



# Crop yields over the first nine years of LTRAS, a long-term comparison of field crop systems in a Mediterranean climate

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## Abstract

The Long-Term Research on Agricultural Systems (LTRAS) experiment has been monitoring the long-term effects of conventional and alternative practices on crop yields and soil properties since 1993, with a planned duration of 100 years. Data for the first 9 years are presented here. Ten, 2-year rotations, each with three 0.4 ha plots per phase of the rotation, range from low-input rainfed unfertilized wheat to high-input irrigated conventional and organic maize–tomato systems. For years 3–9, average yields of alternative (organic and green manure) systems were significantly lower than those of comparable conventional systems, except that there were no significant differences in average yields of tomato. Delayed seeding after a winter legume cover crop (LCC) limited maize yields. Yield trends over years were somewhat obscured by variability due to weather. Negative yield trends over years in unfertilized wheat controls were statistically significant, but only when data for the 9th year were included. Yield trends for organic maize were also significantly negative, but tomato yields in the same system showed a significant positive trend, as did yields of conventional maize. As this experiment continues, long-term trends in soil properties and processes could alter the magnitude or direction of trends seen to date.

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## 1. Introduction

There are many criteria by which agriculture may be judged, but agronomic sustainability, i.e. “whether the production level can be maintained over years at the same site” (Loomis and Connor, 1992, p. 5) is essential. Practices that cause irreversible damage to the soil (e.g. erosion) are of greater concern than those, like nutrient depletion, whose effects usually can be corrected once detected. Particularly insidious are practices with

adverse effects that are irreversible, yet not readily apparent until after the damage has been done.

A dramatic example of unsustainable practices comes from the long-term Agdell experiment, started at Rothamsted, UK in 1848 (Powlson and Johnston, 1994). Turnip (*Brassica rapa*) yields increased for the first 40 years—the system appeared to be sustainable—but then began to decrease, approaching zero by 1951. Scientific advances over the course of this experiment helped identify the cause, which would have been difficult to predict with the information available when the experiment began. Soil acidification caused by the form of nitrogen fertilizer used had favored the growth of the root pathogen, *Plasmodiophora brassicae*,

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which remained a problem even after soil pH was corrected.

Even when deterioration in soil quality has some immediate effect on yield, gradual changes may be difficult to detect. Soil salinization in southern Iraq, caused by irrigation without adequate drainage, led to a decrease in barley (*Hordeum vulgare*) yields from 2537 l/ha in 2400 B.C. to 1460 l/ha in 2100 B.C. (Jacobsen and Adams, 1958). This gradual decline, a 40% decrease over 12 generations, might not have been apparent within the lifetime of an individual farmer, yet it contributed to the collapse of urban centers in the region. Even if some farms experienced faster deterioration than the region as a whole, such slow change could easily have been obscured by weather variability among years.

The UC Davis Long-Term Research on Agricultural Systems (LTRAS) project was designed as an early warning system to detect subtle or gradual deleterious changes in soil properties that might, perhaps, result from common agricultural practices. The results discussed above show that nitrogen fertilizer or irrigation water can sometimes have serious adverse effects on soil quality, but this is not always the case. For example, continuous wheat (*Triticum aestivum*) that received only inorganic fertilizers doubled in yield over a period of 150 years at Rothamsted, a trend similar to that for plots fertilized with animal manure (Johnston and Powlson, 1994).

Few if any long-term field experiments have compared the sustainability of irrigated with rainfed agriculture in a Mediterranean climate. Given what we have learned about soil management, it is not unreasonable to hope that irrigated agriculture (with adequate drainage) and careful use of inorganic fertilizers (with pH adjustment when needed) may be sustainable. But the possible regional and national consequences of unanticipated decreases in agricultural productivity are serious enough to warrant this long-term assessment of sustainability, so that any practices found to be unsustainable can be changed. Alternatively, if concerns about the sustainability of current practices prove unjustified, data from LTRAS should help to allay those concerns. Although the emphasis is on agronomic sustainability (termed “sustainability” for brevity), LTRAS was also intended to address environmental issues, such as nitrate leaching or efficient use of scarce resources like water.

Cropping systems at LTRAS include some alternative practices that are considered by some to be more sustainable, including low-input and organic methods. Because manure supplies are limited—the statewide supply of manure in California is only about 2000 kg per irrigated hectare (Chaney et al., 1992, p. 13)—only 1 of 10 cropping systems receives external inputs of composted manure. Four systems rely on green manures, winter legume cover crops (LCCs) which could, in principle, be grown widely. Because competition for water is expected to increase in California and in other regions with Mediterranean climates, six cropping systems requiring little or no irrigation (variants on a wheat–fallow rotation) were included.

The only experiment with LCCs whose longevity approaches the fertility experiments at Rothamsted, suggests that some of their beneficial effects may take 20 years or more to become apparent (Mitchell et al., 1996). The effects of manure additions on soil organic matter may take even longer to reach steady state. At Rothamsted, the soil organic matter content of manure-amended plots continued to increase for more than 50 years before leveling off (Jenkinson, 1991). Because the soil properties underlying the agronomic and environmental performance of conventional and alternative cropping systems may depend in part on soil properties that change over decades rather than years, LTRAS has a planned duration of 100 years. It is anticipated that, as in other long-term experiments, there will be some changes (at least in cultivars used) over the course of the experiment.

This paper explains the overall experimental design of LTRAS, describes “time zero” characterization of the site, and presents crop yield data for the first 9 years. Data on N, C, and water balances and related issues will be published separately. A companion paper (Martini et al., 2003) provides details particularly relevant to organic farming.

## 2. Materials and methods

### 2.1. Spatial characterization of initial conditions

The LTRAS site was previously farmed commercially. Alfalfa (*Medicago sativa*) was the last commercial crop, grown over the entire plot area. The soils

are mapped as Yolo silt loam (fine-silty, mixed non-acid, thermic Typic Xerothents) and Rincon silty clay loam (fine, montmorillonitic, thermic Mollic Haploxeralfs). The site was laser-leveled in 1991 to facilitate furrow irrigation, typical of field crop production in the Sacramento Valley, and was subdivided into 72 square, 0.4 ha plots.

In 1992 and 1993, irrigated but unfertilized sudangrass (*Sorghum vulgare*) hay was grown over the entire site to assess the intrinsic productivity of each plot prior to the imposition of treatments. Variability across the field and within plots was documented by measurement of biomass yield for each plot, and by a preharvest false-color IR aerial photograph, used to calculate a normalized difference vegetation index (NDVI) as described previously (Denison et al., 1996). Three plots with particularly low yields (apparently due to topsoil removal during leveling) were excluded when treatments were randomly assigned within blocks.

“Time zero” archival soil samples were collected during autumn 1993. In anticipation of possible future subdividing of plots, soil samples were composited separately from the east and west half of each plot, for depths of 0–15, 15–30, 30–60, 60–100 and 100–200 cm, and air-dried. Six 1 cm × 5 cm soil cores per plot were collected with a flame-sterilized sampler and freeze-dried aseptically, to allow future assessments of initial soil microbial diversity by DNA-based methods. Additional archival samples from time zero include sudangrass hay samples from each plot and a collection of weed seeds, stored at –70 °C, from four areas at plot edges where weeds were allowed to set seed.

## 2.2. Weather

Monthly rainfall data from weather station Davis.A, which is surrounded by irrigated grass, were obtained from the web page of the University of California’s Integrated Pest Management program (<http://www.ipm.ucdavis.edu/calludt.cgi/WXSTATIONDATA?STN=DAVIS.A>). Monthly rainfall totals and air temperature averages were calculated for each month and year. Conditions during March and December were considered likely to have the greatest effect on establishment of summer and winter crops, respectively. Wet soil generally prevails during January and February, but the timing of germination of wheat and LCC depends on December rainfall. Conditions in March may affect the risk of soil compaction as plots are prepared for irrigated summer crops.

## 2.3. Experimental design and cropping systems

The main LTRAS experiment has a split-plot design with water (dryland versus irrigated) as the main factor. Subplots differ mainly in nitrogen input levels and source, but the overall design is not factorial. For example, production of processing tomato (*Lycopersicon esculentum*), which is currently the most profitable field crop in the area, is impractical without irrigation, so all systems with tomato are irrigated. The 10 cropping systems are summarized in Table 1, which also gives the three-letter abbreviation for each system. Table 2 provides additional information on planting and harvest dates and on inputs to each system. Each cropping system is represented by three replicate plots

Table 1  
Crop sequence for cropping systems at LTRAS

System	Winter	Summer	Winter	Summer
Conv. maize–tomato (CMT)	–	Maize	–	Tomato
Organic maize–tomato (OMT)	LCC <sup>a</sup>	Maize	LCC	Tomato
Legume–maize–tomato (LMT)	LCC	Maize	–	Tomato
Conventional wheat–tomato (CWT)	Wheat	–	–	Tomato
Irrigated wheat–fallow (IWF)	Wheat	–	–	–
Irrigated wheat–legume (IWL)	Wheat	–	LCC	–
Irrigated wheat control (IWC)	Wheat	–	–	–
Rainfed wheat–fallow (RWF)	Wheat	–	–	–
Rainfed wheat–legume (RWL)	Wheat	–	LCC	–
Rainfed wheat control (RWC)	Wheat	–	–	–

<sup>a</sup>LCC is a winter legume cover crop, incorporated in spring.

Table 2  
Summary of crop management. Dates are medians

Crop	System(s)	Planting		Harvest date	Fertilizer (kg/ha)		Irrigation (cm)
		Date	Plants/m <sup>2</sup>		N	P	
Wheat	RWC, RWL	11/18	200 <sup>a</sup>	6/24	0	0 <sup>b</sup>	0
Wheat	RWF	11/18	200	6/24	110	0	0
Wheat	IWC	11/18	300 <sup>a</sup>	6/24	0	0	18
Wheat	IWL	11/18	300	6/24	0	0	18
Wheat	IWF, CWT	11/18	300	6/24	165	0	18
Maize	CMT	4/19	8.0	10/20	235	44	67
Maize	LMT	5/15	6.1	10/20	0	0	74
Maize	OMT	5/15	8.0	10/20	373 <sup>c</sup>	300 <sup>c</sup>	85
Tomato	CMT, CWT	4/24	2.5	8/21	160	44	47
Tomato	LMT	4/24	2.5	8/21	160	44	59
Tomato	OMT	4/24	2.5	8/21	214 <sup>c</sup>	173 <sup>c</sup>	91
LCC	RWL, IWL	11/3	148 <sup>d</sup>	4/12	0	0	0
LCC	LMT, OMT	11/3	148	4/3	0	0	0

<sup>a</sup>Seeding rates for rainfed and irrigated systems were 110 and 132 kg/ha, respectively, but cultivar ‘Yolo’ used in irrigated plots had lower weight per seed than did ‘Serra’.

<sup>b</sup>No annual P inputs to wheat, but occasional additions (100 kg/ha in 1998) based on a soil test.

<sup>c</sup>N and P inputs to organic system are from compost, using measured N-content and published N/P ratio (Hartz et al., 2000). N input from N<sub>2</sub> fixation by green manure was not included.

<sup>d</sup>Approximately 24% peas and the remainder vetch.

with both phases (years) of each 2-year rotation represented every year.

Crops are planted to beds and applied water is furrow run in all irrigated systems. Fall planted crops are rainfall initiated and spring-summer irrigations are scheduled to eliminate water stress, particularly during sensitive physiological stages such as anthesis. Preplant irrigation to germinate weed seeds, followed by tillage, was initiated in autumn of 2000 in the irrigated wheat systems. Similarly, the planting setback in the OMT and LMT systems provides the opportunity for similar weed-controlling preplant irrigations in the spring.

LCCs, wheat and maize (*Zea mays*) are direct seeded. All tomato systems are transplanted simultaneously for a relatively synchronous harvest. Fertilizer applications are split in all systems to best correspond to crop demands. Currently, legume biomass and compost inputs in the LMT and OMT systems are incorporated using bed-preserving tillage equipment. All other in-season cultivations are accomplished using full-scale equipment to be representative of commercial farming operations. Fallow weed control is completed with a combination of herbicides and mechanical tillage as appropriate. A computer database

with additional detail on crop management is available from the authors.

#### 2.4. Comparing systems, not factors

LTRAS compares the performance of cropping systems, not the effects of single factors. Some management practices that might not be cost-effective in a conventional system (e.g. preirrigation and tillage to germinate and kill weeds) may be profitable in an organic system, and vice versa. Similarly, irrigation can increase the crop's N demand by increasing yield potential, so higher N inputs are an intrinsic feature of irrigated systems.

A valid comparison among cropping systems requires that each system comes as close as possible to achieving its own potential. For example, failure to use a valuable synthetic input in a conventional system, just because there is no equivalent product certified for organic use, would bias comparisons between organic and conventional systems. The best cultivar for an irrigated system is not necessarily the best cultivar for a rainfed system. Rather than arbitrarily biasing our results in favor of one system or another, we attempted to identify and use the most appropriate

cultivar for each system. The optimum timing of irrigation or harvest might also differ among systems. This approach has implications for the interpretation of our results. It allows an unbiased comparison of irrigated versus rainfed systems, for example, but provides no information on how a cultivar best suited to irrigation would have performed without irrigation.

When possible, we have tested the key assumption in this approach, namely that differences in management among systems (e.g. cultivar choices) do in fact contribute to the goal of achieving the full potential of each system. For example, expected planting delays associated with reliance on an LCC led to the decision to use a shorter-season maize cultivar (NC + 4616) in the LMT and OMT systems, but a longer-season cultivar (Pioneer 3162) in the CMT system. The two main assumptions upon which this decision was based were: (i) adequate N accumulation by the LCC would require late planting of following maize, and (ii) this reduction in the time available for maize growth would give short-season cultivars a higher grain yield (in an average year) than long-season cultivars.

These assumptions were tested in two related experiments, each replicated over 3 years. Growth and N accumulation of our standard mixture of vetch (*Vicia dasycarpa*) and pea (*Pisum sativum*) was determined by successive harvests of 2 plots, each 1.5 m × 3.0 m, on four or five dates each year. A vetch-only treatment was included. N-content was determined by nitrogen gas analyzer (Sweeney, 1989). To test the relative performance of the two maize cultivars following growth and incorporation of an LCC, they were grown at five different plant populations each year with management identical to the LMT system in the main experiment. Because this cultivar comparison was conducted in different plots in different years, years were used as blocks in analysis of variance.

### 2.5. Yield measurements

Hand harvests were used to establish total above ground biomass measurements and as a source of archival samples. Yield data reported here were obtained using full-scale commercial harvesters and combines typical to the area. All crop yield data were collected from the undisturbed central 0.2 ha sampling area in each plot.

For tomatoes, four independent full-length rows per plot were machine-harvested using mechanical and electronic color sorters to provide yield measurements representing a commercially saleable product. Reported plot yields are the mean of the four rows, each 1.5 m by approximately 61 m in length. For wheat and maize grain, two 61 m swaths through the central plot area were combined for each yield measurement. Wheat and maize swaths were 7.6 and 6.1 m wide, respectively. Exact row lengths for all crops were measured at time of harvest.

### 2.6. Analysis of yield data

Yield data are presented for all years, but statistical analyses exclude the first 2 years. With 2-year rotations, the effects of previous crops would not be reflected fully in crop yields until the third year. In the first cropping year (1994 harvests), wheat in the IWL and RWL systems did not follow a LCC, nor was wheat in the IWC and RWC systems preceded by a fallow year. Similarly, any effect of the previous growth of a particular crop species on subsequent yields of that crop (e.g. due to crop-specific soilborne pathogens) would not occur until at least 1996, the third year of the experiment. Excluding the first 2 years from statistical analyses also avoids confounding improvements in drainage infrastructure after winter flooding in 1995 with yield trends intrinsic to the cropping systems. Some cases for which inclusion or exclusion of 1 year affects statistical significance will be discussed.

Average yields of each crop for 1996–2002 were compared among cropping systems using one-way randomized block analysis of variance, treating years as repeated measures. Mean separations were based on SNK tests. Yield trends for each crop and system, over years 1996–2002, were analyzed by linear regression. All statistical analyses used CoStat software.

## 3. Results and discussion

### 3.1. Initial conditions

Aerial photos showing the unfertilized, irrigated sudangrass uniformity trial have been published (Denison et al., 1996). The field is divided by a

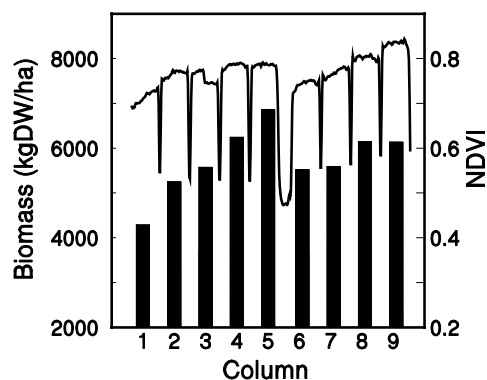


Fig. 1. West to east gradients in biomass yield (bars) and in NDVI (line) across a uniformly managed sudangrass crop. Each yield value is the average for a N–S column of eight plots, while each NDVI value is the average for a N–S line across the field.

N–S road, apparent in the NDVI trace in Fig. 1, separating five N–S columns of eight plots each to the west from four columns of plots to the east. Smaller alleys separating columns of plots are also visible in NDVI data. The slight offset in NDVI data within column 3 resulted from the initial use of only one half of a plot for the weather station. Since 1995, that plot has been uniformly managed with irrigated grass.

Both NDVI and sudangrass biomass yields increase from west to east within each half of the field. Topsoil was moved from west to east during land leveling. The low yield values for column 1 include three plots that were excluded from the long-term experiment because of their atypically low yields. Because percent cover

by sudangrass was nearly 100% in all plots, differences in NDVI and yield may largely reflect differences in soil N supply, which in turn may depend on differences in organic matter content. Analyses of archival soil and sudangrass hay samples to test this hypothesis will be published separately.

### 3.2. Weather

Tables 3 and 4 summarize some differences in weather among years. March was rainiest in 1995 and coldest in 1999, resulting in wet soil conditions that delayed maize seeding both years. Wet winter conditions also prevented ground application of herbicides to wheat in 1995 and 1999. December was driest in 1999. Although total rainfall in January 2000 was adequate, the first significant rain (>5 mm) was on 18 January, by which time growth of rainfed wheat in rotation with a LCC (RWL) was visibly less than even the corresponding unfertilized control (RWC).

### 3.3. Cultivar suitability

Test results supported the need for a shorter-season maize cultivar following the LCC. The peak N-content of aboveground LCC biomass ranged approximately from 100 to 200 kg N/ha (Fig. 2A). Inclusion of peas in the LCC mixture did not consistently increase total N-content at the time of incorporation, but we observed that peas did improve ground cover early in the winter, when vetch plants were still small. This could affect runoff and competitiveness with winter

Table 3  
Precipitation (mm) by month and year

	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
January	265	53	285	117	186	125	45	112	69	55
February	147	80	8	155	7	298	104	186	122	19
March	48	2	200	57	11	47	39	40	58	39
April	13	19	24	43	3	32	30	32	26	2
May	18	31	29	60	9	59	1	12	0	14
June	33	0	17	1	5	2	0	0	9	0
July	0	0	1	0	0	0	0	0	0	0
August	0	0	0	0	4	0	1	0	0	0
September	0	0	0	0	1	12	0	3	0	0
October	8	15	0	33	11	17	5	53	11	0
November	51	99	0	37	113	62	36	18	70	70
December	42	69	122	128	56	16	2	9	163	206

Table 4  
Mean air temperature by month and year

	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
January	7.1	8.4	10.6	9.2	8.5	9.2	7.0	9.2	7.2	7.0
February	9.4	9.2	11.5	12.2	11.0	9.5	8.8	10.3	9.0	10.4
March	14.4	12.8	11.8	13.2	13.9	12.0	10.2	12.7	14.1	11.5
April	15.0	15.1	14.4	15.9	16.1	13.9	14.2	16.1	12.9	14.5
May	17.7	17.6	17.2	18.2	20.9	14.6	17.4	19.0	22.1	17.9
June	22.0	21.3	20.7	21.9	21.5	19.5	20.7	22.5	22.3	22.3
July	23.2	22.7	23.4	24.6	23.2	23.5	21.5	21.6	22.4	23.4
August	22.9	22.4	23.1	23.7	22.9	24.3	22.2	22.6	22.8	22.3
September	21.9	21.4	21.4	20.3	22.8	21.8	22.1	21.4	21.2	21.8
October	18.3	16.9	18.1	16.8	16.8	16.1	18.5	16.4	18.7	16.6
November	11.1	8.6	14.4	12.2	12.8	11.3	12.6	9.1	13.1	12.3
December	6.9	6.3	10.2	9.9	7.8	6.0	8.6	8.2	8.9	9.2

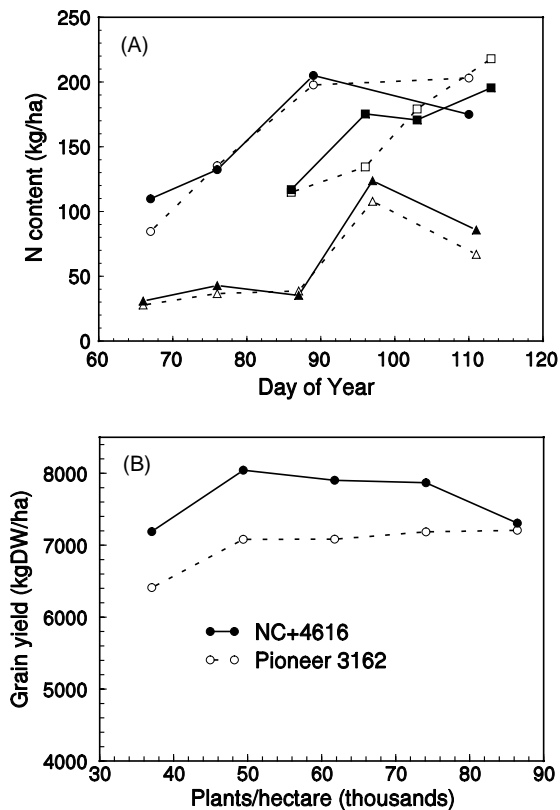


Fig. 2. Data supporting choice of a short-season maize cultivar in systems relying on a winter LCC. (A) Timing of N accumulation in LCCs in 3 different years. Solid symbols: vetch + pea; open symbols: vetch-only. (B) Grain yield of unfertilized maize, following LCC, for two cultivars at five densities.

weeds. There was considerable variation in LCC growth among years. Wet, cloudy conditions in the winter of 1994–1995 delayed significant LCC growth and N accumulation until April. In two of three years, incorporating the LCC early enough to seed maize by the typical date for conventional maize would have substantially reduced the N contribution of the LCC.

Seeding of maize in the OMT and LMT systems must be delayed at least 3 weeks after LCC incorporation, because fresh organic matter stimulates growth of the seed corn maggot (*Hylema ciliarura*). Given this delay, the 3-year maize cultivar comparison confirmed that NC + 4616, the shorter-season cultivar used in the LMT and OMT systems, outyielded the longer-season Pioneer 3162 when planted after a LCC. Results averaged over years are shown in Fig. 2B. Analysis of variance found a highly significant difference between the two cultivars. The effect of plant population was not statistically significant, with similar yields for populations between about 50,000 and 75,000 plants/ha. Based on these results, NC + 4616 was used for the OMT and LMT systems every year. NC + 4616 was also used for the CMT system in 1995 and 1999, when seeding of conventional maize was delayed by wet soil conditions.

### 3.4. Wheat yields

Crop yields for the first 9 years (1994–2002 harvests) are presented in Figs. 3 and 4. There was considerable

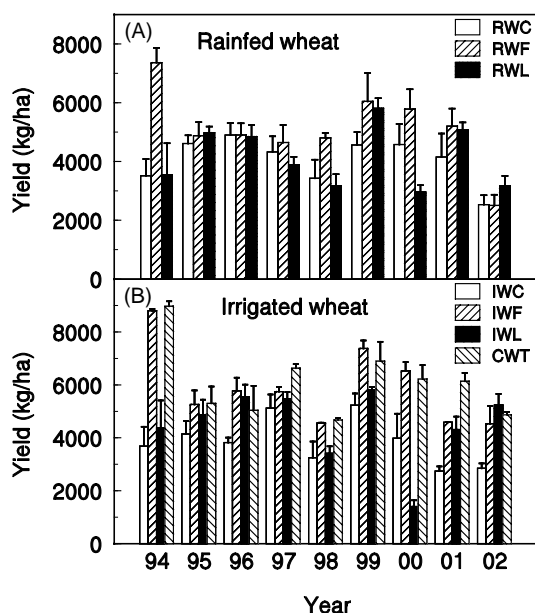


Fig. 3. Grain yield of rainfed (A) and irrigated (B) wheat cropping systems over the first 9 years of the LTRAS experiment. See Table 1 for abbreviations of systems. Error bars are standard deviations of three replicate plots.

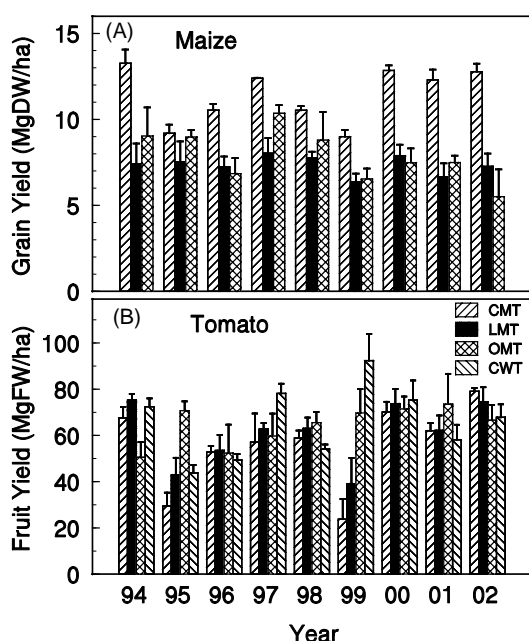


Fig. 4. Maize (A) and tomato (B) yields over the first 9 years of the LTRAS experiment. See Table 1 for abbreviations of systems. Error bars are standard deviations of three replicate plots.

variability among years. Cropping systems that were managed similarly in the first year had similar yields in 1994 harvests, before diverging in subsequent years. For example, the RWL and IWL systems had not yet had the LCC in 1994, so it is not surprising that their wheat yields were similar to the corresponding unfertilized controls, RWC and IWC (Fig. 3A and B). Similarly, the wheat phase of the CWT system was not preceded by tomato in 1994, and wheat yields were similar to the IWF system (Fig. 3B). Because of N uptake by the unfertilized sudangrass uniformity trial in the summer of 1993, the wheat–fallow systems seeded in autumn 1993 had access to N mineralized over a shorter period of time than those seeded in subsequent years. This may explain why yields in the RWC and IWC systems were lower in 1994 than in some subsequent years, despite the fact that no N fertilizer has been supplied to these plots since the experiment began.

Wheat systems with N from an LCC grown during the fallow year sometimes had yields similar to the fertilized control, as seen in 1996 and 2001 for both irrigated and rainfed wheat–fallow systems (Fig. 3). Negative effects of water use by the LCC on subsequent wheat yields were not apparent in most years, consistent with results previously reported for the first 3 years (McGuire et al., 1998). It appears that, in most years, rain in autumn and early winter replaced water used by the cover crop the previous spring. The year 2000 was a clear exception to this pattern, however. Lack of significant rain before the middle of January 2000 resulted in yields for the RWL that were even less than the unfertilized RWC. As a result of low yields in 2000 and, to a lesser extent, in 1998, the average yields of the RWL system for 1996–2002 were significantly lower than those of the RWF system and similar to those of the RWC (Table 5).

In the IWL system, the effects of water deficit in 2000 (prior to irrigation) were compounded by *Fusarium*, perhaps maintained on volunteer wheat during the LCC year. Average yields for the IWL system from 1996–2002 were significantly less than those of the fertilized IWF and CWT systems, although still significantly greater than IWC yields (Table 5). Since 2000, preplant irrigation and cultivation to kill wheat and weed seeds, prior to seeding of the LCC in these systems, has reduced volunteer wheat populations.

Table 5  
Mean crop yields for 1996–2002 harvests<sup>a</sup>

System	Rainfed wheat (kg DW/ha)	Irrigated wheat (kg DW/ha)	Irrigated maize (kg DW/ha)	Irrigated tomato (mg FW/ha)
CMT			11484 a	59.0 a
OMT			7559 b	65.6 a
LMT			7317 b	61.3 a
CWT		5779 a		67.9 a
IWF		5571 a		
IWL		4456 b		
IWC		3812 c		
RWF	4841 a			
RWL	4131 b			
RWC	4069 b			

<sup>a</sup>Values within a column are not significantly different ( $P < 0.05$ ) by SNK test if they are followed by the same letter.

### 3.5. Maize and tomato yields

Maize yields in the OMT and LMT systems were significantly lower than those in the CMT system, for 1996–2002 (Table 5). Some of the difference in maize yields appears to be a consequence of later seeding, resulting from delays associated with the LCC. In 1995, when wet weather delayed seeding of the conventional maize, there was no significant difference in maize yield between the conventional and organic systems (Fig. 4A). In 1999, however, conventional maize outyielded organic maize, despite being seeded on the same day. In both of these years, the same short-season cultivar NC + 4616 was used in all systems.

In contrast to maize, there was no statistically significant difference in tomato yields among systems for the period from 1996 to 2002 (Table 5). In 1999, there was a large difference in tomato yields between two conventional systems, CMT and CWT, differing in rotation crop (Fig. 4B). We attribute the low yields of CMT tomatoes in 1999 to compaction caused by plot preparation under wet soil conditions in spring 1999. Earlier harvest of wheat, relative to maize, allowed most plot preparation in the CWT to be completed in autumn 1998, under drier soil conditions. Somewhat similar results were seen in 1995 (Fig. 4B), which was not included in our statistical analyses (Table 5), for reasons discussed above. As discussed in a companion paper (Martini et al., 2003), the organic system seems to be less affected by soil

compaction, despite the additional spring tillage operations required to incorporate the LCC.

### 3.6. Yield trends over years

Yield trends over years are a direct measure of sustainability and may indicate improvement or deterioration in important soil properties. Yield trends could also be caused by trends in weather or by increasing experience. If weather or experience were the key factors, however, we would expect all systems to show similar yield trends, at least for a given crop. This was not the case. Most crop-system combinations showed no significant trends, and trends for maize in the conventional and organic systems were in opposite directions (Table 6). As archived samples are analyzed we will publish data on soil trends that may help to explain the few significant trends that did occur.

In the two unfertilized controls, RWC and IWC, nutrients removed in grain harvests were not replaced, so we expected yields to decrease over years. These systems did show statistically significant negative yield trends for 1996–2002 (Table 6), as expected. It is more surprising that, for both unfertilized controls, the trend was not significant if data for 2002 were excluded. The statistical uncertainty, over the first 8 years, about the sustainability even of unfertilized controls suggests that it may take another decade or more to draw conclusions about the sustainability of some other systems. In particular, yields in the RWL and IWL systems probably still reflect a significant N contribution from mineralization of soil organic matter, given that yields of the unfertilized controls still exceeded 50% that of their fertilized counterparts in 2001 and 2002 (Fig. 3). Yields in the legume-based

Table 6  
Statistically significant yield trends for 1996–2002<sup>a</sup>

System	Crop	Trend $\pm$ S.E. (kg ha <sup>-1</sup> per year)	P-value
Rainfed wheat control	Wheat	-225 $\pm$ 96	0.0298
Irrigated wheat control	Wheat	-236 $\pm$ 111	0.0467
Conv. maize–tomato	Maize	+314 $\pm$ 145	0.0433
Organic maize–tomato	Maize	-404 $\pm$ 179	0.0356
Organic maize–tomato	Tomato	+2717 $\pm$ 1176	0.0322

<sup>a</sup>Tomato yields are fresh weight.

systems will be an inadequate indicator of the sufficiency of N supply from N<sub>2</sub> fixation until yields in the unfertilized controls drop to a small fraction of yields in the fertilized systems.

Results for the OMT system appear contradictory. There was a significant positive trend for tomatoes and a significant negative trend for maize, over the years 1996–2002 (Table 6). The positive trend for organic tomatoes could be seen as evidence for improvement in soil quality with duration of organic management (MacRae et al., 1990), but the results for organic maize call this conclusion into question. A simultaneous improvement in some soil properties (e.g. organic matter content) and deterioration of others (e.g. increase in pathogen populations) might explain these contrasting trends. The negative trend for maize could be partly a function of cultivar-specific susceptibility to *Fusarium* (Martini et al., 2003). A resistant short-season cultivar might reverse the trend of decreasing yields and decrease the difference in maize yield between conventional and organic systems, but this remains to be seen.

Conventional maize showed a significant positive yield trend for 1996–2002 (Table 6). This result, in combination with the lack of a significant trend for tomato in the same CMT system, suggests that this high-input system may be sustainable. However, the Agdell results discussed in the introduction show that it is much too early to draw firm conclusions about the sustainability of any of our systems.

#### 4. Conclusions

The UC Davis Long-Term Research on Agricultural Systems experiment, with a planned duration of 100 years, will provide a direct test of the sustainability of conventional and alternative practices for field crop production in a Mediterranean climate. So far, average yields of alternative (organic and LCC-based) systems (for years 3–9) were significantly lower than those of comparable conventional systems, with one important exception. Average yields of tomato, the most profitable crop, were at least as high (not significantly different) under organic management as in the comparable conventional system. Statistically significant negative trends of yield over years in the unfertilized systems were consistent with the expected unsustainability of

these systems, with or without irrigation. Even after 9 years, however, N supply from mineralization is apparently substantial. This makes it difficult to assess the long-term contribution from N<sub>2</sub>-fixation in systems with LCCs. It remains to be seen whether a maize cultivar more resistant to *Fusarium* will reverse the negative yield trend for organic maize. Positive yield trends for organic tomato and for conventional maize suggest that these systems may be sustainable. Long-term yield trends could depend on trends in soil properties that changed relatively little during the first 9 years of this experiment. Therefore, long-term yield trends could differ in magnitude, or even in direction, from those reported here.

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