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Effect of urban plant debris and soil management practices on plant parasitic nematodes, Phytophthora blight and Pythium root rot of bell pepper

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Abstract

Soil management practices were examined for their effects on plant parasitic nematodes and soilborne diseases of field grown bell pepper (*Capsicum annuum*). Field plots were established on a diversified organic vegetable farm that had been under certification for 5 years and on a conventional pepper farm that had been fumigated with methyl bromide/chloropicrin and cropped annually to bell pepper for 25 years. The plot design was a split plot where the main treatment was the application of 67 t ha^{-1} of urban plant debris (UPD), and sub plots were; (1) no-till production into residue remaining from a cover crop of Sunn Hemp (*Crotalaria juncea*), (2) or Iron-clay Pea (*Vigna unguiculata*), (3) creation of raised polyethylene-mulched beds and, (4) soil solarization for a 6–8 week period. Soil fumigation with methyl bromide/chloropicrin (67/33) was evaluated only at the conventional farm site. Experiments were conducted in 1999 and repeated in 2000. At the organic farm only Pythium root rot was identified whereas, at the conventional farm Phytophthora blight was the predominant soilborne disease. UPD application significantly reduced the incidence of Pythium root rot from 24.7% to 12.1% in 2000 at the organic site and the incidence of Phytophthora blight from 49.8% to 31.1% in 1999 at the conventional site. At the conventional site, Phytophthora blight was significantly lower in solarized (21.9%) and fumigated (22.1%) plots when compared to plots with untreated soil covered by polyethylene mulch (46.1%) in 1999. In 2000, Phytophthora blight was significantly higher in the no-till treatments (91.1–91.8%) when compared to the other soil management treatments (50.2–63.5%). UPD application significantly reduced the populations of plant parasitic nematodes from 64.5 to 37.5 per 100 cm^3 soil in 2000 at the organic site and from 94.3 to 12.9 in 1999 at the conventional site, when compared to treatments not receiving UPD. At the organic site the populations of plant parasitic nematodes were significantly higher in the no-till Sunn Hemp plots than solarized plots. At the conventional site, significantly higher populations of *Meloidogyne* spp. were found in solarized and no-till Sunn Hemp treatments then in untreated soil covered with plastic mulch, while significant reductions in *Meloidogyne* spp. only occurred with soil fumigation. The results demonstrate that several nonchemical management practices can reduce the impact of soilborne pests for fresh market bell pepper production in a humid, subtropical climate.

Keywords: Conservation tillage; Cover crops; Low-input agriculture; Methyl bromide; Organic agriculture; *Phytophthora capsici*; Soil solarization

1. Introduction

Florida is the leading producer of fresh market bell pepper (*Capsicum annuum*) in the United States with annual sales exceeding $218 million (Florida Agricultural Statistical Service, 2005). Field production takes place in a humid, subtropical climate with an annual precipitation exceeding 1450 mm and sandy soils that are low in fertility, contain little organic matter and have a low cation exchange capacity (CEC). Phytophthora blight is a major disease of pepper production in Florida (Chellemi and Sonoda, 1983; Rosskopf et al., 2005). In addition to causing damping-off of newly transplanted seedlings in the field, four species of *Pythium* can cause significant root rot and reductions in growth of mature pepper plants in Florida (Chellemi et al., 2000). Several genera of plant parasitic nematodes are also capable of causing yield reductions in the field. To compensate for these conditions and pests and to maintain high yields, conventional

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growers rely upon complex, high input production systems requiring high amounts of rapidly mobile N and K sources, plastic mulch, herbicides and soil fumigation with methyl bromide (Cantliffe et al., 1995; Maynard and Olson, 2002). There is a growing impetus to investigate alternatives to several key management tools critical to the production systems. Methyl bromide is considered critical for the control of soilborne pests, but has been classified as a Class I Stratospheric Ozone Depleting Substance and its use in the United States is being phased out according to a schedule agreed upon by the parties to the Montreal Protocol (USEPA, 2005). Herbicide resistance has been reported for several key weed species present in the major pepper production areas of Florida including American black nightshade (*Solanum americanum*) and goosegrass (*Eleusine indica*) (Weed Science Society of America, 2005). Rapid urbanization and development in key winter production areas has reduced the availability of land suitable for crop rotation. Finally, input costs have continued to escalate and now exceed $25,730 per ha (Food & Resources Economics Department, 2005).

Alternative soil management practices derived from organic and conservation production systems have been shown to reduce the severity of soilborne diseases and plant parasitic nematodes and could be applicable to conventional pepper production in Florida. van Bruggen (1995) reviewed comparative farming system studies and found a consistent reduction in root disease severity in organic and reduced-input systems when compared to conventional systems. Differences were attributed to longer rotations, regular applications of organic amendments and reductions in pesticide use.

While crop rotation remains one of the oldest practices used to manage soilborne pests, difficulty in stand establishment and the length of rotation time required for pest suppression are major impediments to its widespread adoption in subtropical climates. Cover crops are grown primarily between the growing seasons of the main cash crop and reduce the density of plant parasitic nematodes in soil in Florida production systems (McSorley et al., 1994) but their role in disease suppression is not well known. The prospects for composts as an alternative to soil fumigation with methyl bromide was reviewed by De Ceuster and Hoitink (1999) and several examples of disease reduction were cited. In organic systems, disease suppression from organic amendments was commonly associated with increased microbial and microfauna activity resulting from the regular application of organic amendments and reduced levels of pesticides (Malajczuk, 1983; Workneh and van Bruggen, 1994). However, De Ceuster and Hoitink (1999) attributed the lack of consistent results in disease suppression to differences in the composition of the organic matter from which the compost was prepared and the composting process itself.

Conservation tillage practices can minimize agricultural inputs and improve soil quality. However, in some instances, reduced tillage may exacerbate soilborne diseases (Cook and Haglund, 1991). Soil solarization is adaptable to conventional fresh market tomato and pepper production systems in humid subtropical climates and is technically feasible (Chellemi et al., 1997a–c). It has also been combined with the application of organic amendments to improve its level of efficacy (Gamliel and Stapleton, 1997). Although soil solarization is well adapted for use in organic production systems, its impact on soilborne pests has not been extensively documented for organic production systems located in humid, subtropical climates.

The objective of the current research was to measure the effects of alternative soil management practices on the density of plant parasitic nematodes and the incidence of soilborne disease for field production of bell pepper in a subtropical production region. This study was conducted concomitantly with another measuring the effects of nonchemical soil management practices on indicators of soil quality and yield potential of fresh market bell pepper in a humid, subtropical production region (Chellemi and Rosskopf, 2004). To generate valid information for organic producers and those transitioning to organic production, experimental sites were selected on commercial conventional and organic farms. To minimize variability due to the source of nitrogen and to comply with organic regulations at one of the experimental sites, poultry litter was used as the main source of nitrogen, phosphorus, and potassium in all field experiments.

2. Materials and methods

2.1. Experimental design

Two sites were selected in southeastern Florida. The Vero Beach site was an organic vegetable farm with continuous (5 years) and current organic certification. Before producing vegetables, this site was an abandoned grapefruit grove. The soil was a Winder fine loamy sand (sandy, siliceous, hyperthermic, Typic Glossaqualfs) and had a pH of 6.4 and a texture of 90%–5%–5% sand–silt–clay, respectively. Soil organic carbon, detected from samples collected at 15 cm depths using wet oxidation with $K_2Cr_2O_7$ in H_2SO_4, was 37.8 t C ha^{-1}.

The Boynton Beach site was a conventional pepper farm in production since 1957 and fumigated with a mixture of methyl bromide/chloropicrin (76/33) annually since 1973. Prior to initiation of this study, a cover crop of crabgrass (*Digitaria ciliaris*) was allowed to establish for 2 years. The soil was Myakka fine sand (sandy, siliceous, hyperthermic, Aeric Haplaquad) and had a pH of 7.4 and a texture of 95%–2%–3% sand–silt–clay, respectively. Soil organic carbon was 42.4 t C ha^{-1}.

Experiments were conducted in 1999 and 2000. Poultry (broiler) litter was used as fertilizer at both farm sites to provide a consistent source of slow-release N that conformed to organic production standards. The broiler litter consisted of a mixture of chicken manure and pine shavings collected from commercial broiler production houses and composted in static windrows. It was broadcast to fields at a rate of $22\,t\,ha^{-1}$ and immediately disked to a depth of 12–15 cm. Applications were made on 14 June 1999 and 16 June 2000 at the organic farm site and on 7 July 1999 and 24 July 2000 at the conventional farm site. The poultry litter analysis averaged 17% ash, 3.3% total nitrogen, 0.9% ammonia nitrogen, 1% elemental P and 2% elemental K. Thus, the corresponding application rates were 726 kg N, 220 kg elemental P (504 kg P_2O_5), and 440 kg elemental K (528 K_2O) per hectare. A high application rate was selected because of an estimated loss of 30% N during application and the high mineralization rates in Florida soils.

Treatments were arranged in a split-plot design with main plots consisting of the application of urban plant debris (UPD) at 0 or $67\,t\,ha^{-1}$. The UPD was derived from green waste deposited at a public landfill by homeowners and small landscape maintenance companies that was tub ground, passed through 10- and 2.5-cm-mesh screens and static-piled for a minimum of 30 days. Samples were removed from piles and tested for residues of metal, chlorinated herbicides and organochlorine pesticides. Only UPD with heavy metal residues below $10\,mg\,kg^{-1}$ and herbicide and trace pesticide residues below $1\,\mu g\,kg^{-1}$ was used in the study. The UPD analysis averaged $29\,g\,N\,t^{-1}$, $52\,g\,P\,t^{-1}$, $280\,g\,K\,t^{-1}$, $2.3\,kg\,Ca\,t^{-1}$ and $110\,g\,Mg\,t^{-1}$ with a pH of 7.1 The UPD was broadcast and incorporated to a depth of 15 cm immediately following the poultry litter application on 15 June 1999 and 22 June 2000 at the organic farm site and on 8 July 1999 and 25 July 2000 at the conventional farm site. Main plots were 60×7.5 m at the organic site and 75×10 m at the conventional site and were arranged with four replications in a randomized complete block design.

At the organic site, the split-plot treatments consisted of no-till production into the stubble remaining from a cover crop of Iron-clay Pea (*Vigna unguiculata*), no-till using the stubble remaining from a cover crop of Sunn Hemp (*Crotalaria juncea*), soil solarization over an 8–9 week period, and the use of a white over black, co-extruded, low-density polyethylene (LDPE) plastic mulch (Pliant Corp., Schaumburg, IL). Split-plots were randomized within each main plot and consisted of 3 rows 15 m in length and spaced 2 m apart. Treatments were implemented on 90 cm wide $\times$ 25 cm tall beds on 18 June 1999 and 27 June 2000. Cover crops were seeded by drilling seed in two rows spaced 30 cm apart using a seeding rate of $45\,kg\,ha^{-1}$ and were mowed 60 and 64 days after seeding with a high-speed flail mower. Soil solarization was terminated after 56 days in 1999 and 65 days in 2000 by painting the plastic white, thus enabling it to function as a mulch.

Identical split-plot treatments were applied at the conventional site except that a soil fumigation subplot was added using a 67:33 mixture of methyl bromide/chloropicrin, applied at $400\,kg\,ha^{-1}$ to a depth of 25 cm using 3 shanks spaced 25 cm apart. Immediately after fumigation, the raised beds were covered with white over black LDPE mulch. Split-plot treatments were applied on 22 July 1999 and 30 July 2000. Cover crops were mowed 65 days after planting. Soil solarization was terminated after 56 days in 1999 and 66 days in 2000.

Six-week-old pepper seedlings ('var. Enterprise') were transplanted into subplots at the organic farm site on 25 August 1999 and 2 September 2000. Two rows were planted 20 cm from the edge of the bed. Plant spacing within rows was 25 cm. In the subplots where the cover crops were mowed, pepper seedlings were transplanted into the stubble without tilling the soil (no-till). In the conventional site, 6-week-old 'var. Enterprise' seedlings were planted on 27 September 1999 and 9 October 2000 using the same row and plant spacing.

2.2. Disease incidence

Plants were examined visually for symptoms of Phytophthora blight and Pythium root rot. Phytophthora blight, caused by *Phytophthora capsici*, induces a root and crown rot of pepper with distinctive black lesions on stems and circular, grayish brown, water-soaked lesions on leaves (Ristaino, 2003). Periodically, diagnosis of symptomatic plants in each replicate plot was confirmed by isolation of the fungus from root and crown tissue using a selective medium (Kannwischer and Mitchell, 1978). Colonies were transferred to V-8 juice agar and examined for sporangial formation typical of *P. capsici*. Symptoms of Pythium root rot include chlorosis, stunting, and reduced vigor (Chellemi et al., 2000; Roberts, 2003). Diagnosis was confirmed by obtaining fungal isolates from symptomatic plants in each replicate plot using a general medium consisting of potato dextrose agar ($39\,g\,l^{-1}$), ampicillin ($0.25\,g\,l^{-1}$), rifampicin ($0.01\,g\,l^{-1}$), and tergitol ($0.1\,ml\,l^{-1}$). *Pythium* spp. were identified using a grass leaf culture technique (Waterhouse, 1967). In 1999, disease incidence was low at the organic site and ratings were extended out to 82 days after transplanting. In 2000, the incidence of disease was assessed 48 days after transplanting at the organic site. At the conventional site, disease incidence was assessed 46 days after transplanting in 1999. Due to a severe epidemic of Phytophthora blight that occurred shortly after transplanting the seedlings, disease incidence was assessed 13 days after transplanting in 2000.

2.3. Plant parasitic nematodes

In 1999, soil samples for nematode analysis were collected 91 days after transplanting at the organic site and 100 days after transplanting at the conventional site. In 2000, soil samples were collected 93 days after transplanting at the organic site. The conventional site was not sampled in 2000 due to the early epidemic of Phytophthora blight. Soil samples for nematode analysis were collected by removing and combining soil cores 2.5 cm wide and 15 cm deep from the root zone of each of six plants per replicate plot. Nematodes were extracted from 100-cm^3 soil sub-samples with a modified sieving and centrifugation procedure (Jenkins, 1964). They were then identified and counted (Taylor and Sasser, 1978).

2.4. Data analysis

Disease incidence data was transformed using the arc sine transformation ($\sin^{-1}$ square root x) prior to analysis to satisfy assumptions of normality. Nematode counts were log-transformed ($\log_{10}[x+1]$) prior to analysis. Results from each farm site by year combination were analyzed separately. Analysis of variance (ANOVA) was performed to determine the influence of UPD and soil management practices on disease incidence and nematode density using the general linear models procedure in STATISTICA (StatSoft, Inc., Tulsa, OK).

3. Results

3.1. Disease incidence

At the organic site only Pythium root rot was observed and confirmed. In 1999, *Pythium aphanidermatum* was isolated from symptomatic plants. Soil incorporation of UPD did not affect disease incidence (2.3% vs. 3.2%) (Table 1). In the no-till treatments, disease was significantly lower (0.0%) when compared to soil solarization (5.2%) and the white plastic mulch treatment (6.4%). No significant interactions between UPD and soil management practices were observed (Table 1). In 2000, *P. aphanidermatum*, *P. arrhenomanes* and *P. myriotylum* were isolated from symptomatic plants at the organic site. Disease incidence was significantly higher (24.7%) in plots without UPD when compared to plots were UPD was added (12.1%) (Table 2). Here again disease incidence was lowest in the no-till treatments at 7.3% and 6.2% (Table 2). No interaction was observed between addition of UPD and the other soil management practices. No other soilborne diseases were detected.

At the conventional site, Phytophthora blight was the predominant soilborne disease observed and confirmed. On occasion, *Pythium aphanidermatum*, *P. helicoides* and *P. myriotylum* were isolated in addition to *Phytophthora capsici* from root and crown tissue of plants symptomatic of Phytophthora blight. UPD significantly reduced disease from 49.8% to 31.1% (Table 3). Phytophthora blight was significantly lower in solarized or fumigated treatments (21.9% and 22.1%, respectively) than in the no-till and white plastic mulch treatments (51.5%, 60.2% and 46.1%). No interactions were detected by ANOVA between UPD and soil management practices. In 2000, a major epidemic of Phytophthora blight occurred shortly after transplanting. At 13-days-after transplanting, disease incidence exceeded 90% in many of the replicate plots (Table 4). Shortly thereafter the crop was destroyed by the grower to prevent additional spread into adjacent commercial production areas. Addition of UPD did not affect the incidence of disease. Disease was significantly higher in the no-till treatments (91.1% to 91.8%) when compared to the other treatments (50.2% to 63.5%). No interaction between UPD and soil management treatments was observed.

Table 1
Effect of urban plant debris and soil management practices on soilborne pests of bell pepper at an organic farm in 1999

Soil management practice	Application rate of urban plant debris		
	($67\,t\,ha^{-1}$)	($0\,t\,ha^{-1}$)	Mean
Pythium root rot[a]			
White plastic mulch	5.1[b]±2.0	7.7±2.9	6.4±2.0 A[c]
Soil solarization	4.3±4.3	6.0±0.3	5.2±2.0 A
No-till (Sunn Hemp)	0.0±0.0	0.0±0.0	0.0±0.0 B
No-till (Iron-clay Pea)	0.0±0.0	0.0±0.0	0.0±0.0 B
Mean	2.3±1.3 A	3.2±1.1 A	
All plant parasitic nematodes[d]			
White plastic mulch	8.0±2.8	98.0±49.7	53.0±28.6 AB
Soil solarization	35.0±2.8	12.0±6.9	23.5±8.7 B
No-till (Sunn Hemp)	61.0±7.0	86.8±10.9	73.9±7.7 A
No-till (Iron-clay Pea)	46.0±17.9	61.2±26.9	53.6±15.2 AB
Mean	37.5±7.4 A	64.5±15.5 A	
Paratrichodorus species[d]			
White plastic mulch	3.0±1.9	11.2±4.7	7.1±2.8 B
Soil solarization	7.2±6.0	4.0±4.0	5.6±3.4 B
No-till (Sunn Hemp)	22.5±7.1	30.8±12.2	26.6±7.0 A
No-till (Iron-clay Pea)	28.8±10.3	16.2±8.9	22.5±6.7 A
Mean	15.4±4.2 A	15.6±4.4 A	
Tylenchorhynchus species[d]			
White plastic mulch	3.0±1.9 b	63.5±34.4 a	33.3±19.6
Soil solarization	26.8±16.6 ab	2.0±2.0 b	14.4±9.0
No-till (Sunn Hemp)	6.0±2.0 b	7.0±3.4 b	6.5±1.8
No-till (Iron-clay Pea)	1.0±1.0 b	20.5±20.5 b	10.8±10.2
Mean	9.2±4.6	23.2±11.0	
Heliocotylenchus species[d]			
White plastic mulch	0.0±0.0	4.0±4.0	2.0±2.0 B
Soil solarization	1.0±1.0	2.0±2.0	1.5±1.0 B
No-till (Sunn Hemp)	19.5±7.1	32.8±12.2	26.1±10.2 A
No-till (Iron-clay Pea)	12.2±9.8	10.0±3.8	11.1±4.8 AB
Mean	8.2±3.3 A	12.2±5.7 A	

[a]Disease incidence expressed as percent of plants with identifiable symptoms of root rot caused by *Pythium aphanidermatum*.
[b]Mean and standard error.
[c]Main effect means for urban plant debris or soil management practice followed by the same letter (A or B) do not differ according to Fischer's protected LSD ($P \leqslant 0.05$). Means for the interaction of urban plant debris and soil management practice followed by the same letter (a or b) do not differ according to Fischer's protected LSD ($P \leqslant 0.05$).
[d]Density 100 cm of soil.

3.2. Plant parasitic nematodes

In 1999, *Meloidogyne* spp., *Paratrichodorus* spp., *Tylenchorhynchus* spp., *Helicotylenchus* spp., *Criconemoides* spp. and *Hemicriconemoides* spp. were identified in soil samples collected from the base of mature bell pepper plants at the organic site. *Paratrichodorus* spp.,

Table 2
Effect of urban plant debris and soil management practices on soilborne pests of bell pepper at an organic farm in 2000

Soil management practice	Application rate of urban plant debris		
	(67 t ha^{-1})	(0 t ha^{-1})	Mean
Pythium root rot[a]			
White plastic mulch	18.8[b] ± 3.8	33.6 ± 11.0	26.2 ± 6.1 A[c]
Soil solarization	29.8 ± 13.1	38.1 ± 9.4	33.9 ± 7.6 A
No-till (Sunn Hemp)	0.0 ± 0.0	14.8 ± 12.0	7.2 ± 6.2 B
No-till (Iron-clay Pea)	0.0 ± 0.0	12.5 ± 12.5	6.2 ± 6.2 B
Mean	12.1 ± 4.5 A	24.7 ± 5.8 B	
All plant parasitic nematodes[d]			
White plastic mulch	6.0 ± 2.0	18.2 ± 6.2	12.1 ± 3.8 B
Soil solarization	1.0 ± 1.0	24.8 ± 3.4	12.9 ± 4.8 B
No-till (Sunn Hemp)	3.5 ± 6.4	143.2 ± 19.6	88.4 ± 22.8 A
No-till (Iron-clay Pea)	11.0 ± 4.4	191.0 ± 36.0	101.0 ± 37.9 A
Mean	12.9 ± 3.7 B	94.3 ± 21.4 A	
Paratrichodorus species[d]			
White plastic mulch	1.0 ± 1.0	12.2 ± 7.2	6.6 ± 4.0 B
Soil solarization	1.0 ± 1.0	20.7 ± 4.2	10.9 ± 4.2 B
No-till (Sunn Hemp)	16.2 ± 5.9	61.5 ± 21.9	38.9 ± 13.5 A
No-till (Iron-clay Pea)	4.0 ± 2.3	53.2 ± 15.3	28.6 ± 11.7 AB
Mean	5.6 ± 2.2 B	36.9 ± 8.2 B	
Tylenchorhynchus species[d]			
White plastic mulch	4.0 ± 2.3	0.0 ± 0.0	2.0 ± 1.3 B
Soil solarization	0.0 ± 0.0	4.0 ± 2.3	2.0 ± 1.3 B
No-till (Sunn Hemp)	6.2 ± 6.2	61.5 ± 38.0	33.8 ± 20.6 A
No-till (Iron-clay Pea)	3.0 ± 1.9	73.8 ± 39.2b	38.4 ± 22.6 A
Mean	3.3 ± 1.6 B	34.8 ± 14.9 A	
Heliocotylenchus species[d]			
White plastic mulch	1.0 ± 0.0 b	0.0 ± 0.0 b	0.5 ± 0.5
Soil solarization	0.0 ± 0.0 b	0.0 ± 0.0 b	0.0 ± 0.0
No-till (Sunn Hemp)	0.0 ± 0.0 b	12.2 ± 5.4 b	6.1 ± 3.4
No-till (Iron-clay Pea)	2.0 ± 2.0 b	45.5 ± 20.5 a	23.8 ± 12.6
Mean	0.8 ± 0.5	14.4 ± 6.7	

[a]Disease incidence expressed as percent of plants with identifiable symptoms of root rot caused by *Pythium aphanidermatum*, *P. helicoides* and *P. myriotylum*.
[b]Mean and standard error.
[c]Main effect means for urban plant debris or soil management practice followed by the same letter (A or B) do not differ according to Fischer's protected LSD ($P \leqslant 0.05$). Means for the interaction of urban plant debris and soil management practice followed by the same letter (a,b or c) do not differ according to Fischer's protected LSD ($P \leqslant 0.05$).
[d]Density 100 cm of soil.

Table 3
Effect of urban plant debris and soil management practices on soilborne pests of bell pepper at a conventional farm in 1999

Soil management practice	Application rate of urban plant debris		
	(67 t ha^{-1})	(0 t ha^{-1})	Mean
Phytophthora blight[a]			
White plastic mulch	24.1 ± 8.3[b]	68.0 ± 8.3	46.1 ± 10.0 A[c]
Methyl bromide	29.6 ± 14.8	15.2 ± 5.1	22.4 ± 7.7 B
Soil solarization	7.3 ± 4.0	36.4 ± 17.5	21.9 ± 10.0 B
No-till (Sunn Hemp)	40.5 ± 5.0	62.5 ± 7.2	51.5 ± 5.8 A
No-till (Iron-clay Pea)	53.9 ± 16.0	66.6 ± 12.3	60.2 ± 9.7 A
Mean	31.1 ± 5.6 B	49.8 ± 6.4 A	
All plant parasitic nematodes[d]			
White plastic mulch	10.2 ± 10.2	105.5 ± 41.0	57.9 ± 26.6 B
Methyl bromide	0.1 ± 0.1	1.0 ± 1.0	0.5 ± 0.5 C
Soil solarization	62.5 ± 61.2	243.8 ± 104.2	153.1 ± 65.6 A
No-till (Sunn Hemp)	11.0 ± 3.0	284.0 ± 236.9	147.5 ± 121.2 A
No-till (Iron-clay Pea)	21.5 ± 6.2	171.0 ± 42.8	96.2 ± 34.6 BC
Mean	21.0 ± 12.2 B	161.0 ± 52.5 A	
Meloidogyne species[d]			
White plastic mulch	10.2 ± 10.2	104.5 ± 41.5	57.4 ± 26.6 C
Methyl bromide	0.0 ± 0.0	1.0 ± 1.0	0.5 ± 0.5 D
Soil solarization	61.5 ± 61.5	243.7 ± 104.2	152.6 ± 65.7 A
No-till (Sunn Hemp)	5.0 ± 1.9	270.8 ± 232.9	137.9 ± 119.0 A
No-till (Iron-clay Pea)	14.5 ± 6.3	149.8 ± 40.7	82.1 ± 31.8 B
Mean	18.2 ± 12.2 B	153.9 ± 51.6 A	

[a]Disease incidence expressed as percent of plants with identifiable symptoms of Phytophthora blight caused by *Phytophthora capsici*.
[b]Mean and standard error.
[c]Main effect means for urban plant debris or soil management practice followed by the same letter (A or B) do not differ according to Fischer's protected LSD ($P \leqslant 0.05$). Means for the interaction of urban plant debris and soil management practice followed by the same letter (a or b) do not differ according to Fischer's protected LSD ($P \leqslant 0.05$).
[d]Density 100 cm of soil.

Table 4
Effect of urban plant debris and soil management practices on Phytophthora blight of bell pepper[a] at a conventional farm in 2000

Soil management practice	Application rate of urban plant debris		
	(67 t ha^{-1})	(0 t ha^{-1})	Mean
White plastic mulch	59.8[b] ± 13.8	67.2 ± 11.2	63.5 ± 8.4 B[c]
Methyl bromide	57.3 ± 16.3	49.5 ± 17.0	53.4 ± 11.0 B
Soil solarization	50.6 ± 9.7	49.8 ± 17.1	50.2 ± 9.1 B
No-till (Sunn Hemp)	92.0 ± 4.8	91.7 ± 1.7	91.8 ± 3.7 A
No-till (Iron-clay Pea)	89.7 ± 7.5	92.4 ± 2.4	91.1 ± 3.7 A
Mean	70.1 ± 6.4 A	70.0 ± 6.0 A	

[a]Disease incidence expressed as percent of plants with identifiable symptoms of Phytophthora blight caused by *Phytophthora capsici*.
[b]Mean and standard error.
[c]Main effect means for urban plant debris or soil management practice followed by the same letter (A or B) do not differ according to Fischer's protected LSD ($P \leqslant 0.05$). Means for the interaction of urban plant debris and soil management practice followed by the same letter (a or b) do not differ according to Fischer's protected LSD ($P \leqslant 0.05$).

Helicotylenchus spp and *Tylenchorhynchus* spp. were the most frequently identified genera. The combined density of nematodes was 37.5 and 64.5 100 cm^{-3} soil in treatments with and without UPD (Table 1). Significantly higher densities of *Paratrichodorus* spp. were observed in the no-till treatments (22.5–26.6) when compared to the soil solarization (5.6) and white plastic mulch treatments (7.1). Significantly higher populations of *Heliocotylenchus* spp. were observed in the Iron-clay Pea no-till treatment (26.2) when compared to the soil solarization (2.0) and white plastic mulch treatments (1.5). No interaction was observed between UPD and soil management practices. In 2000, the same six genera plus *Pratylenchus* spp. were identified in soil samples collected at the organic site. *Paratrichodorus* spp., *Helicotylenchus* spp., and *Tylenchorhynchus* spp. were the most frequently identified genera. Addition of UPD significantly reduced the combined density of plant parasitic nematodes from 94.3 to 12.9 (Table 2). Significantly higher populations of *Paratrichodorus* spp. were observed in the Sunn Hemp no-till treatments (38.9) when compared to the white plastic mulch (6.6) and soil solarization treatments (10.9). Significantly higher populations of *Helicotylenchus* spp. were observed in the Iron-clay Pea no-till treatment (23.8) when compared to the white plastic mulch (0.5) and soil solarization treatments (0.0). No interactions between addition of UPD and other soil management practices were observed.

In 1999, *Meloidogyne* spp., *Paratrichodorus* spp., *Helicotylenchus* spp., *Criconemoides* spp. and *Hemicriconemoides* spp. were identified in soil samples collected from the base of mature bell pepper plants at the conventional site. However, only *Meloidogyne* spp. was found in high numbers from the samples. Addition of UPD significantly reduced the density of *Meloidogyne* spp. from 153.9 to 18.2 100 cm^{-3} soil (Table 3). Soil fumigation with methyl bromide/chloropicrin significantly reduced the population density of *Meloidogyne* spp. to less than 1 cm^{-3} soil while high populations (>50 cm^3 soil) remained in other soil management practices (Table 4). No significant interaction between addition of UPD and other soil management practice was observed. In 2000, nematode samples were not collected because the crop was destroyed by the grower 14 days after transplanting due to a severe epidemic of Phytophthora blight.

4. Discussion

Phytophthora blight reached epidemic proportions at the conventional farm but was not detected at the organic farm. Contrasts in cropping history and land management practices and their differential effects on the biology and ecology of *P. capsici* and the pathogenic *Pythium* spp. likely contributed to the observed disease complexes and severity at the two farms. *P. capsici* has a limited host range and propagule densities are greatly reduced in the absence of a susceptible crop (Ristaino and Johnnston, 1999). *Pythium aphanidermatum*, *P. helicoides* and *P. myriotylum* have a wider plant host range, allowing them to persist in the soil under a variety of crop rotations. Bell pepper has been cultivated annually at the conventional site since the 1950s. Except for an occasional double (second) crop of cucumber or cover crop of sorghum–sudangrass (*Sorgum bicolor* × *S. sudanense*), it has remained the dominant plant species in the agroecosystem providing an opportunity for *P. capsici* populations to increase in plots and adjacent irrigation canals. Also plants are irrigated by maintaining the water table perched on an impermeable layer found between 45 and 60 cm from surface with canals spaced 30 m apart (seep irrigation). Maintaining a zone of saturated water underneath and adjacent to plants provides an optimum habitat for movement and survival of *P. capsici* propagules. Consequently, epidemics of Phytophthora blight have occurred periodically in the past at the conventional site. Conversely, the organic farm is typified by a high degree of plant diversity and the grower cultivates a wide assortment of vegetables, herbs and cover crops in the plots over a 3 year crop rotation and ensures that continuous cultivation of bell pepper does not occur. Additionally, plants are watered via drip irrigation minimizing flooding and movement of water into the fields.

Significant reductions in plant disease were observed at both sites following the incorporation of UPD at 67 t ha^{-1}. Disease reductions did not occur under conditions of low (organic site, 1999) or high (conventional site, 2000) overall disease. In a previous study conducted near the conventional site, variability in the suppression of Phytophthora blight was observed following amendment of soil with chitosan or crab shell waste (Kim et al., 1997). In years where multiple disease cycles of Phytophthora blight occur in the same field, foliar and rain-splash dispersal and movement through surface water may overwhelm the effects of soil management treatments. This may explain the lack of disease control in no-till treatments at the conventional site, where previously a stubble crop has been shown to reduce the severity of Phytophthora blight of pepper (Ristaino et al., 1997).

The UPD was not a finished compost and was not stabilized when it was added to soil. Fresh organic matter does not support biocontrol, even when inoculated with biological control agents (De Ceuster and Hoitink, 1999). One explanation for the observed reductions in disease is that the UPD was incorporated into soil 10 weeks prior to planting pepper. This provided ample time for the organic matter in the UPD to become fully colonized by soil microorganisms capable of introducing microbiostasis even though populations of the plant pathogen may have been elevated. A similar effect was documented for reductions in avocado root rot (caused by *Phytophthora cinnamomi*) following the addition of manure, straw and green manures. Disease reductions were attributed to increases in hyphal lysis and the formation of abortive sporangia after decomposing organic matter was added to disease conducive soils (Malajczuk, 1983; Nesbit et al., 1979). Combining the applications of chicken manure and UPD may also have contributed to the observed disease suppression. While considered an essential component, high soil organic matter on its own is not sufficient to create conditions for disease suppression (Aryantha et al., 2000). Addition of the chicken manure provided the nitrogenous compounds that support the growth of disease suppressive microbes (Hoitink and Boehm, 1999).

Plant disease was not observed at the 1999 organic site in the no-till treatments using the stubble mulch from Sunn Hemp or Iron-clay Pea. The same treatments also significantly reduced disease at the organic site in 2000. The incidence of Phytophthora blight was reduced when peppers were grown without tillage in the stubble from rye or wheat (Ristaino et al., 1997). Disease reductions were achieved by reducing splash dispersal of inoculum from soil covered by a stubble mulch. A similar mechanism may have occurred in the organic site. However, in 1999, <20% of seedlings survived the transplanting process in the no-till treatments as opposed to 80% in the other treatments (Chellemi and Rosskopf, 2004). In 2000, transplant survival in the no-till treatments was <35% as compared to 85%–100% in the other treatments. The low transplant survival rate in the no-till treatments may have also reduced plant to plant spread of Pythium root rot in the no-till treatments.. At the conventional site, >60% of the pepper seedlings survived the transplanting process Chellemi and Rosskopf, 2004) and the no-till treatments had significantly higher levels of disease in 1999 when compared to soil solarization and methyl bromide fumigation treatments.

Addition of UPD significantly reduced the numbers of *Paratrichodorus* spp. and *Tylenchorhynchus* spp. in the organic site and *Meloidogyne* spp. in the conventional site. Previous studies revealed inconsistencies in the reduction of plant–nematode populations on vegetable crops following the incorporation of UPD (McSorley and Gallaher, 1995a, b). One major difference in this study was that soil at both sites had an enhanced nutrient status due to incorporation of the chicken litter concomitantly with the UPD and this may have further enhanced microbial activity towards the nematode populations. In nonfumigated soil, significant reductions in root galling of tomato (*Lycopersicon esculentum*) from *Meloidogyne* spp. occurred when chicken litter was combined with olive pomace as compared to either treatment alone (Marull et al., 1997).

Significantly higher densities of *Meloidogyne* spp. were observed in the Iron-clay Pea and Sunn Hemp no-till treatments. Both of those tropical legume cover crops have been reported to reduce populations of *Meloidogyne* spp. in soil following their cultivation and the reductions by iron-clay were shown to extend to a subsequent pepper crop (McSorley et al., 1999; Rotar and Joy, 1983; Wang et al., 2004). These beneficial effects were not observed in this study. Additionally, at the organic site, significantly higher populations of *Paratrichodorus* spp. were observed in the Sunn Hemp treatments and *Heliocotylenchus* spp. in the Iron-clay Pea treatment when compared to untreated soil covered by white plastic mulch suggesting that these plants may serve as hosts for the nematodes.

Results from this study demonstrated that soil incorporation of UPD can reduce the impact of several important soilborne pests of bell pepper in humid, subtropical climates such as Florida in both conventional and organic crop production systems. Yields under plastic mulch also increased with addition of UPD (Chellemi and Rosskopf, 2004). Marketable yields equal to, or above, the 1999/2000 statewide average for conventional bell pepper production in Florida were obtained with soil solarization at the conventional site (Chellemi and Rosskopf, 2004). Marketable yields at the organic site approached the statewide average in the soil solarization treatment (Chellemi and Rosskopf, 2004). Thus, results reported in this study provide additional evidence of the beneficial effects of several nonchemical soil management practices on fresh market bell pepper production in a humid, subtropical climate.

No-till production into stubble crops remaining from the tropical legumes Sunn Hemp and Iron-clay Pea did not effectively reduce plant parasitic nematode populations and were inconsistent in the reduction of plant disease. When considered with additional observations regarding reductions in plant stand and marketable yield (Chellemi and Rosskopf, 2004), the no-till soil management practices are not recommended for bell pepper production in humid, subtropical production regions.

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References

Aryantha, I.P., Cross, R., Guest, D.I., 2000. Suppression of *Phytophthora cinnamomi* in potting mixes amended with uncomposted and composted animal manures. Phytopathology 90, 775–782.

van Bruggen, H.C., 1995. Plant disease severity in high-input compared to reduced-input and organic farming systems. Plant Dis. 79, 976–984.

Cantliffe, D.J., Hochmuth, G.J., Locascio, S.J., Stansly, P.A., Vavrina, C.S., Polston, J.E., Schuster, D.J., Seal, D.R., Chellemi, D.O., Olson, S.M., 1995. Production of Solanaceae for fresh market under field conditions: current problems and potential solutions. Acta Hortic. 414, 229–244.

Chellemi, D.O., Rosskopf, E.N., 2004. Yield potential and soil quality under alternative crop production practices for fresh market pepper. Renewable Agric. Food Syst. 19, 168–175.

Chellemi, D.O., Sonoda, R.M., 1983. Outbreak of *Phytophthora capsici* on vegetable crops in southeast Florida. Proc. Fla. State Hortic. Soc. 96, 69–71.

Chellemi, D.O., Olson, S.M., Mitchell, D.J., Secker, I., McSorley, R., 1997a. Adaptation of soil solarization to the integrated management of soilborne pests of tomato under humid conditions. Phytopathology 87, 250–258.

Chellemi, D.O., Hochmuth, R.C., Winsberg, T., Guetler, W., Shuler, K.D., Datnoff, L.E., Kaplan, D.T., McSorley, R., Dunn, R.A., Olson, S.M., 1997b. Application of soil solarization to fall production of cucurbits and pepper. Proc. Fl. State Hortic. Soc. 110, 333–336.

Chellemi, D.O., McSorley, R., Rich, J.R., Olson, S.M., 1997c. Field validation of soil solarization for fall production of tomato. Proc. Fl. State Hortic. Soc. 110, 330–332.

Chellemi, D.O., Mitchell, D.J., Kannwischer-Mitchell, M.E., Rayside, P.A., Rosskopf, E.N., 2000. *Pythium* spp. associated with bell pepper production in Florida. Plant Dis. 84, 1271–1274.

Cook, R.J., Haglund, W.A., 1991. Wheat yield depression associated with conservation tillage caused by root pathogens in the soil not phytotoxins from the straw. Soil Biol. Biochem. 23, 1125–1132.

De Ceuster, T.J.J., Hoitink, A.J., 1999. Prospects for composts and biocontrol agents as substitutes for methyl bromide in biological control of plant diseases. Compost Sci. Utilizat. 7, 6–15.

Florida Agricultural Statistical Service, 2005. Florida agriculture facts. Available at http://www.nass.usda.gov/fl/homepage.htm (verified 02/28/2005).

Food & Resources Economics Department, 2005. Institute of Food & Agriculture. University of Florida, Florida Commodity Budges. Available at http://www.fred.ifas.ufl.edu/extprograms/fre/commodity (verified 2/28/2005).

Gamliel, A., Stapleton, J.J., 1997. Improvement of soil solarization with volatile compounds generated from organic amendments. Phytoparasitica 25 (Suppl.), 31S–38S.

Hoitink, H.A.J., Boehm, M.J., 1999. Control within the context of soil microbial communities: a substrate-dependent phenomenon. Ann. Rev. Phytopathol. 37, 427–446.

Jenkins, W.R., 1964. A rapid centrifugal-flotation technique for separating nematodes from soil. Plant Dis. Rep. 48, 692.

Kannwischer, M.E., Mitchell, D.J., 1978. The influence of a fungicide on the epidemiology of black shank of tobacco. Phytopathology 68, 1760–1765.

Kim, K.D., Nemec, S., Musson, G., 1997. Effects of composts and soil amendments on soil microflora and Phytophthora root and crown rot of bell pepper. Crop Prot. 16, 165–172.

Malajczuk, N., 1983. Microbial antagonism to *Phytophthora*. In: Erwin, D.C., Bartnicki-Garcia, S., Tsao, P.H. (Eds.), Phytophthora—Its Biology, Taxonomy, Ecology, and Pathology. American Phytopathological Society, St. Paul, MN, pp. 97–218.

Marull, J., Pinochet, J., Rodriguez-Kabana, R., 1997. Agricultural and municipal compost residues for control of root-knot nematodes in tomato and pepper. Compost Sci. Utilizat. 5, 6–15.

Maynard, D.N., Olson, S.M., 2002. Vegetable Production Guide for Florida. University of Florida, IFAS Publ. HS710, Gainesville, FL.

McSorley, R., Gallaher, R.N., 1995a. Cultural practices improve crop tolerance to nematodes. Nematropica 25, 53–60.

McSorley, R., Gallaher, R.N., 1995b. Effect of yard waste compost on plant parasitic nematode densities in vegetable crops. J. Nematol. 27 (Suppl.), 545–549.

McSorley, R., Dickson, D.W., De Brito, J.A., Hochmuth, R.C., 1994. Tropical rotation crops influence nematode densities and vegetable yields. J. Nematol. 26, 308–314.

McSorley, R., Ozores-Hampton, M., Stansly, P.A., Conner, J.M., 1999. Nematode management, soil fertility and yield in organic vegetable production. Nematropica 29, 205–213.

Nesbit, H.J., Malajczuk, N., Glenn, A.R., 1979. Effect of organic matter on the survival of *Phytophthora cinnamomi* Rands in soil. Soil Biol. Biochem. 11, 133–136.

Ristaino, J.B., 2003. Phytophthora blight. In: Pernezny, K., Roberts, P.D., Murphy, J.F., Goldberg, N.P. (Eds.), Compendium of Pepper Diseases. APS Press, St. Paul, MN, pp. 17–19.

Ristaino, J.B., Johnnston, S.A., 1999. Ecologically based approaches to management of Phytophthora blight on bell pepper. Plant Dis. 83, 1080–1089.

Ristaino, J.B., Parra, G., Campbell, C.L., 1997. Suppression of Phytophthora blight in bell pepper by a no-till wheat cover crop. Phytopathology 87, 242–249.

Roberts, P.D., 2003. Damping-off and root rot. In: Pernezny, K., Roberts, P.D., Murphy, J.F., Goldberg, N.P. (Eds.), Compendium of Pepper Diseases. APS Press, St. Paul, MN, pp. 12–13.

Rosskopf, E.N., Chellemi, D.O., Burelle, N.K., Church, G., 2005. Methyl bromide: a Florida perspective. http://www.apsnet.org/online/feature/methylbromide, Verified 02/14/2006.

Rotar, P.P., Joy, R.J., 1983. Tropic Sunn Hemp *Crotolaria juncea* L. College of Tropical Agriculture and Human Resources, Research and Extension Series 036. University of Hawaii, Honolulu 7pp.

Taylor, A.L., Sasser, J.N., 1978. Biology, identification and control of root-knot nematodes (*Meloidogyne* species). North Carolina State University, Raleigh NC.

United States Environmental Protection Agency (USEPA), 2005. Ozone depletion rules & regulations fact sheet. Available at http://www.epa.gov/Ozone/mbr/CueFRfactsheet.html (verified 02/28/2005).

Wang, K.H., McSorley, R., Gallaher, R.N., 2004. Effect of winter cover crops on nematode population levels in North Florida. J. Nematol. 36, 517–523.

Waterhouse, G.M., 1967. Key to Pythium Pringsheim. Mycological Paper 109, Commonw. Mycol. Inst. Kew, England.

Weed Science Society of America, 2005. International Survey of Herbicide Resistant Weeds. Available at website http://www.weedscience.org/in.asp (verified 28 February, 2005).

Workneh, F., van Bruggen, A.F.C., 1994. Suppression of corky root of tomatoes in soils from organic farms associated with soil microbial activity and nitrogen status of soil and tomato tissue. Phytopathology 84, 688–694.