusions

The findings of this study illustrate the dramatic differences in the potential to reduce pesticide use in processing tomato and corn systems in northern California. Based on this comparison of organic, low-input, and conventional cropping systems, pesticide reductions in processing tomato production, particularly for weed management, appear to be economically costly using currently utilized non-chemical practices and available technologies. Although the amount of pesticide applied could be reduced by 50%, resulting in less potential environmental degradation, premium prices are needed to compensate growers for increased pest management costs which may average 50% more than conventional pest management costs. By contrast, the amount of pesticide applied in corn grown in a 4-year rotation could be reduced by 50–100% with little or no reduction in yield. Furthermore, the substitution of cultivation for some or all herbicide applications may reduce pest management costs by 50% or more and result in less potential environmental impact. Without premium prices for corn, however, an economically and environmentally acceptable approach should involve an integration of non-chemical methods with occasional pesticide applications.

Acknowledgements

The authors gratefully acknowledge expertise and hard work of Diana Friedman, Oscar Somasco, and Mary Kirk Wyland, former research managers on the SAFS project, and William Cruickshank and Don Stewart, SAFS crop production managers. Many students, faculty, and staff members from the University of California at Davis have contributed to this study over the years, especially Jim Marois, Ted Wilson, Mike Hoffmann, Rob Venette, Sean Lau, Cindy Anderson, Joe Wakeman, Pete Livingston, Kelly Brewer, Anne Juurma, Greg Parra, and Hans van der Muelen. Support for the SAFS project has been provided by USDA/EPA SARE/ACE, University of California Sustainable Agriculture and Education (UC SAREP) Program, California Department of Food and Agriculture (CDFA) Fertilizer Research and Education Program (FREP), University of California Division of Agriculture and Natural Resources (UC DANR), and many local businesses that have contributed supplies.

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