EFFECT OF CROPPING SYSTEM COMPLEXITY ON PLANT-PARASITIC NEMATODES ASSOCIATED WITH ORGANICALLY GROWN VEGETABLES IN FLORIDA

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ABSTRACT

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Two field experiments were initiated in summer 2006 in north-central Florida to compare the effects of integrating cover crops, living mulches, and intercropping on plant-parasitic nematode populations, as well as the effect of fall and spring vegetables on the multiplication rate of root-knot nematodes. Treatments consisted of seven organic cropping systems that included a summer cover crop followed by fall and spring vegetables. The summer cover crop included: pearl millet (*Pennisetum glaucum*), sorghum sudangrass (*Sorghum bicolor* × *S. bicolor* var. *sudanense*), sunn hemp (*Crotalaria juncea*), velvetbean (*Mucuna pruriens* var. *pruriens*), weedy fallow, mixture of pearl millet-sunn hemp, and mixture of sorghum sudangrass-velvet bean. One experiment utilized fall yellow squash (*Cucurbita pepo*) and spring bell pepper (*Capsicum annuum*) as vegetable crops, and fall broccoli (*Brassica oleracea*) and spring sweet corn (*Zea mays*) were used in the other experiment. Nematode populations were monitored at the end of the cover crop and vegetable seasons. Summer cover crops of sorghum-sudangrass or pearl millet increased root-knot nematode (*Meloidogyne incognita*) population levels in some instances while sunn hemp suppressed it in the broccoli-sweet corn experiment. The multiplication rate of root-knot nematodes was lowest when broccoli was planted in the cropping system. Systems with sorghum-sudangrass (alone or in mixture) increased population densities of ring (*Mesocriconema* spp.) and lesion (*Pratylenchus* spp.) nematodes, and occasionally increased stubby-root nematodes (*Paratrichodorus* spp.). Cover crops that increased nematode numbers when planted alone usually gave the same result when planted in mixtures with another cover crop. Other cropping systems failed to suppress plant-parasitic nematodes but maintained low densities similar to weedy fallow.

Key words: Broccoli, bell pepper, cover crops, crop rotation, *Helicotylenchus,* intercropping, living mulches, *Meloidogyne*, *Mesocriconema*, *Paratrichodorus*, *Pratylenchus*, sweet corn, yellow squash.

RESUMEN

Bhan, M., R. McSorley, and C. A. Chase. 2010. Efecto de la complejidad del sistema de cultivo sobre los nematodos fitoparásitos asociados con hortalizas cultivadas orgánicamente en Florida. Nematropica 40:53-70.

Se iniciaron dos experimentos de campo en el verano del 2006 en Florida para comparar los efectos de cultivos de cobertura e intercultivos sobre las poblaciones de nematodos fitoparásitos, así como para evaluar los efectos de hortalizas de otoño y primavera sobre la tasa de multiplicación de nematodos agalladores. Los tratamientos fueron siete sistemas de cultivos orgánicos que incluían un cultivo de cobertura en el verano seguido de hortalizas de otoño y de primavera. Los cultivos de cobertura de verano fueron *Pennisetum glaucum*, *Sorghum bicolor* × *S. bicolor* var. *sudanense*, *Crotalaria juncea*, *Mucuna pruriens* var. *pruriens*, barbecho, y mezclas de las especies anteriores. El primer experimento usó calabaza amarilla de otoño (*Cucurbita pepo*) y pimentón de primavera (*Capsicum annuum*) como hortalizas. El segundo experimento usó brócoli de otoño (*Brassica oleracea*) y maíz dulce de primavera (*Zea mays*). Se monitorearon las poblaciones de nematodos al final del cultivo de cobertura de verano y al momento de cosecha de las hortalizas. Los cultivos de cobertura con sorgo y penisetum aumentaron los niveles de población de *Meloidogyne incognita,* mientras la crotalaria los redujo en el experimento con brócoli y maíz dulce. La tasa de multiplicación de nematodos agalladores más baja se observó cuando se incluyó brócoli en el sistema de cultivos. Los sistemas con sorgo (solo o en mezclas) aumentaron las poblaciones de *Mesocriconema* spp. y de *Pratylenchus* spp., y en algunos casos las de *Paratrichodorus* spp. Con los cultivos de cobertura que aumentaron las densidades de población de nematodos se obtuvieron los mismos resultados sembrados solos y en mezclas. Los demás sistemas evaluados no redujeron las densidades de nematodos fitparásitos, pero mantuvieron densidades similares a las del barbecho.

Palabras clave: Brócoli, calabaza amarilla, cultivos de cobertura, *Helicotylenchus,* intercultivos, maíz dulce, *Meloidogyne, Mesocriconema, Paratrichodorus,* pimentón, *Pratylenchus,* rotación de cultivos.

INTRODUCTION

The increasing popularity of organic foods in the US is reflected in sales returns, which have jumped from $3.5 billion in 1997 to nearly $10.4 billion in 2003 with an annual growth rate of about 20% (Nutrition Business Journal, 2004) or about 1.8% of total US retail food sales (ERS/USDA, 2009). Organic farming employs both traditional methods and modern farming techniques without the use of synthetic pesticides and fertilizers (Hallmann *et al.,* 2007). Vegetable production in the absence of synthetic pesticides and soil fumigants may result in crops that are more vulnerable to weeds, insect pests, and plant-parasitic nematodes. The incidence of pest problems might be greater with high temperature and rainfall, particularly in tropical and sub-tropical regions (Oerke, 2006) like Florida. Root-knot (*Meloidogyne* spp.) and reniform (*Rotylenchulus* spp.) nematodes are probably the most important nematode pests of vegetable crops in tropical and warm temperate areas (Sasser and Freckman, 1986). Annual plant-parasitic nematode-induced yield losses in major crops worldwide are estimated to be 12.3% (Sasser and Freckman, 1986). In practice, nematode infestations may be overlooked or misidentified as other pest symptoms, and as a result they may not be properly managed, allowing increases in population levels and damage to crops (Hallmann *et al.,* 2007).

Several different types of cultural practices can be used for nematode management including use of resistant cultivars, and elements of multiple cropping systems such as cover crops, crop rotation, and nematode-antagonistic crops (McSorley, 1998). Crop sequences in a cropping system should be designed to minimize the damage caused by plant-parasitic nematodes by including nematode resistant plants as rotational crops (Noe, 1988; Noe *et al.,* 1991; McSorley and Gallaher, 1991a). Crop rotation is ideal for managing plant-parasitic nematode populations by planting susceptible and non-susceptible crops in an alternate sequence (Trivedi and Barker, 1986; Noe 1988); however, use of a rotational crop depends on the economics and adaptability for a specific region (McSorley, 1998). In organic farming, crop rotations typically have short fallow periods to minimize nutrient leaching, which may affect plant-parasitic nematodes in the soil (Hallmann *et al.,* 2007). Sometimes, crop rotation can become complex when a crop resistant to one nematode species acts as a host for another nematode species (McSorley *et al.,* 1994b).

Incorporating cover crops for nematode management may be an important approach for developing sustainable agricultural systems (Wang *et al.,* 2004; McSorley and Porazinska, 2001). Several different grassy and legume cover crops have been used to maintain low numbers of plant-parasitic nematodes. Sunn hemp (*Crotalaria juncea* L.) cover crop planted in fall maintained lower population densities of both *M. incognita* (Kofoid & White) Chitwood and *Helicotylenchus dihystera* (Cobb) Sher (Wang *et al.,* 2004). Velvetbean (*Mucuna pruriens* DC also known as *M. deeringiana* (Bort.) Merrill) suppressed population densities of both *M. incognita* and *R. reniformis* Linford & Oliveira prior to the cultivation of susceptible short-term vegetable crops (Quénéhervé *et al.,* 1998). Sorghum-sudangrass (*Sorghum bicolor* × *S. sudanense* [Stapf] Hitchc.) was effective in maintaining low population density of *Meloidogyne* spp. but increased the population levels of *Paratrichodorus minor* (Colbran) Siddiqi (McSorley *et al.,* 1994b) and *Mesocriconema* spp. (Crow *et al.,* 2001). Forage pearl millet (*Pennisetum glaucum* L. var. CFPM 101) (Ball-Coelho *et al.,* 2003) and grain pearl millet (var. CGPMH-1) have potential for managing lesion nematodes (*Pratylenchus* spp.) in the potato (*Solanum tuberosum* L.) production system in Quebec (Belair *et al.,* 2006). Another useful grass cover crop is rye (*Secale cereale* L., cv. Wrens Abruzzi), which resulted in decline of *M. incognita* when grown as a winter cover crop (Opperman *et al.,* 1988).

Nematode management is particularly critical in the southeastern United States, where root-knot nematodes can cause serious damage to many vegetable crops. For example, when *M. incognita* was managed by soil fumigation, yield of squash (*Cucurbita pepo* L.) was 180% greater and yield of sweet corn (*Zea mays* L.) was 220% greater in fumigated than in nonfumigated plots (Johnson, 1985). Among the other nematodes affecting corn, sting nematodes (*Belonolaimus* spp.) can cause damage even if present in numbers just above detection (Windham, 1998). Damage thresholds of lesion (*Pratylenchus* spp.) and stubby-root nematodes (*Paratrichodorus* spp.), which are commonly associated with corn, are typically >20/100 cm^3 soil (Windham, 1998). In a recent study on bell pepper, (*Capsicum annuum* L.), *M. incognita* population levels increased and caused crop injury (Saha *et al.,* 2007). However, *Paratrichodorus* spp. and *Pratylenchus* spp. declined on the pepper crop. Ring nematode (*Mesocriconema* spp.) levels following pepper remained similar to initial levels or declined slightly. Although root-knot nematodes can reproduce on cruciferous crops, such as broccoli, (*Brassica oleracea* L.), they may not build up to very high numbers, particularly if the crop is grown during the winter months (McSorley and Frederick, 1995).

The current study focused on understanding population dynamics of plant-parasitic nematodes as a result of integrating cultural practices like crop rotation, summer cover crops, living mulch, and intercrops in multiple cropping systems for organic vegetable production. This information will be useful for managing nematode populations over time, recognizing suppressive effects of poor or non-hosts of plant-parasitic nematodes, and ultimately in designing cropping systems with minimal nematode impact. Therefore, the objective of the current research is to examine the effect of cropping systems of various levels of complexity on the densities of selected plant-parasitic nematodes in organic vegetable production systems. Specifically, the impact of summer cover crops and vegetable cropping sequences on plant-parasitic nematodes are examined. In addition, the buildup of root-knot nematode population levels on different fall and spring vegetables was also examined because they are the key nematode pest of most vegetable crops. Two hypotheses are examined: 1) components of cropping systems may affect population densities of plant-parasitic nematodes in summer cover crops and subsequent fall- and spring-planted organic vegetables, and 2) planting different vegetables in the cropping system may affect population multiplication rates of root-knot nematodes, therefore, two cropping systems with different vegetables crops were examined.

MATERIALS AND METHODS

Two experiments were established concurrently in summer 2006 on certified organic land at the University of Florida Plant Science Research and Education Unit, Marion County, Florida. The cropping systems for each experiment consisted of a summer cover crop, fall and spring vegetables in 2006-07, with the entire sequence repeated in 2007-08. Although the focus of this paper is on plant-parasitic nematodes, the study was designed with the ultimate goal of utilizing a holistic approach to manage pest insects, weeds and nematodes in organic cropping systems. The field site was used for the production of bahiagrass (*Paspalum notatum* Flüggé) prior to establishing the experiments. The soil is a Candler sand (Hyperthermic, uncoated Lamellic Quartzipsamment) with a soil pH of 7.1.

Prior to the experiments, the field was dominated by ring (54/100 cm^3 soil, 93% of all plant-parasitic nematodes) followed by lesion (2/100 cm^3), spiral (*Helicotylenchus* spp., 1/100cm^3), and stubby-root (1/100 cm^3) nematodes. Because of the low incidence of root-knot nematodes, the field was planted in May 2006 to a root-knot nematode susceptible crop, southern pea (*Vigna unguiculata* Walp) cv. White Acre and then inoculated with *M. incognita* to increase the nematode population. The southern pea cover crop was mowed on 13 July 2006 with a New Holland 918H flail mower (Purdy Tractor and Equipment, Inc. Hillsdale, MI) and was followed by application of finished mushroom compost (Quincy Farms, Quincy, FL) at 2500 kg/ha using a check drop spreader (Newton Crouch Inc., Griffin, GA). The field was disked, and incorporating the compost to a depth of about 20 cm. Both experiments were started on 27 July 2006 with a summer fallow consisting of either summer cover crops or a weedy fallow. The experimental design was a randomized complete block with seven treatments (Table 1) and four replications. Plots measured 12 m × 12 m and were separated by 12-m alleys. Cultivars, seed sources, and seeding rates of cover crops are summarized in Table 2. The cultivars of both grass cover crops were forage types that produce a large amount of biomass. Pearl millet and sorghum-sudangrass were planted with a Sukup 2100 planter (Sukup Manufacturing Company, Sheffield, IA) at 5-cm soil depth and 17-cm intra-row spacing. Sunn hemp and velvetbean seeds were inoculated with cowpea type *Rhizobium* sp., (Nitragin Inc., Brookfield, WI) before broadcasting onto plots. Overhead irrigation was used during the first three days after planting to promote germination and establishment of the cover crops.

Above-ground biomass of summer cover crops was flail mowed on 2 October 2006 and disked to incorporate into the soil. This was followed by the application of lime (Aglime Sales Inc., Babson Park, FL) to the entire field at 2500 kg/ha. Fall vegetables were planted on four beds (1.8-m bed-center size) per plot (12-m length × 7.2-m width plot size). Before planting fall vegetables, fertilizer (10-2-8 N-P_2O_5-K_2O, NatureSafe, Griffin Industries, Cold Spring, KY) was applied at the rates of 1685

Table 1. Cropping systems used as treatments[z].

Summer	Fall	Spring
Experiment I (Squash-bell pepper)		
Weedy fallow	Squash	Bell pepper
Pearl millet	Squash	Bell pepper
Sorghum sudangrass	Squash	Bell pepper
Sunn hemp	Squash	Bell pepper
Velvetbean	Squash	Bell pepper
Pearl millet-sunn hemp	Squash + Rye-hairy vetch	Bell pepper + bush beans
Sorghum sudangrass-velvetbean	Squash + Rye-hairy vetch	Bell pepper + bush beans
Experiment II (Broccoli-sweet corn)		
Weedy fallow	Broccoli	Sweet corn
Pearl millet	Broccoli	Sweet corn
Sorghum sudangrass	Broccoli	Sweet corn
Sunn hemp	Broccoli	Sweet corn
Velvetbean	Broccoli	Sweet corn
Pearl millet-sunn hemp	Broccoli + crimson clover	Sweet corn + bush beans
Sorghum sudangrass-velvetbean	Broccoli + crimson clover	Sweet corn + bush beans

[z]For convenience, cropping systems are referred to in the text by the name of the summer cover crop.

kg/ha in squash and 1976 kg/ha in broccoli based on the conventional fertilizer recommendations for these crops (Olson and Simonne, 2006). The fertilizer was applied as a 30-cm band over the center of the bed and incorporated before planting the vegetables.

Experiment I (Squash - bell pepper)

Squash

Yellow squash (cv. Cougar F1 untreated; Harris Seeds, Rochester, NY) was direct seeded on 19 October 2006 as single row per bed with an in-row plant distance of 45 cm (12,037 seeds/ha) in one experiment. Squash was irrigated daily through a drip irrigation system. To maintain the intercropped nature of the treatments with mixed cover crops, during fall the cash crop was intercropped with a living mulch and in spring with a second cash crop. The living mulch planted between squash beds was a combination of rye (*Secale cereale* cv. Wrens Abruzzi; Alachua County Feed and Seed Store, Gainesville, FL) and hairy vetch (*Vicia villosa* Roth., cultivar unknown; Adams Briscoe Seed Company, Jackson, GA). The seeding rates were 48 kg/ha for rye and 22 kg/ha for hairy vetch. Before planting, hairy vetch was inoculated with *Rhizobium leguminosarum* bv. *viceae* (Nitragin C, Nitragin Inc, Brookfield, WI). Both types of living mulch seeds were mixed and broadcasted on 9 November 2006 by hand onto shallowly tilled soil followed by covering the seeds with the help of roller. Row covers were placed on squash plots on 8 December 2006 to protect the crop from frost. Squash was harvested from 14 December 2006 to 9 January 2007 with six harvests.

Table 2. Cover crops, seed sources, and seeding rates used.

Treatments	Botanical name	Cultivar	Source	Seed-rate (kg/ha)
Weedy fallow (WF)	—	—	—	—
Pearl millet [PM]	*Pennisetum glaucum*	Tifleaf 3	Production Plus, Plainview, TX	4.5
Sorghum sudangrass [SS]	*Sorghum bicolor* × *S. bicolor var sudanense*	Brown Midrib	Production Plus, Plainview, TX	7.2
Sunn hemp [SH]	*Crotalaria juncea*	Unknown	Kaufman seeds, Ashdown, AR	7.2
Velvetbean [VB]	*Mucuna pruriens var pruriens*	Georgia Bush	Georgia Seed Development Commission, Athens, GA	18.0
Pearl millet—sunn hemp [PMSH]	—	—	—	3.0 PM + 3.6 SH
Sorghum sudangrass—velvetbean [SSVB]	—	—	—	4.8 SS + 12.0 VB

Methods used for the squash crop in 2007-08 were similar to those of previous year, with minor exceptions. It was direct-seeded on 10 October 2007. Row covers were used from 16-19 November 2007. Squash was harvested from 21 November to 14 December 2007 with 8 harvests.

Bell pepper

Squash plots were rotated with green bell pepper (cv. Red Knight F1 untreated; Johnny's Selected Seeds, Winslow, ME). A compliant blended fertilizer (NatureSafe, 10-2-8 N-P_2O_5-K_2O, NatureSafe, Griffin Industries, Cold Spring, KY) was applied at the rate of 2232 kg/ha based on University of Florida's synthetic fertilizer recommendations for these crops (Olson and Simonne, 2006). Half of the fertilizer was broadcast and incorporated with a roto-tiller prior to planting on 7 March, 2007. The remaining fertilizer was banded and lightly incorporated on 10 April, 2007. Forty-five-day-old bell pepper seedlings were transplanted on 15 March 2007 in double rows per bed. There were four beds per plot (12 m × 7.2 m plot area) with distances of 45 cm between plants in rows and between rows (24,074 plants/ha). Green bush beans (*Phaseolus vulgaris* cv. Bronco untreated, Seedway, Elizabethtown, PA) were intercropped with pepper in mixed cover crop plots. On 16 March 2007, bush bean was direct-seeded between bell pepper beds using a manual push planter at a distance of 15 cm between seeds. Both bell pepper and bush beans were irrigated daily using drip irrigation. Bell pepper was harvested from 21 May to 20 June 2007 with four harvests. Bush bean was harvested on 16 May and 30 May 2007. In spring 2008, bell pepper was transplanted on 13 March and bush bean on 14 March, while bell pepper was harvested from 13 May to 9 June with four harvests and bush bean with a single harvest on 13 May.

Experiment II (Broccoli - sweet corn)

Broccoli

Thirty-day-old broccoli (cv. Marathon F1 untreated; Harris Seeds, Rochester, NY)) seedlings were transplanted on 31 October 2006 in double rows (30 cm distance between rows) per bed at a distance of 45 cm between plants in rows, and a total of 8 rows per plot (24,074 plants/ha). Broccoli was drip-irrigated daily. Crimson clover (*Trifolium incarnatum* L. cv. Dixie; Adams Briscoe Seed Company, Jackson, GA) was planted as living mulch between beds in mixed cover crop plots at a seeding rate of 28 kg/ha. On 9 November 2006, crimson clover seeds were inoculated with *R. leguminosarum* biovar *trifolii* (Nitragin R/WR, Nitragin Inc, Brookfield, WI), broadcasted by hand onto shallowly tilled soil, and then rolled to embed the seeds in the soil. Broccoli was harvested from 4 January to 16 January 2007 with three harvests. On 5 March 2007, the field was flail mowed and disked to 20-cm soil depth to prepare a seedbed for planting spring vegetables.

Similar methods were used for management of the broccoli crop in the second year. In 2007-08, thirty-five-day-old broccoli seedlings were transplanted on 16 October 2007 and crimson clover was planted on 26 October 2007. Broccoli was harvested three times between 20 December 2007 and 2 January 2008.

Sweet corn

Broccoli plots were rotated with sweet corn (cv. Montauk F1 untreated; Johnny's Selected Seeds, Winslow, ME). A compliant blended fertilizer 10-2-8 N-P_2O_5-K_2O (Nature-Safe, Cold Springs, KY) was applied at the same rate and time as in bell pepper. Sweet corn was direct-seeded on 12 March 2007 with a Monosem planter (Monosem Inc., Edwardsville, KS) at 76 cm between rows and plant distances of 18 cm within rows, with a plot size of 144 m^2 (74,444 plants/ha). Bush beans were also intercropped with sweet corn in mixed cover crop plots. Bush bean was direct-seeded on 12 March 2007 with a Monosem planter in four strips (4 rows / strip) arranged alternately with strips of sweet corn. Bush bean inter-row and inter-plant distances of 76 cm and 13 cm were used. Sweet corn was harvested on 31 May and 12 June 2007 while bush bean was harvested on 16 May and 30 May 2007. During spring 2008, sweet corn and bush beans were direct-seeded on 11 March.

Potassium fertilizer, 0-0-6 N-P_2O_5 -K_2O (Biolink, Westbridge Agricultural Products, CA) was applied as a foliar application to the beans in spring 2008 using a CO_2 sprayer at a nozzle rate of 0.76 L/min and 189.3 L/ha water to correct a deficiency that was detected by tissue sample analysis. Sodium nitrate (Probooster, 10-0-0 N-P_2O_5-K_2O, North Country Organics, Bradford, VT) was also applied in sweet corn plots at 868 kg/ha on 7 May 2008 in response to nitrogen deficiency symptoms. Sweet corn was harvested on 29 May and 4 June and bush bean on 13 May 2008.

Both experiments were rotated in the second year using methods described for the previous seasons. The field was mowed on 6 July 2007 followed by elemental sulfur (Tiger 90 with 90% sulfur, Tiger-Sul Products, Atmore, AL) application at 250 kg/ha using a drop spreader to lower soil pH. To avoid having the same cover crop in the same plot in both years (growers would typically not plant the same crop in a two-year rotation), the pearl millet cover crop was rotated with sorghum sudangrass while sunn hemp was rotated with velvetbean and vice versa. Similarly, the sorghum sudangrass-velvetbean mixture was rotated with the pearl millet-sunn hemp mixture and vice versa. In the second year, the cover crops were planted on 31 July 2007; sorghum sudangrass and pearl millet were direct-seeded with a John Deere 450 planter while sunn hemp was planted with a Sukup 2100 planter at an 18-cm row distance. Potassium (257 kg/ha) was applied to each cropping system prior to planting cover crops and again after mowing the cover crops as a broadcast application of sulpomag (0-0-21 N-P_2O_5-K_2O, Diamond R Fertilizer, Winter Garden, FL). The cover crops were terminated on 3 October 2007.

Data collection and analysis

Soil temperatures were monitored during each cropping cycle at a depth of 20 cm using Watchdog dataloggers, Model 100 8k (Spectrum Technologies, Inc. East Plainfield, IL) at 30-minute time intervals. Soil was sampled from each plot after each cover crop and vegetable to estimate population densities of plant-parasitic nematodes. Six soil cores (2.54-cm diameter, 20-cm depth) were collected randomly from each plot near the plant roots and composited to form a single sample. Nematodes were extracted from a subsample of 100 cm^3 soil by a sieving and centrifugal flotation method (Jenkins, 1964). Nematode counts were log-transformed ($log_{10}[x + 1]$) to normalize the data and to accommodate zero counts. Analysis of variance was performed on transformed values using the GLM procedure in Statistical Analysis System (SAS, 2008). Means were separated by the least significant difference (LSD) test at 5% level of significance. The data are reported as untransformed means.

Non-zero observations of initial (Pi) and final (Pf) populations of root-knot nematode were used to calculate multiplication rate (Pf/Pi) for different vegetable crops in the second year. The final nematode populations from the summer cover crops were used as the initial nematode populations for broccoli and yellow squash, since the vegetables were planted within two weeks after the termination of the summer cover crops. Multiplication rates were calculated for each vegetable crop, and additional Pf/Pi values were also calculated for each double-crop vegetable system. In calculating Pf/Pi for a double vegetable crop, Pi for the double crop was the Pi for the first crop in the sequence (e.g., yellow squash), and Pf for the double crop was Pf from the second crop (e.g., bell pepper). To determine whether nematode multiplication in a system was significant, values of Pi and Pf were compared using a t-test at 5% level of significance.

RESULTS

Soil temperatures under cover crops ranged from <23° C in September 2006 to >37°C in August 2007. Soil temperatures under vegetable crops ranged from a low of 9.1°C in winter to a high of 38.7°C in bell pepper in June (data not shown). In summer 2006, weedy fallow plots were dominated by Florida pusley (*Richardia scabra* L., 12% based on weed numbers), hairy indigo (*Indigofera hirsuta* L., 16%), southern crabgrass (*Digitaria ciliaris* (Retz.) Korler, 11%), carpetweed (*Mollugo verticillata* L., 9%), bahiagrass (4%), and various sedge species (18%). After one year in summer 2007, these weed species remained dominant, except bahiagrass in weedy fallow plots. Plant-parasitic nematodes recovered in these cropping systems included root-knot, ring, lesion, spiral, and stubby-root nematodes.

Root-knot nematodes

Root-knot nematode populations remained low (< 10 per 100 cm^3) and did not differ significantly among cropping systems by the end of the summer cover crops and fall crops during 2006-07 in both experiments (Table 3). Their populations

Table 3. Root-knot nematode population density in both experiments and years at Citra, FL[z].

	Nematodes /100 cm^3 soil											
	Experiment I (Squash-bell pepper)						Experiment II (Broccoli-sweet corn)					
	Cover crop	Squash	Bell Pepper	Cover crop	Squash	Pepper	Cover crop	Broccoli	Sweet corn	Cover crop	Broccoli	Sweet corn
Treatments	29 Sep 2006	18 Jan 2007	22 Jun 2007	03 Oct 2007	18 Dec 2007	04 Jun 2008	29 Sep 2006	18 Jan 2007	22 Jun 2007	03 Oct 2007	09 Jan 2008	04 Jun 2008
Weedy fallow	0 a	1 a	7 ab	4 a	19 b	46 ab	0 a	0 a	1 ab	9 ab	9 ab	65 ab
Pearl millet	0 a	2 a	14 ab	0 a	160 a	57 ab	1 a	0 a	7 ab	13 ab	1 b	83 ab
Sorghum sudangrass	6 a	3 a	53 a	5 a	53 ab	142 a	9 a	0 a	5 ab	4 ab	3 ab	88 a
Sunn hemp	0 a	0 a	0 b	1 a	21 b	37 b	3 a	0 a	13 a	0 b	0 b	4 d
Velvetbean	0 a	0 a	0 b	8 a	26 ab	110 a	2 a	0 a	3 ab	2 ab	7 ab	63 ab
Pearl millet-sunn hemp	2 a	3 a	2 ab	1 a	91 a	85 ab	1 a	0 a	0 b	1 b	1 b	10 cd
Sorghum sudangrass- velvetbean	3 a	0 a	0 b	2 a	88 ab	12 b	8 a	0 a	3 ab	37 a	13 a	23 bc

[z]Data are means of four replications. Data are final population levels on each crop shown, collected on the date indicated. On each sampling date, means in columns followed by the same letters were not different according to least significant difference (LSD) at $P \leq 0.05$ based on the $\log_{10}$ transformed value. Untransformed means are presented in columns.

were highest in sorghum sudangrass and lowest in sunn hemp, velvetbean, and sorghum sudangrass-velvetbean systems by the end of the spring pepper season on 22 June 2007 in the squash-pepper experiment. In the same season, root-knot nematode numbers were significantly higher in sunn hemp than pearl millet-sunn hemp systems in the broccoli-sweet corn experiment. However, no cropping systems were significantly different from the weedy fallow in either experiment. After cover crop termination on 3 October 2007, root-knot nematode populations remained low and did not differ significantly among systems in the squash-pepper experiment, whereas the sorghum sudangrass-velvetbean system had a significantly higher population than systems containing pearl millet or sunn hemp in the broccoli-sweet corn experiment. By the end of the fall squash season on 18 December 2007, root-knot populations were highest in pearl millet and pearl millet-sunn hemp systems and lowest in weedy fallow and sunn hemp systems. Sunn hemp alone had lower numbers of root-knot nematodes but failed to reduce root-knot nematode populations if planted in a mixture with pearl millet as a summer cover crop. In the same experiment at the end of the bell pepper crop, the use of sorghum sudangrass or velvetbean alone resulted in significantly higher root-knot nematode populations than systems with these two crops planted together. However, in all three of these systems, numbers were not significantly different than those in the weedy fallow system. In the broccoli-sweet corn experiment, the root-knot population reached its highest level by the end of the spring sweet corn crop in the sorghum sudangrass system and lowest in the sunn hemp and pearl millet-sunn hemp systems.

Population multiplication rates of root-knot nematodes are shown in Table 4, which includes final nematode populations from one and two crop sequences in the second year of both experiments. Significant ($P \leq 0.10$) population increases were observed in all crops and sequences except

Table 4. Ratio of final (Pf) to initial (Pi) root-knot nematode population levels in soil at different cropping seasons in 2007-08.

Initial population (Pi)	Final Population (Pf)	Number of observations[v]	Pf/Pi[w]	Pr > |t|[x]
Experiment I (Squash-bell pepper for the year 2007-08)				
Squash[y]	Squash	11	46.1	0.0707
Squash[z]	Bell pepper	11	43.0	0.0375
Bell pepper[y]	Bell pepper	20	4.2	0.7829
Experiment II (Broccoli-sweet corn for the year 2007-08)				
Broccoli[y]	Broccoli	14	2.0	0.2362
Broccoli[z]	Sweet corn	14	13.0	0.0295
Sweet corn[y]	Sweet corn	14	11.2	0.0025

[v]Maximum non-zero observations present in both initial (Pi) and final (Pf) population.
[w]Average multiplication rate of Pf/Pi values based on the number of observations.
[x]Significance level for t-test between Pi and Pf. Significant t-test indicates population change.
[y]Single vegetable crop. Pi for squash and broccoli = Pf from previous cover crop.
[z]Double vegetable crop. For the double-crop system, Pi is from first vegetable crop (squash or broccoli), Pf is from second vegetable crop (bell pepper or sweet corn).

for the single crops of broccoli and bell pepper. The lowest multiplication rate was obtained following a single crop of broccoli.

Ring nematodes

Ring nematode populations were significantly higher in sorghum sudangrass - velvetbean and sorghum sudangrass systems than other cropping systems by the end of the summer cover crop on 29 September 2006 in both experiments (Table 5). Although ring nematode population level was lowest in pearl millet and pearl millet-sunn hemp systems at that time, it was not significantly different from the population in weedy fallow. Similar high levels of ring nematodes on systems that contained sorghum sudangrass persisted to the end of fall squash and broccoli seasons on 18 January 2007 in both experiments. Differences became less distinct by the end of the spring vegetable crop in June 2007, although ring nematode population levels remained highest in the sorghum sudangrass system in both experiments. It is interesting that in the broccoli-sweet corn experiment at this time, numbers in the pearl millet-sunn hemp system were lower ($P < 0.05$) than in weedy fallow.

In the second year of both experiments, the sorghum sudangrass system contained significantly higher numbers of ring nematodes than most of the other cropping systems including weedy fallow by the end of the summer cover crop season on 3 October 2007. Numbers in the sorghum sudangrass-velvetbean system were statistically similar to those in the system with sorghum sudangrass alone. Differences among treatments disappeared after the fall vegetable season of the second year in both experiments, and population levels following broccoli were especially low (< 5 ring nematodes per 100 cm^3). A few inconsistent differences among treatments occurred following the spring crops of pepper and sweet corn; however, the ring nematode population level in the weedy fallow was not significantly different from other cropping systems at that time.

Lesion nematodes

The sorghum sudangrass system contained the highest lesion nematode populations on all sampling dates except 22 June 2007 in the squash-bell pepper and 3 October 2007 in the broccoli-sweet corn experiments (Table 6). The sorghum sudangrass-velvetbean system also had high lesion nematodes by the end of cover crop season in both years in both experiments. Lesion nematode population levels were lowest in pearl millet and pearl millet-sunn hemp systems; however, they were not significantly different from numbers in weedy fallow in both experiments. By the end of the spring bell pepper crop, lesion populations were very low (< 1 nematode/ 100cm^3) in all cropping systems in both years. Similar results were observed by the end of the fall broccoli and spring sweet corn seasons in 2008 in the broccoli-sweet corn experiment.

Other nematodes

Spiral nematode population levels were low (< 5 per 100 cm^3) and rarely affected by the treatments. They did not build up in any of the cropping systems as the experiments progressed.

Stubby- root nematode population levels were low (< 4 per 100 cm^3) and showed few differences among cropping systems in the squash-bell pepper experiment and in the first year of the broccoli-sweet corn experiment. However, at summer cover crop termination on 3 October 2007, the sorghum sudangrass-velvetbean system had

Table 5. Ring nematode population density in both experiments and years in Citra, FL[z].

	Nematodes /100 cm ^{3} soil											
	Experiment I (Squash-bell pepper)						Experiment II (Broccoli-sweet corn)					
	Cover crop	Squash	Bell Pepper	Cover crop	Squash	Pepper	Cover crop	Broccoli	Sweet corn	Cover crop	Broccoli	Sweet corn
Treatments	29 Sep 2006	18 Jan 2007	22 Jun 2007	03 Oct 2007	18 Dec 2007	04 Jun 2008	29 Sep 2006	18 Jan 2007	22 Jun 2007	03 Oct 2007	09 Jan 2008	04 Jun 2008
Weedy fallow	15 bc	2 c	3 bc	27 cd	25 a	3 ab	15 b	3 bc	4 bc	14 bc	2 a	7 ab
Pearl millet	9 c	1 c	1 c	16 d	16 a	3 ab	13 b	1 c	3 cd	38 ab	2 a	13 a
Sorghum sudangrass	280 a	50 a	16 a	228 a	19 a	1 b	267 a	37 a	12 a	106 a	4 a	11 a
Sunn hemp	38 b	15 b	5 ab	31 cd	22 a	7 a	28 b	2 bc	2 cd	5 c	2 a	3 ab
Velvetbean	14 bc	2 c	4 ab	47 bc	22 a	4 ab	20 b	5 b	9 ab	17 bc	1 a	6 ab
Pearl millet-sunn hemp	12 c	1 c	1 c	30 cd	11 a	2 b	11 b	1 c	0 d	22 bc	1 a	1 ab
Sorghum sudangrass-velvetbean	176 a	29 a	4 ab	144 ab	17 a	1 b	190 a	46 a	5 bc	40 ab	1 a	0 b

[z]Data are means of four replications. Data are final population levels on each crop shown, collected on the date indicated. On each sampling date, means in columns followed by the same letters were not different according to least significant difference (LSD) at $P \leq 0.05$ based on the $\log_{10}$ transformed value. Untransformed means are presented in columns.

Table 6. Lesion nematode population density in both experiments and years in Citra, FL[z].

	Nematodes /100 cm^3 soil											
	Experiment I (Squash-bell pepper)						Experiment II (Broccoli-sweet corn)					
	Cover crop	Squash	Bell Pepper	Cover crop	Squash	Pepper	Cover crop	Broccoli	Sweet corn	Cover crop	Broccoli	Sweet corn
Treatments	29 Sep 2006	18 Jan 2007	22 Jun 2007	03 Oct 2007	18 Dec 2007	04 Jun 2008	29 Sep 2006	18 Jan 2007	22 Jun 2007	03 Oct 2007	09 Jan 2008	04 Jun 2008
Weedy fallow	5 b	1 b	0 b	3 b	3 bc	0 a	5 c	1 d	3 bc	0 b	0 a	0 b
Pearl millet	1 c	0 b	0 b	2 b	3 bc	0 a	2 c	0 d	2 bc	1 b	1 a	0 b
Sorghum sudangrass	37 a	8 a	0 b	25 a	6 ab	0 a	73 a	10 a	11 a	1 b	0 a	1 a
Sunn hemp	10 b	3 ab	0 b	8 ab	1 c	0 a	18 b	1 d	1 bc	1 b	0 a	0 b
Velvetbean	3 b	4 ab	0 b	4 b	2 c	0 a	13 b	3 c	5 ab	1 b	0 a	0 b
Pearl millet-sunn hemp	6 b	1 b	0 b	5 b	1 c	0 a	3 c	0 d	0 c	1 b	0 a	0 b
Sorghum sudangrass-velvetbean	47 a	6 ab	1 a	13 ab	20 a	0 a	48 a	5 b	1 c	11 a	1 a	0 b

[z]Data are means of four replications. Data are final population levels on each crop shown, collected on the date indicated. On each sampling date, means in columns followed by the same letters were not different according to least significant difference (LSD) at $P \leq 0.05$ based on the $\log_{10}$ transformed value. Untransformed means are presented in columns.

a significantly higher stubby-root nematode population level (8/100 cm^3 soil) than several other cropping systems including weedy fallow (0/100 cm^3 soil).

DISCUSSION

The vegetables planted in both experiments are highly susceptible to root-knot nematodes, except broccoli. Squash and bell pepper were affected by root-knot nematodes in the southeastern United States (Desaeger *et al.*, 2008; Webster *et al.*, 2001) while sweet corn has the ability to increase root-knot, lesion, and ring nematodes (Seaman *et al.*, 2005). Before the beginning of the experiment, root-knot nematodes were not detectable at the site. This may be because of the prior use for the site had been for bahiagrass sod production. Bahiagrass was effective in managing *Meloidogyne arenaria* (Neal) Chitwood in peanut and soybean (Rodríguez-Kábana *et al.*, 1994). The root-knot nematode population was either absent or so low that it was statistically not possible to detect differences among cropping systems in both experiments by the end of the cover crop and fall vegetable seasons during first year. One reason for the low population densities in soil samples collected on 18 January 2007 in both experiments may be due to the fact that nematode growth and development are directly affected by temperature (Noe, 1988). Root-knot nematodes develop quickly and produce large numbers of eggs at 30 to 35°C (Carter, 1982). *Meloidogyne hapla* and *M. incognita* females are reported to reach maturity at a temperature range of 25 to 30°C (Irrizarry *et al.*, 1971). The low soil temperatures recorded during the winter months in the current experiments are well below optimum temperatures for nematode reproduction.

Although somewhat inconsistent, there was some evidence that the presence of sorghum sudangrass in the cropping system resulted in higher numbers of root-knot nematodes in some instances. The same occurred with pearl millet, especially in the squash-pepper experiment in the second season. This is unusual because sorghum sudangrass and pearl millet are considered useful cover crops for suppressing root-knot nematodes (Ball-Coelho *et al.*, 2003; Belair *et al.*, 2006; McSorley *et al.*, 1994b), but may be explained by the fact that the cultivars used in those studies were different from the cultivars used in these experiments. Although sorghum cultivars have been useful for managing root-knot nematodes (Gallaher *et al.*, 1991; McSorley and Gallaher, 1991), the sorghum cultivar 'Chaparral' increased numbers of *M. incognita,* at times reaching the high levels found on field corn (McSorley and Gallaher, 1992). Although cropping system treatments affected root-knot nematode numbers, rarely did the numbers obtained differ from those in the weedy fallow system. The only systems that showed long-term suppression (through both vegetable crops) of root-knot nematodes below levels in weedy fallow were systems that contained sunn hemp, in the broccoli-sweet corn experiment. These results suggest that sunn hemp planted alone as a summer cover crop or even in mixture with pearl millet had the ability to suppress populations of root-knot nematodes in this organic broccoli-sweet corn cropping system. Wang *et al.,* (2004) and McSorley *et al.* (1994a) also suggested that sunn hemp maintains low population densities of *Meloidogyne* spp. Sunn hemp as a cover crop can reduce plant-parasitic nematode populations by acting as a poor host (Rodríguez-Kábana *et al.,* 1994), producing allelochemicals that could be toxic or inhibitory (Wang *et al.*, 2001), providing a niche to antagonists that repel or inhibit nematodes (Kloepper *et al.,* 1991), and encouraging major groups of nematode-antagonistic fungi (Wang *et al.,* 2001).

The relationship between nematode population growth and initial population density provides a good description of resistance or susceptibility of a suitable host (McSorley, 1998). The multiplication rate of root-knot nematode was lowest during the broccoli crop. This implies that broccoli, although a host of the nematode (Pf/Pi = 2.0), may maintain root-knot nematode populations at lower levels than the yellow squash and the spring vegetable crops. Root-knot nematode multiplication on the spring bell pepper crop was also relatively low, but this augmented the high population levels that already had built up on squash. The squash-pepper crop sequence increased root-knot levels nearly four times as much as the broccoli-sweet corn crop sequence, which reflected the advantage of including broccoli in the system.

The sorghum sudangrass system resulted in significantly higher ring nematode populations as compared to weedy fallow during first year in both the experiments. No cropping systems resulted in fewer ring nematodes than the weedy fallow except for the pearl millet-sunn hemp system in one instance (end of spring sweet corn in 2007). However, on the other sampling dates, pearl millet alone and pearl millet-sunn hemp systems were not effective in decreasing the ring nematode populations but maintained existing low densities. These results suggest that sorghum sudangrass has the ability to increase the ring nematode population while other cropping systems failed to suppress it. Crow *et al.* (2001) observed increased population densities of ring and lesion nematodes when sorghum sudangrass was planted as a summer cover crop in a potato cropping system.

Sorghum sudangrass and sorghum sudangrass-velvetbean systems increased the lesion nematode numbers by the end of the summer cover crop in the first year in both experiments. The increased levels of lesion nematodes persisted through the fall vegetable crops in the first year. These results suggest that sorghum sudangrass has the potential to increase lesion populations if planted during summer, and are consistent with previous findings in north Florida (Crow *et al.*, 2001; McSorley *et al.* (1994b). Additional lesion nematodes would be expected to occur in plant roots, but lesion nematodes can be sampled reliably in soil as well (Alby *et al.*, 1983) especially at the end of crop cycles when they tend to migrate out to roots of senescing plants. Although several cropping systems, particularly those with pearl millet, resulted in lower lesion nematode levels than sorghum sudangrass, none were significantly lower than the weedy fallow system at later stages of both experiments. These results suggest that pearl millet alone and in mixture with sunn hemp in the cropping system was not effective in decreasing lesion populations compared to weedy fallow, but instead maintained existing lower densities than sorghum sudangrass. Amankwa *et al.* (2006) indicated that pearl millet as a rotation crop with tobacco suppressed lesion nematode population with equivalent gross returns. Dauphinais *et al.* (2005) reported that pearl millet had a suppressive effect on lesion nematode when rotated with potato. Perhaps low pressure of lesion nematodes in this site would not allow the examination of the effect of pearl millet on lesion nematode. However, lesion nematode populations declined to very low levels (≤ 1 per 100 cm^3) in pepper cash crops in both years. This result is consistent with another recent study in north Florida in which declines of lesion nematodes on pepper were also observed (Saha *et al.*, 2007).

The major reason for planting living mulches and intercrops was to evaluate their rotational effects on weeds, insect pests, and nematodes in these systems. Effects on weeds and insects are discussed elsewhere (Bhan, 2010; Scott, 2008). Increasing the complexity of the system by including intercrops or living mulches had no apparent impact on plant-parasitic nematodes. No differences were observed in nematode population levels in vegetables planted as monoculture or mixed with living mulches or a bean intercrop. Susceptible crops such as sorghum sudangrass led to higher numbers of root-knot nematodes regardless of whether they were planted alone or as part of a mixture.

In summary, increased numbers of root-knot nematodes were observed in some instances in cropping systems that contained sorghum sudangrass or pearl millet as summer cover crops. A summer cover crop of sunn hemp appeared to be suppressive to root-knot nematodes in the broccoli-sweet corn experiment. Sorghum sudangrass also resulted in consistent increases in numbers of ring nematodes and lesion nematodes, and occasional increases in stubby-root nematodes. Cover crops that increased nematode numbers when planted alone tended to perform similarly when planted in a mixture with another cover crop. Rarely did any of the cropping systems result in suppression of plant-parasitic nematodes; instead they maintained low numbers of nematodes similar to weedy fallow. Root-knot nematode population levels increased more slowly on broccoli than on the other vegetables studied.

It is important for organic growers, particularly those establishing new sites, to prevent the build-up of damaging nematodes. The current study utilized a site where the prior crop had been bahiagrass sod, which resulted in low numbers of the several different plant-parasitic nematodes present. Many of the cropping systems examined were successful in maintaining relatively low nematode numbers throughout the two years and six cropping cycles. The exceptions illustrate the nematode population increases that occur when including good hosts of root-knot nematodes in the system.

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