Variables Associated with Corky Root and Phytophthora Root Rot of Tomatoes in Organic and Conventional Farms

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ABSTRACT

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In 1989 and 1990, a comparative study of organic and conventional tomato-production systems in the Central Valley of California was conducted to determine the effects of management practices on soil properties and tomato diseases and to relate disease severity in tomatoes to various soil and plant variables. Twenty sampling locations were randomly selected at each of nine (1989) and 18 (1990) farms to measure 10 soil variables, plant biomass and nitrogen content, and incidence and severity of Phytophthora root rot caused by *Phytophthora parasitica* and corky root caused by *Pyrenochaeta lycopersici*. *P. parasitica* was detected by leaf bait assay in soil samples from five of the nine conventional farms but not from organic farms, and Phytophthora root rot was observed in three conventional farms only. Corky root was found on most plants in most locations, but incidence and severity were higher in conventional than in organic farms. Corky root-severity values, estimates of *P. parasitica* populations from the leaf bait assay, and Phytophthora root rot-severity values were grouped into three, two, and two classes, respectively, for use in stepwise and canonical discriminant analyses with 11 variables. The distinction among three classes of corky root severity was consistently associated with three variables: tissue nitrogen, soil nitrate, and nitrogen-mineralization potential. Nitrogen in tomato tissue and nitrate concentration in soil were positively correlated with corky root severity; nitrogen-mineralization potential was negatively correlated with this disease. Six soil variables (clay content, water-stable aggregates, soil-nitrate concentration, organic carbon, electrical conductivity, and soil-water content) contributed most to variability in the presence of *P. parasitica* in soil. All variables except organic carbon were positively correlated with the presence of *P. parasitica* in soil. Clay content and water-stable aggregates were also positively associated with Phytophthora root rot, and microbial activity was negatively associated with this disease.

Additional keywords: fluorescein diacetate, root disease.

Highly mechanized and intensive agricultural systems (conventional) have been very successful in crop production due in part to the use of synthetic fertilizers and pesticides. However, conventional agricultural practices have had many adverse effects on the environment (28,29,34). Consequently, many farmers are interested in alternative agricultural systems that may require fewer synthetic inputs and offer greater sustainability than is offered by current conventional farming practices (29). The most common alternative system in use is organic farming (29,47).

California contributes about half of the national farm gate sales of organic produce (46) grown on an estimated 28,000 ha (5). Organic farming systems differ from conventional systems in the elimination of synthetic fertilizers and pesticides. Instead, organic farms rely on organic amendments, such as animal and green manures and off-farm organic wastes to maintain soil fertility and on biological and cultural methods to control weeds, insect pests, and diseases (29,47).

Cropping and management practices may affect physical, chemical, and biological soil properties. Several comparative studies of conventional and organic or integrated (reduced use of fertilizers and pesticides) farming systems indicated that soil organic-matter and polysaccharide content, microbial biomass, and available water were higher in organic or integrated than in conventional farms; soil bulk density and erosion were less in organic than in conventional farms (10,23,37). It is probable that such major changes in soil environment significantly influence activities of saprophytic and pathogenic soilborne microorganisms.

The effects of organic farming practices on plant diseases have not been well documented. In three comparative studies, foliar diseases, such as stripe rust and powdery mildew of wheat, were less severe in organic or integrated farms than in conventional farms (9,12,35), whereas root and stem diseases were either less severe in organic or integrated than in conventional farms (9,12) or were equally as severe as diseases in conventional farms (9,35). Lower disease severity was sometimes related to lower nitrogen concentrations present in organically than in conventionally grown crops (9).

Because few comparative studies of alternative agricultural systems had been published, we conducted a study of conventional and organic tomato-production systems in the Central Valley of California in 1989 and 1990 (42). Conventional production practices have led to increased soil compaction, deteriorated soil structure, decreased water percolation, and increased salinity in California (3,7). The decline in soil structure and increase in soil salinity may have contributed to increased losses from tomato root diseases, such as Phytophthora root rot, caused by *Phytophthora parasitica* Dastur (21,25), and corky root, caused by *Pyrenochaeta lycopersici* R. Schneider & Gerlach (14). Both diseases are widely distributed throughout the Central Valley of California (6,41) and can cause considerable damage under favorable environmental conditions (6,38).

In this paper, we report some of the results of a comparative study of organic and conventional tomato-production systems, with emphasis on incidence and severity of corky root and Phytophthora root rot and the edaphic and plant parameters associated with each of these diseases. Agronomic differences between these production systems have been described elsewhere (42).

MATERIALS AND METHODS

Farm selection. Nine and 18 tomato-producing farms, varying between low and high input of synthetic fertilizers and pesticides, were sampled in the Central and Capay valleys of California in 1989 and 1990, respectively. Five (1989) and nine (1990) of these farms were selected from the Growers List of California Certified Organic Farmers (to be certified as organic, a farm has to be managed without synthetic fertilizers and pesticides for at least 3 yr). These farms are predominantly small (1–20 ha) and produce assorted vegetables and fruits (42). Conventional farms were selected in the general location of the organic farms. Three and five of these conventional farms were large (20 to >200 ha per farm), and one and four were small (0.5–6 ha per farm) in 1989 and 1990, respectively. In 1989, three farms had been managed organically for less than 3 yr and were designated as transitional. All farms were located within a 600-km^2 area in the Central Valley of California (Fig. 1). Mean minimum and maximum temperatures during the tomato-growing seasons, measured at five weather stations 3–30 km from the farms, ranged between seven and 14 and between 29 and 32 C, respectively. Farms were selected so soil types were as homogeneous as possible, ranging from sandy loam to silty clay loam.

Cultural practices. All tomato growers cooperating in this study practiced crop rotation. Large-scale conventional tomato producers grew wheat, corn, beans, or safflower previous to tomato; small-scale conventional and organic growers produced a variety of vegetable crops or corn prior to tomato. The rotation intervals ranged from 2 to 5 yr on conventional farms and were more than 5 yr on organic farms.

In organic farms, legume residues, animal manure, compost, and/or earthworm castings were used to supply nitrogen fertilizer. In conventional farms, inorganic nitrogen fertilizers (and legume residues on one farm in 1990) were applied. The total amount of nitrogen applied was only slightly lower on organic than on conventional farms (60–250 and 60–280 kg/ha of N, respectively) (11).

All tomato varieties were determinant (Celebrity or Ace in 1989, Blazer in 1990), except for one variety on one farm in 1989 (Early Girl). Transplants were grown in a peat moss-vermiculite mix amended with nitrogen and phosphorous fertilizer for conventional farms and with fish meal for organic farms. Seedlings were transplanted 5 wk after emergence.

Most irrigation water was applied in furrows. Drip irrigation was applied on two organic farms in 1989 and on two small conventional and two organic farms in 1990. Sprinkler irrigation was used on two organic farms in 1990.

Weeds were controlled by cultivation on organic farms and by cultivation and herbicides, mainly glyphosate (Monsanto Chemical Co., St. Louis, MO) and trifluralin (Elanco Products Co., Indianapolis, IN), on conventional farms. Insect control was accomplished by spraying pyrethroids, organophosphates, carbamates, insecticidal soap, or *Bacillus thuringiensis* on conventional farms and by releasing parasitoids, planting insectary plants, or spraying *B. thuringiensis* on organic farms. *P. parasitica* was controlled partially by applications of metalaxyl (Ridomil 2E, Ciba-Geigy Corp., Greensboro, NC) at transplanting on two large-scale conventional farms. Sulfur dust (FMC Corp., Philadelphia, PA) was applied on three conventional farms and one organic farm to control powdery mildew and mites, and copper ammonium carbonate (Copper Count-N, Mineral Research and Development Corp., Charlotte, NC) was applied on one conventional farm to control bacterial speck.

Sampling and measurements. During the tomato-growing season, a sampling area of ~0.04–0.1 ha (depending on the number of rows planted to the same cultivar) was selected per farm for measurement of 10 soil variables, plant biomass and nitrogen content, and disease incidence and severity. Each sampling area was divided into 20 sections, and one sampling site (1-m row length containing one or two plants) was randomly selected in each section (stratified random sampling).

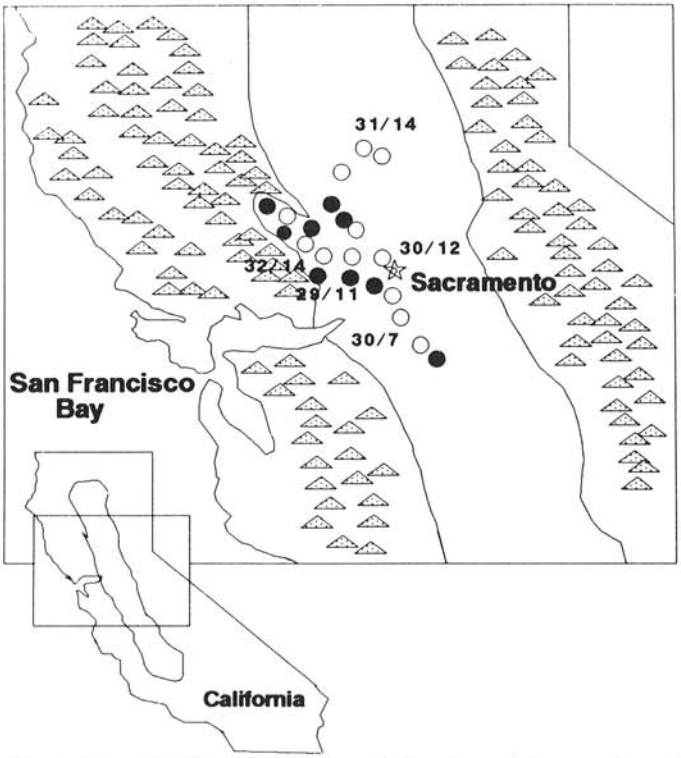

Fig. 1. Map of California indicating the locations of the organic and conventional farms sampled in 1989 and 1990 and the daily maximum/minimum air temperatures at those locations averaged over the two growing seasons. Closed and open circles represent organic and conventional farms, respectively. Inset indicates the location of the Central Valley in California.

Two to 3 days after irrigation at the green-fruit stage, 8–10 soil cores (2-cm diameter, 20-cm deep) were collected within a 15- to 20-cm radius from the base of the selected plants within a sampling site and were composited (20 composite samples per field). Water-stable aggregates (20), percent clay, organic-carbon content (30), nitrate and ammonium (19), soil pH and electrical conductivity (39), total nitrogen content (4), nitrogen-mineralization potential (49), and fluorescein diacetate (FDA) hydrolytic activity (8) were determined for each soil sample. Before assessing FDA hydrolytic activity, the soil-matric potential of 50 g of soil per sample was adjusted to −35 J/kg in a pressure-plate apparatus (Soil Moisture Equipment Co., Santa Barbara, CA) for 48 h. Duplicate 5-g subsamples of soil per sampling site (40 subsamples per farm) were suspended in 20 ml of 60 mM sodium phosphate buffer (pH 7.6) plus 400 μg of FDA and were mixed on a rotary shaker for 30 min at 23–25 C. Hydrolytic reactions were stopped by the addition of 20 ml of acetone (8). An additional 5-g subsample for each sampling site was suspended in the same buffer and FDA solution to serve as a control, but acetone was added immediately to prevent hydrolytic reactions. Soil particles were removed by centrifugation at $4,340 \times g$ for 5 min and by filtration of the supernatant through 2.5-μm glass-fiber filters (Fisher Scientific, Santa Clara, CA). Absorbance was determined on a spectrophotometer (Beckman Instruments Inc., Irvine, CA) at 490 nm. A standard curve was prepared for each soil sample (8).

Two to 3 wk after soils had been sampled, when 1–10% of the fruits started to ripen, two additional soil samples (5-cm diameter, 20-cm deep) were collected from the same sampling sites to quantify *P. parasitica* propagules in soil with a tomato leaf disk bioassay (13). Two subsamples (50 ml) per soil sample were each spread on top of an 8-cm-deep column of UC mix (27) in a 400-ml perforated cup, wetted to saturation, and drained for 96 h on a greenhouse bench. The soil/UC-mix columns were flooded, and 10 leaf disks per cup were floated on the surface. After 24 h, the leaf disks were surface-sterilized with 0.5% NaOCl for 30 s, plated onto Masago's medium (26), and incubated in the dark at 23–27 C. The percentage of leaf disks colonized by *P. parasitica* was determined for each soil sample after 5 days of incubation.

On the same day that soil cores were collected to assess the presence of *P. parasitica*, two soil samples per sampling site were taken with a trowel (20-cm deep). Water content was determined in minimally disturbed soil after adjusting the matric potential to −50 J/kg in a pressure-plate apparatus for 48 h (in 1990 only).

One or two tomato plants (in 1989 and 1990, respectively) were uprooted at each of the same 20 sampling sites after soil samples had been taken. Total nitrogen in the shoot tissue (Kjeldahl procedure), shoot and fruit dry weights, and severity of corky root and Phytophthora root rot were determined for each plant sample. Typical symptoms of corky root, roughness and cracking limited to the cortex, were evident and distinct from symptoms of Phytophthora root rot, brown lesions usually extending deep into the stele. Roots of each plant were excavated with a shovel, washed on site, and assessed for percentage of total root length with visible, typical symptoms of each disease. Assessment of visible symptoms was standardized by comparing visual assessments on greenhouse-grown plants infected with *Pyrenochaeta lycopersici* or *P. parasitica* with assessments made by video-image analysis (Decagon Devices, Inc., Pullman, WA). To verify the diagnosis made in the field, subsamples of two to five roots per field with typical symptoms of corky root or Phytophthora root rot were surface-sterilized with 0.5% NaOCl (for 2–3 min for corky root, 30 s for Phytophthora root rot) and were plated onto Grove and Campbell's medium (14) or Masago's medium (26), respectively.

Statistical analyses. Because pairs of organic and conventional farms could not be found, comparisons at the farm level by means of simple statistical analyses, such as analysis of variance, could not be made. Therefore, multivariate analyses were selected to relate the different measurements to each other for each individual sample. Samples could not be combined per field, because ~10 times as many observations as variables are required for multivariate analyses (1).

Initial analysis consisted of descriptive statistics for each variable, based on management type (organic, conventional, and transitional) or disease-severity class. All soil, plant, and disease measurements were tested for normality by univariate analysis (40). Nonnormal data were transformed by various transformations suggested by the Box-Cox transformation procedure (BMDP Statistical Software, Inc., Los Angeles, CA). The final choice of transformation was based on Levene's test (44) for homogeneity of variances among groups, performed on all transformations suggested by the Box-Cox procedure.

Three types of discriminant analysis (discriminant function, canonical discriminant, and stepwise discriminant analyses [40]) were performed on one plant variable (tissue N) and on 10 soil measurements of each individual sample after appropriate transformation. Indicator values were assigned to each plant and soil sample, corresponding to three management types (conventional, transitional, and organic in 1989; and large-scale conventional, small-scale conventional, and organic in 1990), three corky root-severity classes (0, >0 ≤5, and >5%), or two classes, based on the presence of *P. parasitica* in soil (0 or >0% of the leaf disks infected) or on the presence or absence of Phytophthora root rot. Individual plant and soil samples were classified into one of two or three groups on the basis of corresponding soil and plant measurements by discriminant function analysis. Based on tests for homogeneity of covariance matrices among groups, the within-group covariance matrices were used for all discriminant analyses (44). Posterior probabilities of membership of plant and soil samples in each class were compared with the prior groupings into management types or disease-severity ratings, and percentages of correct classification were calculated. Stepwise discriminant analysis was used to identify variables that contributed most to the classification. Canonical discriminant analysis was used to determine the magnitude and direction of the association of individual variables with indicator variables. Standardized canonical coefficients larger than 0.3 divided by the square root

TABLE 1. Incidence (percentage of plants affected) and severity (percentage of root system affected) of corky root and Phytophthora root rot of tomato and abundance of *Phytophthora parasitica* in soil (percentage of leaf disks infected) in organic, transitional, and conventional farms in 1989 and 1990

			Corky root		Phytophthora root rot		*P. parasitica*
Year	Management type	Number of farms	Incidence (%)[a]	Severity (%)	Incidence (%)	Severity (%)	in soil (%)[b]
1989	Organic	2	0.1	0.0 (0–0.1)[c]	0.0	0.0 (0–0)[c]	0.0 (0–0)[c]
	Transitional	3	51.6	1.0 (0–7)	0.0	0.0 (0–0)	7.3 (0–100)
	Conventional	4	91.1	3.9 (0–25)	0.0	0.0 (0–0)[d]	1.1 (0–40)
1990	Organic	9	23.3	0.4 (0–8)	0.0	0.0 (0–0)	0.0 (0–0)
	Conventional (small)	4	72.5	2.2 (0–13)	7.5	0.3 (0–8)	18.0 (0–100)
	Conventional (large)	5	88.0	11.0 (0–40)	17.0	2.1 (0–32)	26.7 (0–100)

[a] Incidence and severity values are means of the corresponding farms.

[b] Percentage of all leaf disks colonized.

[c] Range.

[d] Phytophthora root rot was observed outside the sampling area.

of the eigenvalue of the canonical function (1) were considered large enough to contribute significantly to the classification.

RESULTS

Diseases observed. The most common tomato disease was corky root (*Pyrenochaeta lycopersici*), followed by Phytophthora root rot (*P. parasitica*). Foliar tomato diseases, such as bacterial speck, caused by *Pseudomonas syringae* pv. *tomato*; powdery mildew, caused by *Leveillula taurica* (Lév) G. Arnaud; and alfalfa mosaic virus, were observed only sporadically.

Corky root was present in most of the farms, but the incidence and severity were higher on conventional farms than on organic farms (Table 1). Small-scale conventional and transitional farms had levels of corky root intermediate to those of organic and large-scale conventional farms. Disease incidence in conventional farms was 91% in 1989 and 88% in 1990. However, disease severities were only moderate with maximum levels of 25 and 40% in 1989 and 1990, respectively.

Phytophthora root rot was not observed on organic farms in either year, and *P. parasitica* was detected in soil from one transitional farm but not in soil from organic farms (Table 1). *P. parasitica* was isolated from soils of two conventional farms and one transitional farm that had been managed conventionally the year before our study. In the second year, Phytophthora root rot was observed in the sampling areas of one small- and two large-scale conventional farms. The incidence and severity were generally low (7.5–17 and 0.3–2%, respectively). *P. parasitica* was detected in four of the five large-scale and in one of the four small-scale conventional farms; it was not detected in organically managed farms. No relationship was obtained between disease severity and plant biomass for either corky root or Phytophthora root rot.

Factors affecting distinctions among management types. Corky root severity was one of several soil and plant variables selected by stepwise discriminant analysis as significantly contributing to the distinction among farm types (squared canonical correlation [SCC] = 0.76 in 1989, SCC = 0.73 in 1990, and $P = 0.0001$ in both years). In 1990, corky root severity was selected as the most important variable for distinguishing among farm types. Severity of Phytophthora root rot and presence of *P. parasitica* in soil could not be used in this analysis because the respective frequency distributions were too skewed. For 1989 and 1990, 100 and 99.9% of plant and soil observations were correctly classified into organic, transitional, or conventional farms and into organic, small-scale conventional, and large-scale conventional farms, respectively, based on all soil and plant variables (Wilks' lambda = 0.05, $P = 0.0001$ for 1989 and Wilks' lambda = 0.07, $P = 0.0001$ for 1990). The first canonical function, containing corky root severity, variables related to the nitrogen cycle, and clay content in both years, separated organic and transitional farms from conventional farms in 1989 and separated organic from small-scale and large-scale conventional farms in 1990 (Fig. 2A and B). The second canonical function, determined mainly by water aggregate stability and electrical conductivity in both years, separated organic from transitional farms in 1989 and small-scale conventional from other farm types in 1990.

Factors affecting distinctions among corky root-severity classes. Discriminant function analysis on 11 soil and plant variables resulted in significant separation of the observations according to three classes of corky root severity in both years. In 1989, 69% of the observations were correctly classified into one of the three classes (Wilks' lambda = 0.37, $P = 0.0001$). In 1990, 75% of the observations were correctly classified (Wilks' lambda = 0.48, $P = 0.0001$). The separation of observations into corky root-severity classes, based on soil and plant variables, is illustrated in a plot of canonical variable two versus canonical variable one (Fig. 3A and B). When management types were indicated in the same plots (Fig. 3C and D), good separation was achieved between organic and conventional farms. However, transitional farms in 1989 and small-scale conventional farms in 1990 overlapped with both organic and conventional farms.

Nitrogen content in tomato tissue, nitrate and ammonium concentrations in soil, nitrogen-mineralization potential, and soil pH were selected as important factors in both years by stepwise discriminant analysis for discrimination among corky root-severity classes (Table 2). Nitrogen content in tomato tissue and nitrate concentrations in soil were positively associated with corky root severity, and nitrogen-mineralization potential was negatively associated with disease severity. In 1990, FDA hydrolytic activity also was negatively associated with corky root severity. The last two variables measure microbial activity and were positively correlated ($r = 0.62$, $P = 0.001$). Soil pH and ammonium concentration were not consistently positively or negatively associated with the disease (Table 2). In addition to the variables that were important in both years, organic carbon in 1989 and percent clay in 1990 were significant (Table 2). Organic carbon, higher in organically managed soils than in conventionally managed soils, was negatively associated with corky root severity. Percent clay was positively associated with the disease, particularly in two large-scale conventional farms with vertisols sampled in 1990 only (L. E. Drinkwater and C. Shennan, *unpublished data*).

A separate analysis of data from conventional farms in 1990 resulted in similar factors selected for discrimination among corky root-severity classes, namely FDA hydrolytic activity, tissue nitrogen, soil-ammonium content, and nitrogen-mineralization poten-

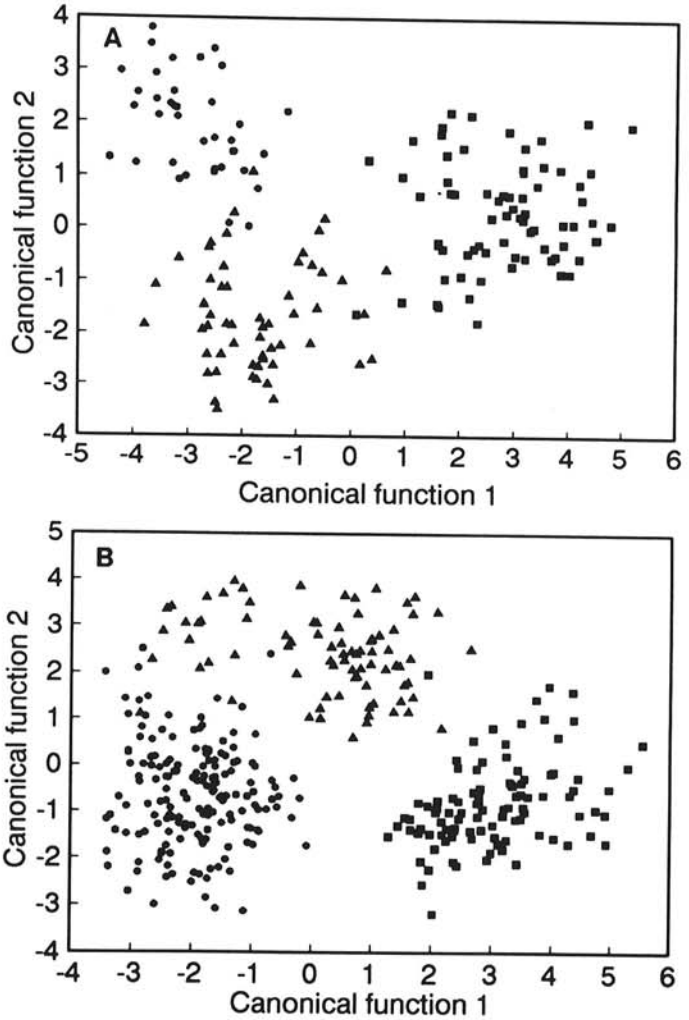

Fig. 2. A, Grouping of samples from organic, transitional, and conventional farms in 1989 and **B,** from organic, small-scale conventional, and large-scale conventional farms in 1990, based on canonical functions one and two. The first canonical function explained 77 and 73% of the variation in 1989 and 1990, respectively. Circles represent organic farms (in both years), triangles represent transitional (1989) or small-scale conventional farms (1990), and squares represent small- and large-scale conventional (1989) or large-scale conventional farms (1990).

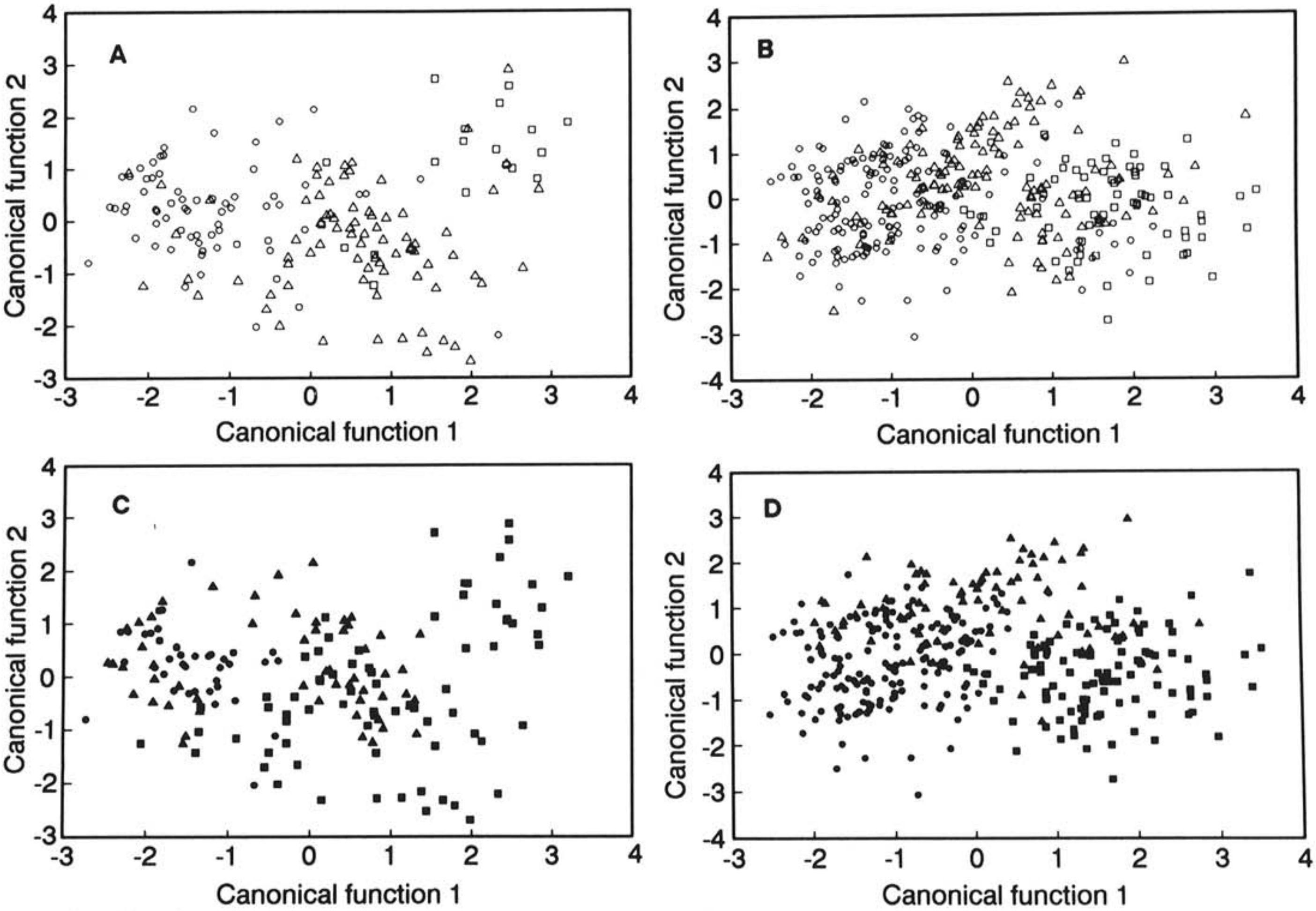

Fig. 3. Grouping of samples according to classes of corky root severity in **A,** 1989 and **B,** 1990, based on canonical functions one and two. Open circles represent 0% corky root, open triangles represent ≤5%, and open squares represent >5%. The first canonical function explained 83 and 94% of the variation in 1989 and 1990, respectively. The farm types from which the samples, as classified under **A** and **B**, originated are indicated in **C** and **D. C,** Closed circles represent organic farms, closed triangles represent transitional farms, and closed squares represent conventional farms in 1989. **D,** Closed circles represent organic farms, closed triangles represent small-scale conventional farms, and closed squares represent large-scale conventional farms in 1990.

TABLE 2. Soil and plant variables that contributed significantly to classification of the observations in corky root-severity classes by stepwise and canonical discriminant analyses, standardized canonical coefficients, pooled within-class correlations with the first canonical function, and mean values per corky root-severity class

		Canonical function 1[b]		Mean values of variables/ corky root severity (%)		
Year	Variables[a]	Standardized coefficient	Pooled within-class correlation	0	0.1–5	>5
1989	Organic carbon (%)	−0.61[c]	−0.75	1.25	0.95	0.62
	Nitrogen-mineralization potential (μg NH4-N/g/wk)[d]	−0.51	−0.42	14.27	9.00	10.31
	Tissue nitrogen (%)	0.20	0.18	2.40	2.72	2.37
	Soil nitrate (μg N/g)[d]	0.53	0.24	16.53	28.16	29.79
	Soil ammonium (μg N/g)[d]	−0.27	−0.18	1.07	0.95	0.41
	Soil pH	0.52	0.27	6.72	6.86	7.31
	Soil nitrogen (%)	−0.24	−0.58	0.11	0.09	0.06
1990	Tissue nitrogen (%)	0.56[e]	0.51	2.21	2.56	2.83
	Clay (%)	0.50	0.31	24.26	26.10	30.88
	Soil ammonium (μg N/g)	0.49	0.46	1.72	2.03	8.30
	Soil nitrate (μg N/g)	0.54	0.47	25.06	50.30	66.47
	FDA hydrolytic activity (μg FDA/g/min)[d]	−0.34	−0.45	0.52	0.42	0.26
	Soil pH	0.26				
	Water-stable aggregates (%)[f]	−0.11	−0.12	7.10	6.81	6.89
	Nitrogen-mineralization potential		0.45	16.79	19.83	31.41
	(μg NH4-N/g/wk)	−0.24	−0.44	15.63	12.79	9.61

[a] Variables are listed in order of selection by stepwise discriminant analysis. All variables listed contributed significantly to the discrimination.

[b] Responsible for 83 and 94% of the variation in 1989 and 1990, respectively.

[c] Standardized canonical coefficients >0.27 were considered large enough for interpretation (1).

[d] Dry soil.

[e] Standardized canonical coefficients >0.30 were considered large enough for interpretation.

[f] Percentage of the 1- to 2-mm aggregates that are stable.

tial (data not shown). Clay content and nitrate concentration in soil were not selected, however.

Factors affecting the distinction between the presence and absence of *P. parasitica*. Stepwise discriminant analysis for the presence or absence of *P. parasitica* in each soil sample identified three soil variables (percent clay, water-stable aggregates, and pH) that contributed significantly to classification in 1989 (data not shown). The squared canonical correlation was low ($R^2 = 0.17$), however, probably because *P. parasitica* was detected in only 13 of 180 soil samples. Percent clay was the only variable with enough canonical loading to be interpretable.

In 1990, percent clay and water-stable aggregates again contributed significantly to the classification between the presence and absence of *P. parasitica* in soil (Table 3). In addition, soil nitrate, organic carbon, and electrical conductivity had significant canonical loading. Water-stable aggregates and clay content were positively correlated ($r = 0.62$, $P = 0.001$) and were both positively associated with the presence of *P. parasitica* in soil (Table 3). Soil nitrate and electrical conductivity also were positively associated with the presence of the pathogen; organic-carbon content was negatively associated with *P. parasitica*.

When soil-water content at −50 J/kg was included in the analysis of data from 1990, this factor was among the most significant factors that contributed to the distinction between the presence and absence of *P. parasitica* in soil, together with water-stable aggregates, nitrate concentration in soil, organic carbon, electrical conductivity, and clay content (Table 4). Soil-water content was higher in soils with *P. parasitica* than in soils without *P. parasitica*. The significance of clay content was reduced compared to the analysis without soil-water content because of the positive correlation between clay and soil-water content ($r = 0.63$, $P = 0.0001$).

P. parasitica was not isolated from organically managed soils, so a separate analysis was conducted for the 1990 data from conventional farms. Water-stable aggregates, organic-carbon content, and soil-water content again were dominant factors for discriminating between the presence and absence of *P. parasitica* in individual soil samples (Table 4). In this analysis, clay content did not contribute to classification between the presence and absence of *P. parasitica* because of the strong, positive correlation with water-stable aggregates ($r = 0.79$, $P = 0.0001$). Nitrate concentration and electrical conductivity in soil did not contribute because they were very similar in conventionally managed soils.

In separate discriminant analyses of 1990 data from five conventional farms in which *P. parasitica* propagules had been detected in soil, clay content, water-stable aggregates, and FDA hydrolytic activity were the only variables that distinguished between plant samples with and without Phytophthora root rot. Clay content and water-stable aggregates were positively asso-

TABLE 3. Soil variables that contributed significantly to classification of the observations, according to detection of *Phytophthora parasitica* by leaf disk bioassays, stepwise, standard, and canonical discriminant analyses, standardized canonical coefficients, pooled within-class correlations with the first canonical function, and mean values per *P. parasitica* class in 1990

	Canonical function 1[b]		Mean values/ *P. parasitica* class	
Variables[a]	Standardized coefficient	Pooled within-class correlation	0	>0
Water-stable aggregates (%)[c]	0.70[d]	0.70	16.73	35.74
Soil nitrate (μg N/g)[e]	0.63	0.34	32.23	77.97
Clay (%)	0.72	0.47	23.95	34.71
Organic carbon (%)	−0.47	−0.21	1.18	1.03
Electrical conductivity (ds/m)[f]	0.41	0.13	0.68	0.90
Nitrogen-mineralization potential (μg NH_4-N/g/wk)[e]	−0.10	−0.33	14.47	9.74

[a] Variables are listed in order of selection by stepwise discriminant analysis. Soil moisture was not included in the analysis. All variables listed contributed significantly to the discrimination.

[b] Responsible for the total variation.

[c] Percentage of the 1- to 2-mm aggregates that are water stable.

[d] Standardized canonical coefficients >0.28 were considered large enough for interpretation (1).

[e] Dry soil.

[f] Decisiemens per meter.

TABLE 4. Soil variables that contributed significantly to classification of the observations, according to detection of *Phytophthora parasitica* by leaf disk bioassays, stepwise and canonical discriminant analyses, standardized canonical coefficients, pooled within-class correlations with the first canonical function, and mean values per *P. parasitica* class in 1990

		Canonical function 1[b]		Mean values/ *P. parasitica* class	
Farms	Variables[a]	Standardized coefficient	Pooled within-class correlation	0	>0
Organic and conventional	Water-stable aggregates (%)	0.82[c]	0.70	16.73	35.74
	Soil nitrate (μg N/g)[d]	0.52	0.34	32.23	77.97
	Clay (%)	0.33	0.47	23.95	34.71
	Organic carbon (%)	−0.90	−0.21	1.18	1.03
	Electrical conductivity (dS/m)[e]	0.51	0.13	0.68	0.90
	Soil moisture (%)	0.83	0.31	16.85	19.85
Conventional	Water-stable aggregates (%)[f]	1.23[g]	0.64	22.10	36.46
	Organic carbon (%)	1.27	−0.23	1.14	1.00
	Soil moisture (%)	1.07	0.20	17.88	19.13
	pH	0.57	0.14	6.73	6.93

[a] Variables are listed in order of selection by stepwise discriminant analysis. All variables listed contributed significantly to the discrimination.

[b] Responsible for the total variation.

[c] Standardized canonical coefficients >0.26 were considered large enough for interpretation (1).

[d] Dry soil.

[e] Deciciemens per meter.

[f] Percentage of the 1- to 2-mm aggregates that are water stable.

[g] Standardized canonical coefficients >0.29 were considered large enough for interpretation (1).

ciated with Phytophthora root rot and had more weight than had FDA hydrolytic activity, which was negatively associated with this disease (Table 5).

DISCUSSION

In this study, incidence and severity of both corky root and Phytophthora root rot were higher in conventional than in organic farms. Transitional and small conventional farms had intermediate incidence and severity levels. In three other comparative studies, root and stem diseases of wheat and damping-off of sugar beet also were less severe in organic or reduced-input compared to conventional production systems (9,12,35). These studies (9, 12,35) were conducted in adjacent experimental or production farms. The number of replications (number of farms) was limited or nonexistent, and potential factors associated with disease severity were not investigated. To our knowledge, this is the first study in which differences in plant-disease severity between organic and conventional production systems were related to several soil and plant variables by multivariate analyses.

Stepwise and canonical discriminant analyses indicated that corky root severity was positively associated with nitrogen in tomato tissue and nitrate concentrations in soil, which were higher in conventional farms than in organic farms. In 1989, tissue nitrogen had lower canonical loading than had the rest of the variables selected by stepwise discriminant analysis but was consistently positively associated with disease severity in both years, especially in 1990. Various other root diseases were affected by nitrate or ammonium fertilization in conventional farming systems (16). For example, severe root and stem rot of wheat in conventional farms was associated with higher nitrogen-fertilization rates in conventional than in organic farms (9). Fusarium root rot of beans was positively correlated with soil nitrate but was negatively associated with soil ammonium (22). Corky root of lettuce caused by the bacterium *Rhizomonas suberifaciens* also was enhanced by increased concentrations of nitrate but not by increased ammonium in soil and plant tissue (48).

In addition to the positive association of corky root of tomato with inorganic nitrogen concentrations in soil and plant tissue, there was a negative association between this disease and microbial activity in soil (as expressed by FDA hydrolytic activity and nitrogen-mineralization potential). In the first year, corky root severity also was negatively associated with organic carbon and nitrogen content in soil. These variables are considered indicators of organic-matter content (18,31). In the second year, organic carbon was not significant in distinguishing among corky root-severity classes. This may have been related to relatively high organic-carbon contents on three conventional farms with vertisols that were not included in the first year (L. E. Drinkwater and C. Shennan, *unpublished data*).

Microbial activity (FDA hydrolytic activity and/or nitrogen-mineralization potential) in both years and organic carbon in the first year were higher in the organic farms where compost or green manure had been applied, and corky root was less severe than in conventional farms. Several soilborne diseases have been suppressed by composts (8,24) and other organic amendments (15). Addition of organic amendments may stimulate microbial activities, enhancing competition between soil microorganisms and resulting in suppression of root diseases (8,32).

Clay content was selected as an important factor in the second year, when three conventional farms with vertisols were included in the study. This agrees with a previous study in which severity of corky root of tomato and subsequent yield loss were higher in clay soils than in sandy soils (36).

In contrast to corky root, severity of Phytophthora root rot and presence of *P. parasitica* in soil were not associated with nitrogen concentration in tomato tissue or nitrogen-mineralization potential. Clay content, soil-water content at -50 J/kg, organic carbon, and water-stable aggregates, which were positively correlated, were all major factors that distinguished between the presence and absence of propagules of *P. parasitica* in soil. The positive correlations between soil-water content, clay, and organic-carbon content were expected, based on differences in soil-water release curves, which depend on clay and organic-matter content (33).

Clay content and water-stable aggregates also were significantly correlated with severity of Phytophthora root rot in the second year ($r = 0.51$, $P = 0.0001$ and $r = 0.37$, $P = 0.0001$, respectively). Soil aggregation is influenced by clay type and content as well as by organic matter (45). In our study, however, water-stable aggregates were correlated more strongly with clay than with organic-carbon content. In a previous study, clay content was also an important factor that determined severity of Phytophthora root rot of tomatoes (D. A. Neher, North Carolina State University, Raleigh, *personal communication*). The association of clay with Phytophthora root rot is not surprising because soils with a high-clay content are prone to long periods of saturation, and Phytophthora root rot is favored by prolonged saturation of soils (38).

In addition to clay content and associated factors, electrical conductivity and soil nitrate were important factors that distinguished between the presence and absence of propagules of *P. parasitica* in soil. The last two variables were positively correlated ($r = 0.75$, $P = 0.0001$) and were higher in conventional than in organic farms. Electrical conductivity was not related to sodium concentrations in soil (11). Thus, the higher electrical conductivity in conventional farms may be the result of application of inorganic fertilizers rather than of soil salinity.

Some factors were associated with both corky root severity and presence of *P. parasitica* (e.g. organic carbon, soil nitrate, and clay content). Other factors were unique to one disease or the other, such as nitrogen-mineralization potential and tissue nitrogen, which were related to corky root severity only, versus water-stable aggregates, clay content, and electrical conductivity, which contributed significantly to the distinction between classes of *P. parasitica* in soil. Severity of Phytophthora root rot also was mainly affected by water-stable aggregates and clay content. Taking all significant factors into account, corky root severity seemed to be affected primarily by soil-biology factors and tissue nitrogen, and Phytophthora root rot was affected mainly by

TABLE 5. Soil variables associated with the presence or absence of Phytophthora root rot as determined by stepwise and canonical discriminant analyses, standardized canonical coefficients, pooled within-class correlations with the first canonical function, and mean values per root rot class

	Canonical function 1[b]		Mean values/root rot class	
Variables[a]	Standardized coefficient	Pooled within-class correlations	0	>0
Clay (%)	0.65	0.89[c]	30.45	42.30
FDA hydrolytic activity (μg FDA/g/min)[d]	−0.37	−0.27	0.31	0.21
Water-stable aggregates (%)[e]	0.50	0.66	33.54	42.00

[a] Variables are listed in order of selection by stepwise discriminant analysis. All variables listed contributed significantly to the discrimination.

[b] Responsible for the total variation.

[c] Standardized canonical coefficients >0.38 were considered large enough for interpretation (1).

[d] Dry soil.

[e] Percentage of the 1- to 2-mm aggregates that are water stable.

factors related to soil texture, structure, and chemistry.

The relationships between the most important factors contributing to these two diseases were consistent in both years, despite the fact that different fields were surveyed and different tomato cultivars were used. The use of several tomato cultivars may have obscured some of the relationships in 1989, but in 1990, transplants of one cultivar were supplied to all participating growers to avoid potential confounding effects of tomato cultivars (42). Even in the first year, however, confounding effects of cultivars in disease development probably were minimal, because all cultivars were equally susceptible to Phytophthora root rot (F. Workneh, *unpublished data*) and probably to corky root (17).

Any inconsistencies in the relative importance of the significant factors from year to year may be attributable to intercorrelation of many variables and associated redundancy (44). Redundancy resulting from strong correlations among variables also can affect signs of the coefficients (43), as was the case with water-stable aggregates and pH in 1990. The correlations of individual variables with disease severities were relatively low, but analysis of all variables simultaneously revealed significant and consistent relationships.

In addition to the variables considered in this study, other factors may have affected corky root and Phytophthora root rot. Lower corky root severities in organic farms than in conventional farms may have been partially the result of lower levels of inoculum rather than of higher microbial activity in organic than in conventional farms, resulting in possible disease suppression. However, preliminary results from greenhouse tests in which the pathogen was added to various soils indicate corky root was suppressed by biological factors in organically managed soils (F. Workneh and A. H. C. van Bruggen, *unpublished data*). *P. parasitica* may not have been introduced in some of the organic fields, or different methods of irrigation may have controlled Phytophthora root rot in organic fields rather than the addition of organic matter to soil and concomitant improvements in soil structure. Controlled greenhouse experiments can shed light on this question. In addition, the use of herbicides and other pesticides may have rendered tomato plants more susceptible to root rots in conventional fields compared to organic fields (2).

Results obtained in this study cannot be considered conclusive but have led to hypotheses about the mechanisms that suppress corky root and Phytophthora root rot in organic relative to conventional farms. Additional greenhouse experiments will be needed to test these hypotheses.

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