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Journal

Plant Disease, 93(5)

Author

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Publication Date

2009-04-15

Peer reviewed

This article is from the
May 2009 issue of

plant disease

published by
The American Phytopathological Society

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Comparison of Crop Rotation for Verticillium Wilt Management and Effect on *Pythium* Species in Conventional and Organic Strawberry Production

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ABSTRACT

Njoroge, S. M. C., Kabir, Z., Martin, F. N., Koike, S. T., and Subbarao, K. V. 2009. Comparison of crop rotation for Verticillium wilt management and effect on *Pythium* species in conventional and organic strawberry production. *Plant Dis.* 93:519-527.

The effects of broccoli and lettuce rotations on population densities of *Verticillium dahliae* and *Pythium* spp. in soil and on strawberry (*Fragaria × ananassa*) growth, yield, and Verticillium wilt were evaluated in conventional and organic production systems in California for 2 years. Under both management systems, strawberry was planted after two successive crops of broccoli or lettuce. The control treatment in the conventional field was strawberry planted in soils fumigated with methyl bromide + chloropicrin. Preplant densities of *V. dahliae* and *Pythium* sp. did not differ in these fields. At the end of the second broccoli crop, *V. dahliae* densities in conventional plots had declined by 44% in both years. In contrast, after the second broccoli crop, densities in organic fields decreased 47% in 2000 and 25% in 2001. In general, there were no differences in *V. dahliae* inoculum densities in organic and conventional plots following lettuce rotations. After the second vegetable production cycle, population densities of *V. dahliae* in broccoli rotated organic (24 CFU/g of soil in 2000 and 27 CFU/g of soil in 2001) or conventional (23 CFU/g of soil in 2000 and 19 CFU/g of soil in 2001) fields were significantly lower than those in lettuce rotated organic (40 CFU/g of soil in 2000 and 42 CFU/g of soil in 2001) or conventional (39 CFU/g of soil in 2000 and 35 CFU/g of soil in 2001) fields. However, crop rotation treatments had no consistent effect on the inoculum densities of *Pythium* spp. Canopy diameters of strawberry plants grown in rotation with broccoli were not different from those in fumigated control plots, whereas those from lettuce plots were 10% smaller. Strawberry plant nutrient analysis showed that fertilizer inputs into organic or conventional production were not responsible for the observed differences in plant size. Increases in strawberry yields were not consistent between years. Verticillium wilt incidence on strawberry was 12 to 24% lower in fields rotated with broccoli compared with fields rotated with lettuce. Wilt severity on strawberry was 22 to 36% lower in fields rotated with broccoli compared with those rotated with lettuce. The strategy of using broccoli rotation coupled with postharvest incorporation of broccoli residue continues to show promise as a tool in the management of Verticillium wilt in both conventional and organic strawberry production systems.

Strawberry (*Fragaria × ananassa* Duchesne) is an important crop in California, where more than 80% of total U.S. strawberry production occurs. In 2006, strawberries in California were grown on 14,575 ha with a farmgate value of US\$1.2 billion (23). Nearly all of this production occurs in fumigated soils, although in recent years, there has been an increase in organic strawberry production. In 2000, organically grown strawberry accounted for less than 1% of California strawberries (8) compared to 2.7% in 2006 (7).

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Accepted for publication 23 January 2009.

doi:10.1094/PDIS-93-5-0519
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Pythium spp. are commonly isolated; 20) and binucleate *Rhizoctonia* spp. in AG-A, -G, or -I (21). In adjacent evaluations in fumigated and nonfumigated field plots, this disease caused yield losses ranging from 15 to >50% depending on the cultivar grown (22). Unfortunately, there are no foliar symptoms diagnostic of this disease complex other than a reduction in growth of the plant (which can also be caused by other soilborne pathogens).

Broad-spectrum fumigation with methyl bromide + chloropicrin to eliminate viable microsclerotia of *V. dahliae* has been the mainstay of conventional strawberry production systems in California (43). With the elimination of methyl bromide as a soil fumigant, Verticillium wilt will likely re-emerge as a major threat in strawberry production unless effective alternative control measures are implemented (35). Without an effective alternative to methyl bromide fumigation, crop losses have been projected to be nearly 20 to 30% of the estimated farmgate value of the crop (8,37). Research aimed at finding alternative chemicals to methyl bromide is ongoing, and some candidate chemicals have been identified (1,2,11,17); however, these chemical alternatives will be subjected to increasing review and regulation, potentially making them unavailable in the long-term (12). Therefore, research to identify and evaluate effective nonchemical alternatives for moderating the impact of soilborne diseases is needed. These alternative disease management strategies also will be potentially useful in organic strawberry fields, where Verticillium wilt is already a major problem at some locations.

Currently, Verticillium wilt resistant commercial strawberry cultivars are unavailable. An integrative approach to Verticillium wilt disease management in nonfumigated and organic strawberry production may involve the use of crop rotation to reduce microsclerotia populations in the soil. Owing to the wide host range of the pathogen (4) and the longevity of microsclerotia in soil (26), crop rotation was thought to be ineffective against Verticillium wilt (26). Since the mid-1990s, rotations with broccoli (*Brassica oleracea* Italica group) have repeatedly been shown to reduce Verticillium wilt on cauliflower (29,32,34,45), and more recently on straw-

Verticillium wilt of strawberry, caused by *Verticillium dahliae* Kleb. (42), was first described in California in 1931 (36) and since has been the most important soilborne disease of this crop (41). This pathogen can survive in the soil for many years as microsclerotia (40), which can germinate and infect strawberry roots, resulting in the colonization of the xylem tissue (3). Under California conditions, infected plants begin to show wilting of outer leaves in late spring (42), followed by stunted growth of new or inner leaves (26,42), and may eventually die (42).

In addition to Verticillium wilt, there are other soilborne diseases that, while not lethal to strawberry, can impact the growth and vigor of the host, leading to reductions in yield. One of the more common diseases is referred to as black root rot due to the symptoms it causes on the host (44). In California, this disease complex is caused by *Pythium* spp. (*P. ultimum* and *P. irregu-*

berry grown in conventional soils (35). Broccoli rotations for managing *Verticillium* wilt on strawberries are expected to be equally successful in both conventional and organic strawberry production systems (35), but this has not been demonstrated. Even though broccoli rotations have not been confirmed to be effective in organic fields, organic strawberry growers in California are currently utilizing broccoli as one of the rotation crops.

Lettuce (*Lactuca sativa* L.) is an important crop in the coastal valleys of California that also is susceptible to *Verticillium* wilt (31). Rotating strawberries with lettuce may potentially increase *Verticillium* wilt incidence on strawberry because of the large numbers of microsclerotia that can form on infected lettuce plants (35,38), and also because isolates of *V. dahliae* from lettuce are cross pathogenic to strawberry (4). However, the current practice for conventional lettuce production fields that develop *Verticillium* wilt is to fumigate, plant strawberries, and follow with lettuce crops to exploit the beneficial effects of postfumigation on production. Unfortunately, this option is not available for organic growers, and therefore, lettuce grown in rotation with strawberry may increase *Verticillium* wilt on the latter in organic production systems. Current organic strawberry production schemes in California involve fallowing after strawberry or rotating with lettuce.

Very few comparative studies of disease development under organic and conventional farming systems have been published. One study conducted in California (27) compared the incidence of *Verticillium* spp. recovered from strawberry roots for 3 years in a field that was converted to organic production to that in conventional strawberry fields. Results were not consistent because at the end of the study, population densities of *Verticillium* spp. in the organic fields either were significantly lower or not significantly different from densities in the conventional soils.

Ultimately, strawberry growers are interested in maximizing fruit yield. Inherent differences in strawberry yield between organic and conventional production systems may be caused by the differences in inputs such as fertilizers. Such differences may also influence plant size measured as canopy area or density, which can be correlated with strawberry yield (F. Martin, unpublished). Although strawberry plant canopy diameter was evaluated in a previous study focusing on conventional production (35), it was not related to the nutrient status of the plants. The objectives of this study were to compare the effects of broccoli or lettuce rotations in organic and conventional production systems on (i) the survival of *V. dahliae* and *Pythium* spp., (ii) incidence and severity of *Verticillium* wilt of strawberry, and (iii) plant growth, nutrient content, and strawberry yield.

MATERIALS AND METHODS

Field site. The organic and conventional fields were located 200 m apart at the Monterey Bay Academy in Watsonville, CA. The organic fields had been certified organic for the previous 4 years, and strawberry had been grown during the past 15 years. The soil type was Elder sandy loam (coarse-loamy, mixed, thermic, Cumulic Haploxeroll) with 62% sand, 26% silt, pH 6.1, and organic matter content of 0.6%. All experiments were managed by the same commercial grower using standard practices for coastal California vegetable and strawberry production.

Conventional plots. Three treatments set up in a randomized complete block and replicated four times were evaluated: (i) two successive broccoli (cv. Marathon) crops followed by strawberry (cvs. Aromas in 2001 and Camarosa in 2002), (ii) two successive lettuce (cv. Salinas) crops followed by strawberry, and (iii) strawberry planted after fumigation with methyl bromide and chloropicrin (67:33, applied at 450 kg/ha) (Mb + Pic). Six beds, 9 m long and 1.3 m wide, were formed in each replication, and 450 kg/ha of 15N-15P-15K slow release synthetic fertilizer was applied. In February 2000 and 2001, three rows of 4- to 5-week-old broccoli or lettuce were transplanted into each bed. Two outer rows of broccoli and lettuce were spaced 15 and 25 to 30 cm apart within rows, respectively, and the spacing was halved for the middle row. This was done to maximize the biomass produced per unit area. Two side dressings of slow release synthetic fertilizer 15N-15P-15K were applied at 672 kg/ha on 15 February and 12 March 2000, and on 17 February and 16 March 2001. All marketable lettuce and broccoli were harvested at maturity on 5 April 2000 and 8 April 2001. The remaining residues were flail-shredded, and 48 h later incorporated into the soil using a rototiller. Three to four weeks after incorporation, beds were formed and fertilized as described earlier. In May 2000 and 2001, the second crops of broccoli or lettuce were transplanted as previously described and side-dressed 2 weeks later with a slow release fertilizer (18N-8P-13K) at 672 kg/ha. At maturity, all marketable lettuce and broccoli were harvested 17 July 2000 and 20 July 2001. Residues were mowed as described earlier, and beds were prepared for the strawberry crop. In November 2000, strawberry (cv. Aromas) was transplanted, spaced 31 cm apart, into two rows on raised beds 1.3 m wide. In 2001, a repeat of this experiment was initiated in an adjacent section of the field that was left fallow in 2000. In the repeat experiment, a different strawberry cv. Camarosa was transplanted in November 2001. In the fumigation treatment, Mb + Pic (67:33) was applied by a commercial applicator at a depth of 15 to 25 cm to the center of the beds, through hollow shanks at the rate of

450 kg/ha, on 27 September 2000 and 2 October 2001. Immediately after application of the fumigants, the beds were covered with a high-density brown polyethylene tarp. In both years, strawberry was transplanted in November and managed by the grower in accordance with local commercial practices.

Organic plots. The organic production was managed using nonsynthetic inputs in accordance with the California Health and Safety Code Section 2659.11-17 and the California Certified Organic farmer's guidelines and enforcement provisions. Two treatments in a randomized complete block replicated four times were evaluated: (i) two successive broccoli (cv. Marathon) crops followed by strawberry (cvs. Aromas in 2001 and Camarosa in 2002), and (ii) two successive lettuce (cv. Salinas) crops followed by strawberry. Planting beds were formed, and 672 kg/ha of blood meal 12N-0P-0K was applied. Broccoli and lettuce were transplanted as described for the conventional field. For vegetable crops, fertilizer was applied as two side dressings of blood meal with 15N-0P-0K at 11 to 22 kg/ha on 17 February and 14 March 2000, and 19 February and 18 March 2001. At maturity, broccoli or lettuce crops were harvested, their residues incorporated, and beds reshaped for strawberry production as described for the conventional field. At the time of bed preparation, a total of 1,344 kg/ha blood meal was applied and mixed into the bed profile. To provide supplemental fertilizer during the growing season, the liquid organic fertilizer Phytamin 800 (California Organic Fertilizers Inc., Hartford, CA) was applied in the irrigation water at 93 liters/ha with a drip system every 2 weeks. The Phytamin 800 is derived from seabird guano, fish solubles, and potassium sulfate (6N-1P-1K) with 5.0% water-soluble organic nitrogen and 1.0% water insoluble organic nitrogen, 1% available phosphoric acid (P₂O₅), and 1% available potash (K₂O).

***V. dahliae* inoculum density.** To estimate the inoculum densities of *V. dahliae*, soil samples were taken from 0 to 10 cm depth approximately 1 week after planting broccoli or lettuce and then at monthly intervals until the end of the strawberry season. At each time, we sampled soil from 10 sites per replication and bulked the soils collected within the replication. After air-drying the soil for 4 weeks in the greenhouse, the modified Anderson sampler technique (6) was used to plate the soil on the modified NP-10 medium (16). The plates were incubated for 3 weeks in the dark at room temperature (23 to 25°C), the agar surface then was washed under a gentle stream of tap water, and microsclerotial colonies were counted under a stereomicroscope (×10). The colonies were expressed as microsclerotia per gram of dry soil.

Pythium inoculum density. Densities of *Pythium* spp. were estimated from soil samples collected as described above for *V. dahliae*. To determine the number of colony forming units of *Pythium*, 1 g of air-dried soil was added to 10-ml sterilized

water blanks (triplicate tubes for each sample), vortexed to mix the soil, and 500 μ l of this soil solution was distributed evenly over a petri dish containing a semi-selective *Pythium* medium (five plates per tube). The medium consisted of corn meal

agar (17 g/liter, BBL, Kansas City, MO) amended immediately after autoclaving with 0.1% Tween 20 followed by pimarinic acid (10 mg/liter), ampicillin (250 mg/liter), rifampicin (10 mg/liter), rose bengal (50 mg/liter), and Benomyl 50WP

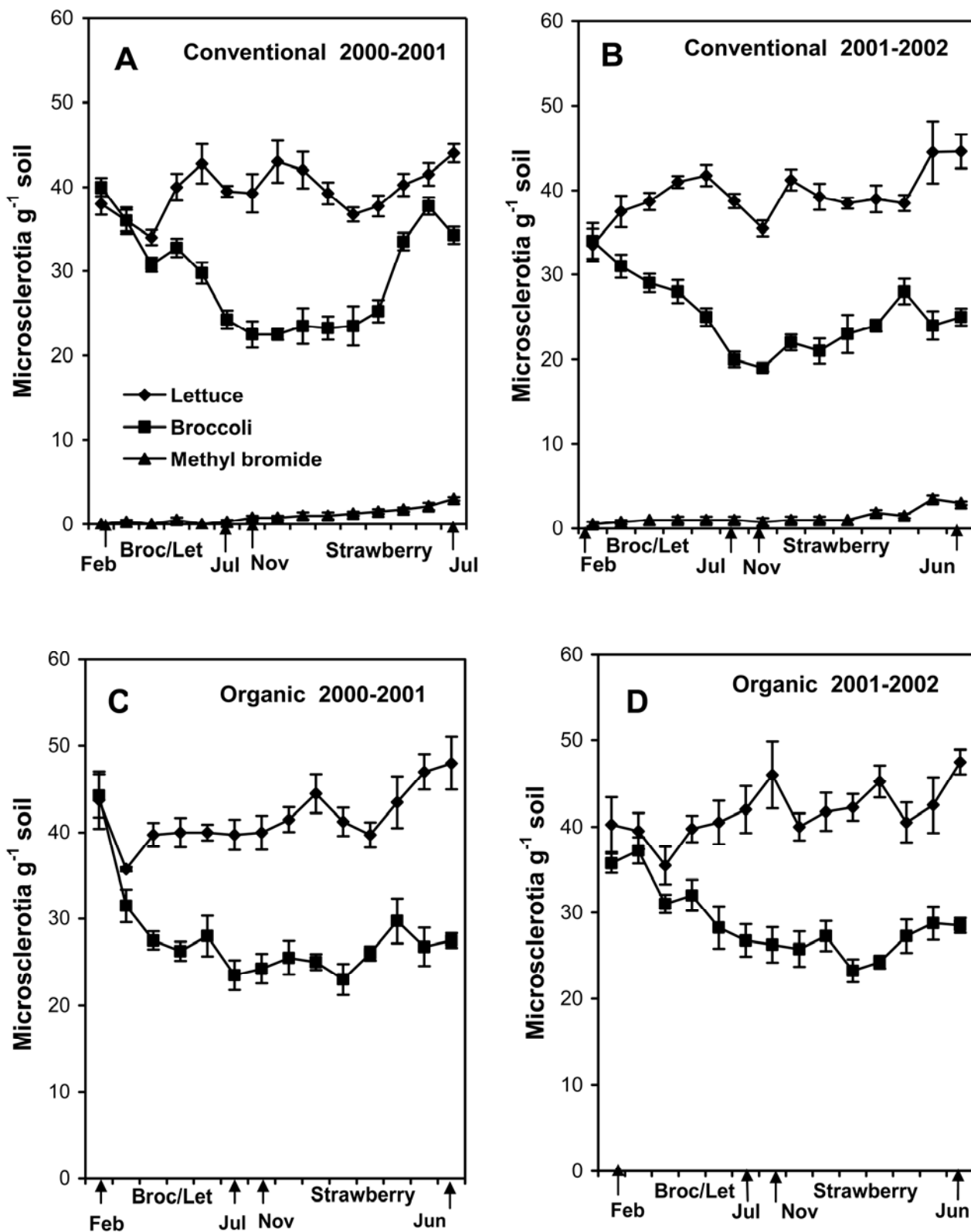


Fig. 1. Inoculum densities of *Verticillium dahliae* assayed at monthly intervals in conventional (A, 2000–2001, B, 2001–2002) or organic (C, 2000–2001, D, 2001–2002) fields during broccoli/lettuce and strawberry rotations. In 2000 and 2001, the first crops of broccoli and lettuce were planted in February and the second crops in May. In both years, strawberry was planted in November. Vertical bars represent one standard error of the mean.

(20 mg/liter, DuPont, Wilmington, DE) after the medium had cooled to 50°C (28). After 24 h incubation at 25°C, the surfaces of the plates were washed free of soil under a gentle stream of water and the number of colonies counted. Plates were placed back into the incubator and subsequent counts made again after an additional 24 h. The total colony counts were expressed as colony forming units per gram (CFU/g) of dry soil, and the data presented are the mean of the three replicates. Prior investigations at these sites revealed that *P. ultimum* was the most commonly encountered species, but other species such as *P. irregulare* were recovered as well (20).

Verticillium wilt incidence and severity assessments. To monitor disease pro-

gress, 20 plants per plot were visually rated for Verticillium wilt severity every other week from May through August (Julian days 149, 168, 192, 205, 214, and 227 in 2001 and 145, 168, 184, 205, 217, and 227 in 2002) based on a scale of 1 to 8, where 1 = no symptoms; 2 = moderately stunted; 3 = moderately stunted, slight rosette of dead leaves; 4 = moderately stunted, moderate rosette; 5 = significantly stunted, slight rosette; 6 = significantly stunted, moderate rosette; 7 = significantly stunted, significant rosette; 8 = dead plant. Disease incidence was recorded on 20 plants from the center portion of the treatment bed that had been flagged out.

Strawberry plant growth, nutrient analyses, and yield. To determine the

relative effects of different rotation treatments on strawberry plant growth during establishment, the canopy diameter of the same 20 plants used for assessing disease incidence was monitored monthly until runners formed. Measurements of each plant were made in the east-west and north-south directions, and averaged. Nutrient levels of the plants were determined from 10 plants per replication, collected on 23 April and 12 May 2001, and 27 April and 15 May 2002. These plants were dried at 60°C and then sent to University of California's Agricultural and Natural Resources Laboratory in Davis for total nitrogen, phosphorus, and potassium analyses. Yield data were collected from the same 20 plants (used for disease and plant

Table 1. Mean inoculum densities of *Verticillium dahliae* at the start of the study and at the end of broccoli (Broc) or lettuce (Let) and end of strawberry (Strawb) production and probabilities associated with contrasts between treatment effects on populations of *V. dahliae* in organic (Org) or conventional (Conv) production systems

Treatment	2000 to 2001 ^v				2001 to 2002 ^v			
	Initial	Broc/Let	Broc/Let	Strawb	Initial	Broc/Let	Broc/Let	Strawb
Broccoli-Org	44.3 ^w	27.5	23.5	27.5	35.8	31.0	26.8	28.5
Broccoli-Conv	40.0	30.8	22.5	34.3	34.0	28.0	19.0	25.0
Lettuce-Org	43.7	39.8	39.8	48.0	40.3	35.5	42.0	47.5
Lettuce-Conv	38.0	34.0	39.3	44.0	33.5	41.0	35.5	44.6
MeBr ^x	0.0	0.8	0.3	1.5	0.5	0.8	1.0	1.5
Contrast ^y								
Broc: Org vs. Conv		0.092 ^z	0.721	0.014		0.831	0.006	0.185
Lettuce: Org vs. Conv		0.009	0.905	0.064		0.042	0.042	0.363
Broc-Org vs. Let-Org		<0.001	<0.001	<0.001		0.003	<0.001	<0.001
Broc-Conv vs. Let-Conv		0.096	<0.001	0.003		0.003	<0.001	<0.001
Broc-Conv vs. MeBr		<0.001	<0.001	<0.001		<0.001	<0.001	<0.001
Lettuce-Conv vs. MeBr		<0.001	<0.001	<0.001		<0.001	<0.001	<0.001

^v In 2000 to 2001 and 2001 to 2002, two crops of broccoli or lettuce were grown and incorporated after harvest into organic or conventional soils, and methyl bromide + chloropicrin was applied in conventional control soils, before planting strawberry.

^w Mean inoculum density of *V. dahliae* per gram of dry soil. Mean initial densities at the start of the experiments in each season and mean densities at the end of the rotations are presented.

^x Methyl bromide + chloropicrin (67:33) fumigation applied at 450 kg/ha.

^y Treatments were compared using single degree-of-freedom contrast statements.

^z *P* values of the respective contrast comparisons.

Table 2. Effect of crop rotations in organic (Org) or conventional (Conv) fields on disease incidence and severity of Verticillium wilt and yield on strawberry

Treatment ^v	2001 ^u			2002 ^u		
	% Incidence ^v	Severity ^v	Yield ^w	% Incidence	Severity	Yield
Broccoli (Broc)-Org	20.3	120	0.631	11.8	116	0.444
Broccoli-Conv	22.8	131	0.987	56.8	216	0.622
Lettuce (Let)-Org	37.2	154	0.527	31.3	170	0.440
Lettuce-Conv	47.2	204	0.863	68.7	276	0.293
MeBr ^x	15.3	114	1.270	24.4	144	0.543
Contrast ^y						
Broccoli: Org vs. Conv	0.446 ^z	0.084	<0.001	<0.001	<0.001	0.001
Lettuce: Org vs. Conv	0.003	<0.001	<0.001	0.003	<0.001	0.004
Broc-Org vs. Let-Org	<0.001	<0.001	0.014	<0.001	<0.001	0.916
Broc-Conv vs. Let-Conv	<0.001	<0.001	0.095	<0.001	<0.001	0.002
Broc-Conv vs. MeBr	0.023	0.011	0.007	<0.001	<0.001	0.269
Let-Conv vs. MeBr	<0.001	<0.001	0.001	<0.001	<0.001	0.008

^u In 2000 to 2001 and 2001 to 2002, two crops of broccoli or lettuce were grown and incorporated after harvest into organic or conventional fields, and methyl bromide + chloropicrin was applied in conventional control soils, before transplanting strawberry.

^v Plants were examined and rated for Verticillium wilt incidence and severity from May to August (Julian days 149, 168, 192, 205, 214, and 227 in 2001 and 145, 168, 184, 205, 217, and 227 in 2002). Final disease incidence is presented. For wilt severity, areas under disease progress curves for each replication were calculated and averaged within treatments.

^w Total marketable yield (kg) per plant.

^x Methyl bromide + chloropicrin (67:33) fumigation applied at 450 kg/ha.

^y Treatments were compared using single degree-of-freedom contrast statements.

^z *P* values of the respective contrast comparisons.

growth assessments) with both marketable and nonmarketable fruit yield data collected in each treatment replication by a specially trained commercial picking crew. Fruit yield data were expressed as grams per plant.

Statistical analysis. Prior to analysis, *V. dahliae* population density, disease incidence, canopy diameter, and yield data sets were checked for normality (PROC Univariate, SAS version 9.1, Cary, NC), and Hartley's test for equality of variance was conducted (18). Repeated measures analysis (PROC Mixed, SAS version 9.1) was done, for each vegetable rotation and strawberry production period, to test the effects of the treatments and time on densities of *V. dahliae*. Autoregressive covariance matrix was used in the analysis. Standard errors of the mean were calculated for *V. dahliae* inoculum densities. Using single degree-of-freedom contrasts, comparisons of mean *V. dahliae* densities at the start of the rotations and at the end of each broccoli or lettuce rotation, and strawberry production, within and across organic or conventional fields were done. Single degree-of-freedom contrasts were also used to compare disease incidence and yield. For disease severity, areas under disease progress curves for each replication were calculated and averaged within treatments, and then contrasts were made between treatments. Strawberry plant nutrient data were analyzed by year, and were compared using Fisher's protected least significant difference ($P \leq 0.05$) and single degree-of-freedom contrasts.

RESULTS

Initial *V. dahliae* densities and methyl bromide treatment comparison. In both

years, initial densities of *V. dahliae* microsclerotia (34 to 44 CFU/g of soil) prior to establishing the broccoli and lettuce rotation treatments did not differ significantly ($P > 0.05$) (Fig. 1). In both years during broccoli and lettuce cropping, *V. dahliae* densities in methyl bromide-treated soils (<2 CFU/g of soil) remained significantly ($P < 0.001$) lower than in broccoli-rotated (19 to 31 CFU/g of soil) or lettuce-rotated (34 to 42 CFU/g of soil) soils in either conventionally or organically managed system (Fig. 1, Table 1).

Effects of vegetable rotations on *V. dahliae* densities. In general, densities of *V. dahliae* did not differ between organic and conventional plots after cropping to broccoli (Table 1). At the end of the second broccoli crop, *V. dahliae* densities in conventional plots had declined by 44% in both 2000 and 2001. In contrast, after the second broccoli crop, densities in organic fields decreased 47% in 2000 and 25% in 2001. In general, densities of *V. dahliae* were not different between organic and conventional plots after cropping to lettuce (Table 1). By the end of the second broccoli and lettuce crops (July) within organic or conventional fields, densities of *V. dahliae* were significantly lower in soils cropped to broccoli than in soils cropped with lettuce (Fig. 1, Table 1).

At the time strawberries were planted, *V. dahliae* densities in broccoli-rotated conventional and organic plots were significantly lower than the corresponding initial densities (Fig. 1). In contrast, *V. dahliae* densities in organic and conventional fields were not significantly different from initial densities in lettuce-rotated plots (Fig. 1).

***V. dahliae* densities during strawberry production.** *V. dahliae* densities remained

significantly lower in plots rotated with broccoli relative to plots rotated with lettuce (Fig. 1, Table 1). In both years, *V. dahliae* densities were significantly ($P \leq 0.02$) higher during strawberry production following lettuce rotations in organic fields (43.1 CFU/g of soil in 2001 and 42.8 CFU/g of soil in 2002) compared with those in the corresponding conventional fields (40.4 CFU/g of soil in 2001 and 39.5 CFU/g of soil in 2002).

The effect of rotation treatments on *Pythium* inoculum densities. Inoculum densities of *Pythium* spp. in the rotation treatments ranged from 8 to 368 CFU/g of soil compared to less than 1 CFU/g of soil for the Mb + Pic fumigated control in the conventional plots. Consistent differences between years in inoculum densities of *Pythium* spp., in response to rotation treatments or conventional compared to organic production practices, was not observed largely due to the level of variability observed among the replicates for each treatment (data not shown).

Verticillium wilt incidence and severity. In both 2001 and 2002, disease incidence and severity were significantly lower in broccoli-rotated organic or conventional fields compared with those in lettuce rotations (Table 2). In 2001, disease incidence or severity was not significantly different between broccoli-rotated organic or conventional fields; but in 2002, both values were significantly higher in broccoli-rotated conventional fields (Table 2). In both years, disease incidence and severity were significantly higher in conventional plots with lettuce rotation compared with the organically managed plots of lettuce rotation (Table 2). In both years, disease incidence was significantly lower in plots

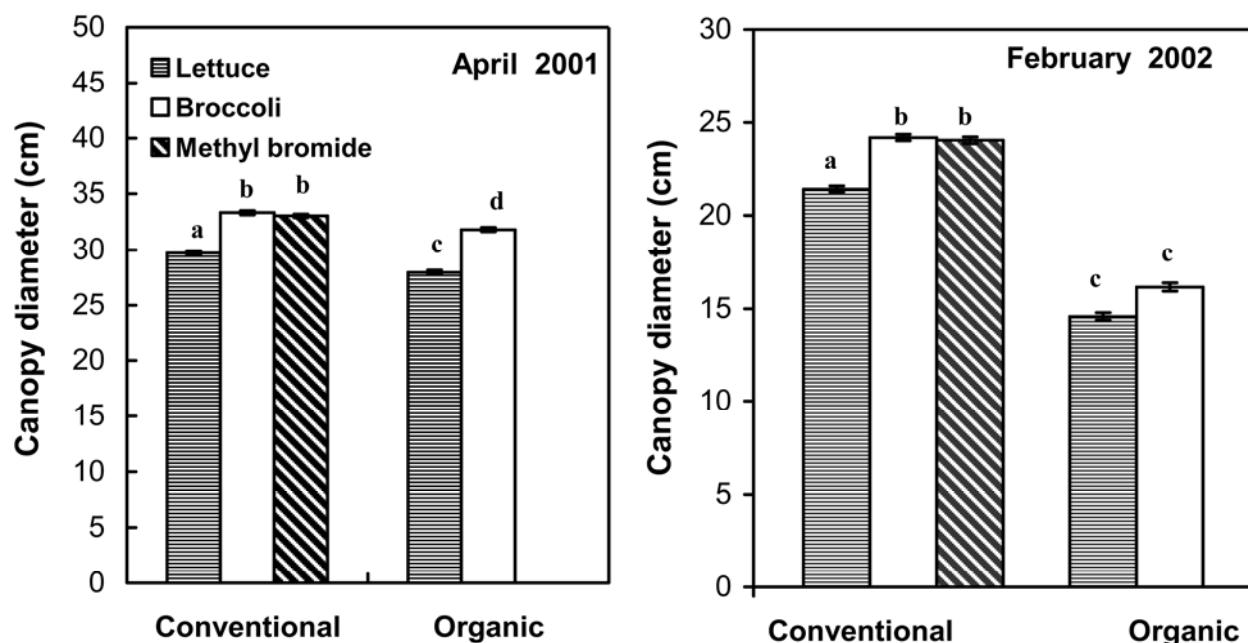


Fig. 2. Canopies of strawberry measured in April 2001 and February 2002. Different letters above the bars indicate significant differences according to LSD $P \leq 0.05$, and vertical bars represent one standard error of the mean.

fumigated with Mb + Pic compared with those from lettuce- or broccoli-rotated conventionally managed plots (Table 2).

Effect on strawberry growth, yield, and nutrient content. In both years, there were no significant differences between the canopy diameters of strawberry plants grown in Mb + Pic fumigated and broccoli rotation treatments (Fig. 2). Strawberry canopies were significantly smaller for

plants grown in rotation with lettuce compared to those grown in broccoli or fumigated plots (Fig. 2). Strawberry yields were significantly higher in conventional fields compared to those in organic fields (Table 2). Yield differences between broccoli and lettuce rotations were not consistent in organically managed plots, with significant differences observed in 2001 but not in 2002 (Fig. 3). In contrast, straw-

berry yields were significantly higher in broccoli-rotated conventional plots compared with those in lettuce rotation in 2002 (Fig. 3, Table 2).

In general, interaction effects of sampling time \times nutrient content were significant ($P \leq 0.01$) within both years. Significant differences between certain elements in the foliage of strawberry plants from different treatments were

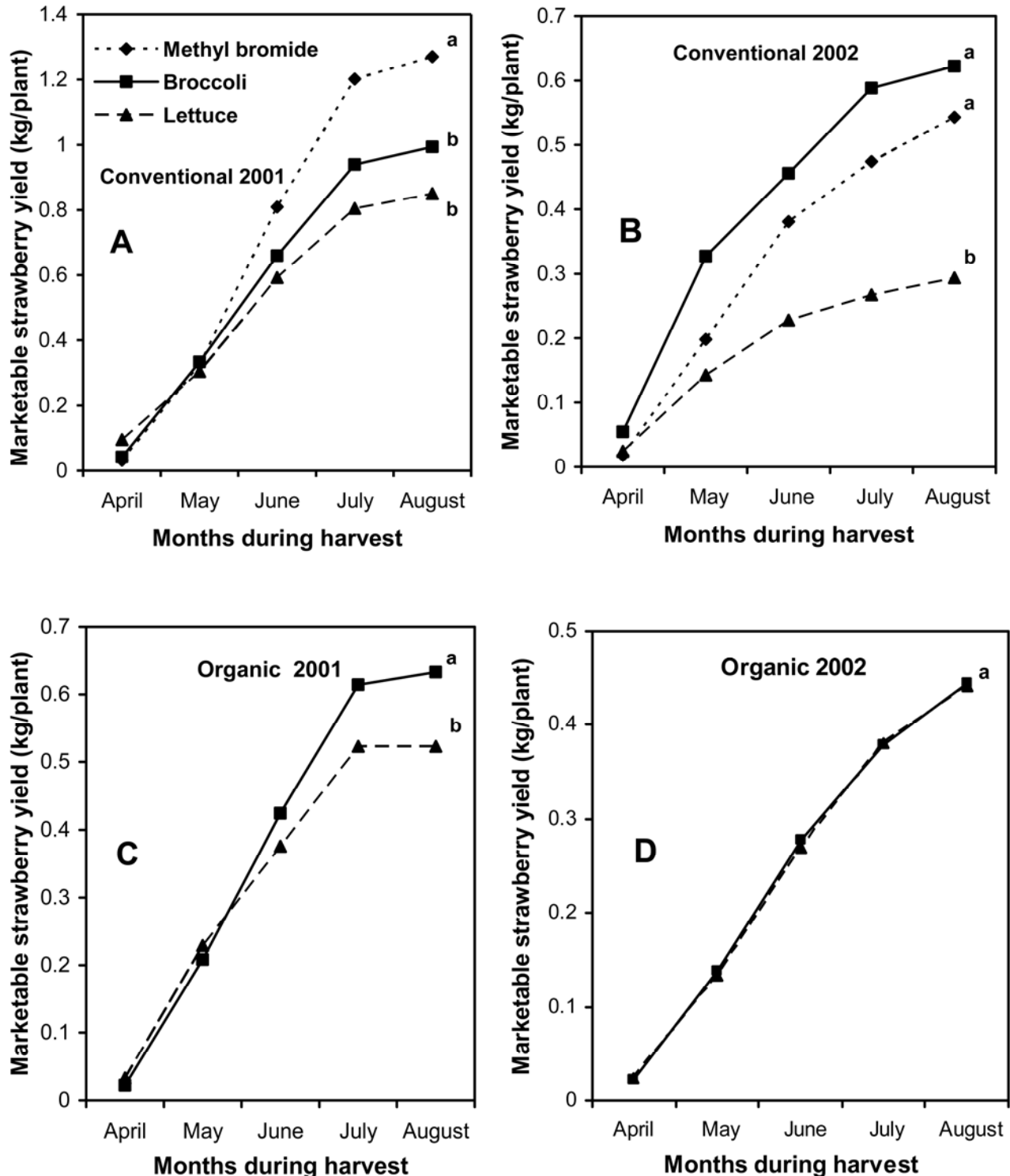


Fig. 3. Cumulative yield of strawberry plants grown in conventional (A, 2001, B, 2002) or organic (C, 2001, D, 2002) fields after crop rotation with broccoli, lettuce, or fumigation with methyl bromide + chloropicrin (67:33) at 450 kg/ha. Different letters on the lines indicate significant differences according to LSD $P \leq 0.05$.

observed, but these differences were inconsistent both between years and sampling times (Table 3).

DISCUSSION

Previous studies conducted under non-fumigated conventional farming systems have demonstrated the effectiveness of rotation with broccoli in the management of *Verticillium* wilt of cauliflower (32,34,45), potato (25), and more recently strawberry (35). Of greater interest in this study was whether *Verticillium* wilt disease intensity would be similarly affected in organic production systems following broccoli rotations. Results obtained in this study clearly demonstrated that rotations with broccoli were equally effective in both conventional and organic production systems and are therefore useful in managing *Verticillium* wilt on strawberries and perhaps on other susceptible crops.

Unlike in 2001, disease incidence and severity on strawberries in 2002 were higher despite similar microsclerotial densities in conventionally managed broccoli rotation plots compared with organically managed broccoli rotation plots. Over time, root disease levels in established organic fields diminish compared to conventionally managed soils (39). Even though data from two growing seasons were insufficient to support this conclusion in our study, the change in strawberry cultivars from Aromas in 2000 to Camarosa in 2001, which is more susceptible to *Verticillium* wilt than Aromas (13), may have allowed for better detection of disease suppression in the organic system.

In coastal California, conventional strawberries are planted following fumigation with Mb + Pic or alternative fumigants. In contrast, lettuce crops are routinely produced in nonfumigated soils. However, in recent years, *Verticillium* wilt on lettuce has become a major threat to lettuce crops in this area and microsclerotial densities of up to 2,500 per gram of dry soil have been documented in these fields (33). Since many crops grown in rotation with lettuce are also hosts for *V. dahliae* and very few crops can be economically produced at such high inoculum densities, fumigation remains the only option to recover these fields for economic crop production. Since regular fumigation is too expensive for producing lettuce, vegetable growers often seek to plant lettuce on ground that in the previous season was fumigated and subsequently planted to strawberry; lettuce crop therefore benefits from residual fumigation effects from the previous crop. Thus, lettuce-strawberry-lettuce rotations are common in conventional production systems. In contrast, organic production is antithetical to fumigation, and thus rotational crops for strawberries have to be selected carefully. Since populations of *V. dahliae* in soil typically increase following lettuce crops (35), it is

not an ideal rotation crop for organic strawberry production in *V. dahliae*-infested soils. Even though populations of *V. dahliae* did not significantly increase following two lettuce crops prior to strawberry planting, *V. dahliae* microsclerotial densities were nonetheless higher than in plots rotated with broccoli. Thus, soil tests to detect the presence of *V. dahliae* and levels of pathogen microsclerotia should be employed before deciding on lettuce as a crop to rotate with strawberries in organic production systems. In both systems, however, broccoli crops not only reduced the existing numbers of microsclerotia but also did not augment microsclerotia in the soil (45).

Interestingly, the incidence and severity of *Verticillium* wilt on strawberry were higher in the conventionally managed lettuce rotation plots compared with organically managed rotation plots even though *V. dahliae* microsclerotial densities at the time of strawberry production were similar in both fields. As previously discussed for disease intensities in broccoli rotations, disease suppression in organic soils may be the reason for lower disease in organic fields in the second year, coupled with the change in cultivars grown in 2001 compared to 2000. In other studies, lower disease incidence in organic compared to conventional fields may occur because *V. dahliae* densities decreased under organic production (27,39), but no such conclusion can be drawn from this study. Disease

suppression due to an increase in antagonistic microflora in organic soils may have played a role in reducing disease incidence, but this was not verified.

As reported by Subbarao et al. (35) in a conventionally managed strawberry production system, *Verticillium* wilt on strawberry grown in broccoli-rotated soils was lower than that in lettuce-rotated soils. Not surprisingly, disease levels in fumigated soils were lower compared with rotation treatments in 2001, but not in 2002. One possible reason for this was an incomplete bed fumigation, which in this particular location can lead to poor control of *Verticillium* wilt (F. Martin, unpublished). Another potential explanation is that even low densities of *V. dahliae* may incite high wilt incidences on strawberries. Harris and Yang (15) reported that on very susceptible cultivars, 3.8 CFU/g of soil incited 29% wilt. In our study, densities of *V. dahliae* in fumigated soils were lower than 2 CFU/g of soil, and wilt incidences in these soils were 15.3 and 24.4% in 2001 and 2002, respectively. Although high, the amount of wilt in fumigated soils therefore was not surprising.

As was observed in a previous study (35), rotation treatments had no consistent effect on populations of total *Pythium*. Inconsistent results from such studies are not uncommon. Amending soil with *Brassica* spp. increased populations of *Pythium* spp., fluorescent pseudomonads, and *Fusarium oxysporum* (10,24,30), and in

Table 3. Analyses of nutrient content of strawberry plants grown in organic (Org) or conventional (Conv) fields following rotation with two plantings of broccoli (Broc) or lettuce (Let), and in methyl bromide (MeBr) treated soils

Treatment	April ^v			May		
	N (%)	P (%)	K (%)	N (%)	P (%)	K (%)
2001						
Broc-Conv	2.76	0.49	2.08	1.95	0.32	1.87
Let-Conv	2.79	0.48	2.22	1.82	0.29	1.67
MeBr ^w	2.78	0.57	2.14	1.95	0.31	1.60
Broc-Org	2.70	0.43	2.07	2.46	0.29	1.73
Let-Org	2.67	0.43	2.00	1.88	0.27	1.45
LSD Conv ^x	0.27	0.05	0.12	0.18	0.04	0.07
LSD Org ^x	0.17	0.08	0.13	0.31	0.05	0.62
Contrast ^y						
Broc: Org vs. Conv	n.s. ^z	n.s.	n.s.	0.001 ^z	n.s.	n.s.
Let: Org vs. Conv	n.s.	n.s.	0.001	n.s.	n.s.	n.s.
2002						
Broc-Conv	2.43	0.30	1.83	2.13	0.30	1.60
Let-Conv	2.14	0.26	1.43	1.68	0.29	1.02
MeBr	2.36	0.29	1.61	1.76	0.29	1.19
Broc-Org	2.55	0.29	1.73	2.01	0.29	1.47
Let-Org	2.45	0.27	1.66	1.60	0.23	0.95
LSD Conv	0.19	0.03	0.18	0.13	0.07	0.14
LSD Org	0.43	0.05	0.19	0.16	0.05	0.08
Contrast						
Broc: Org vs. Conv	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Let: Org vs. Conv	0.01	n.s.	0.01	n.s.	0.001	n.s.

^v In both years, 10 strawberry plants were sampled from each replication in April and May, dried at 70°C, and analyzed for nitrogen, phosphorus, and potassium content.

^w Methyl bromide + chloropicrin (67:33) fumigation applied at 450 kg/ha.

^x Least significant difference ($P = 0.05$) for comparisons within conventional or organic treatments.

^y Contrasts between treatments in organic and conventional production systems.

^z Nonsignificant ($P > 0.05$) and significant P value.

contrast did not significantly reduce inocula of *Fusarium* spp., *R. solani*, and *V. dahliae* (5,46) or suppress populations of fluorescent pseudomonads (10). Reasons for the mixed results are not well understood but may be related to soil type, soil temperature at time of amendment (14,32), amount and size of plant tissue incorporated (9,25), successfully creating reducing conditions after amending by applying polyethylene mulch (5), or incorporating dry or fresh plant material (32).

Because fertilizer inputs into organic and conventional production systems may be unequal and thus affect plant growth and yield, we analyzed strawberry plant nutrient content and measured canopy diameters. Plant nutrient data showed that fertilizer type applied did not alter the levels of N-P-K in either organic or conventional production systems, and the levels of N-P-K in the plants were normal (M. Bolda, *personal communication*). Even though strawberry canopies were statistically smaller in lettuce-rotated plots than in broccoli-rotated plots, differences were not consistent between years. As expected, strawberry yields generally were higher in fumigated soils compared to those from broccoli- or lettuce-rotated conventional soils. The current high-yielding strawberry cultivars used in California were selected for production under fumigated soils (19). Because these cultivars perform differently in nonfumigated conventional fields (22), yield differences from these cultivars may be exaggerated under nonfumigated conventional or organic production (28). However in 2002, strawberry yield was not significantly different in fumigated soils compared to that in broccoli-rotated conventional soils despite higher inoculum densities in the latter, probably because of inefficient fumigation in fumigated plots. Across treatments, yields were lower in 2002 compared to 2001, likely due in part to the change in cultivars planted.

Xiao et al. (45) outlined criteria for assessing rotation crops for effectiveness on persistent pathogens such as *V. dahliae*. The crop should (i) result in a reduction of microsclerotia in soil and a concomitant reduction of wilt in the susceptible crop, (ii) be compatible with current production practices, and (iii) result in grower acceptance of the crop for rotation. Broccoli meets these criteria; therefore, crop rotation with broccoli and its postharvest amendment into the soil continues to show promise as an additional tool in managing Verticillium wilt on susceptible hosts such as strawberry grown in succession with broccoli.

ACKNOWLEDGMENTS

The funding provided by USDA-SARE and the California Department of Food and Agriculture – Department of Pesticide Regulation is gratefully acknowledged. The California Strawberry Commission, Coastal Berries, and Golden Field Green-

houses provided material support for this project. We are grateful to Frank Westerlund for suggestions throughout this study. We thank Stuart Yamamoto for managing the strawberry crops, C. Blackford, T. Price, M. E. Abarca, and M. Orozco for technical assistance, and Mark Bolda for discussions on strawberry plant nutrient data. We also thank the anonymous reviewers whose comments and suggestions have significantly improved the manuscript.

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