INFLUENCE OF CROP ROTATION AND YEARS IN BAHIAGRASS ON PLANT-PARASITIC NEMATODE DENSITY IN AN ORGANIC VEGETABLE PRODUCTION SYSTEM

P. C. Andersen[1]*, B. V. Brodbeck[1], C. M. Bliss[1], and R. McSorley[2]

[1]University of Florida North Florida Research and Education Center, 155 Research Rd., Quincy, FL 32351. [2]Entomology and Nematology Department, University of Florida, Gainesville, FL 32611. *Corresponding author: pcand@ufl.edu

ABSTRACT

Andersen, P. C., B. V. Brodbeck, C. M. Bliss, and R. McSorley. 2016. Influence of crop rotation and years in bahiagrass on plant-parasitic nematode density in an organic vegetable production system. Nematropica 46:60-70.

The population density of six nematode genera was evaluated in an organic crop rotation of oats, *Avena sativa*, and rye, *Secale cereale* (winter); bush beans, *Phaseolus vulgaris*, (spring); soybean, *Glycine max* (summer); and broccoli, *Brassica oleracea* (fall) as a function of prior years in bahiagrass (*Paspalum notatum*) and tillage. Neither conventional nor conservation tillage significantly impacted nematode populations. Root-knot (*Meloidogyne* spp.), reniform (*Rotylenchulus* spp.), spiral (*Heliocotylenchus* spp.), stubby-root (*Tricodorus* and *Paratrichodorous* spp.), ring (*Mesocriconema* spp.), and dagger (*Xiphinema* spp.) nematodes were quantified from 2011 to 2013 in plots that had been previously in bahiagrass for 2 or 25 yr or where bahiagrass had not been grown. In 2011, root-knot nematode population density was low after the winter oats and rye cover crop regardless of whether the plots were in 0-, 2-, or 25-yr bahiagrass rotation. After the bush bean and soybean rotation, there was an increase in root-knot abundance in the 0-yr bahiagrass regime, compared to 2 or 25 yr in bahiagrass. Root-knot population density was low in the second and third year of the crop rotations. Reniform and spiral nematodes were often impacted by prior years in bahiagrass. The abundance of reniform nematodes was highest for the bush bean crop in the 0-yr bahiagrass treatment from 2011 to 2012. For soybeans, the abundance of reniform nematodes was much higher for 0-yr bahiagrass only during the first year of the study. Root-knot nematodes on broccoli remained at very low levels, and reniform nematodes were low except for 2011 in the 0-yr bahiagrass treatment. The influence of weed species on the population density of nematode genera was evaluated in the field. The populations of spiral nematodes were highest of the nematode genera in soil samples collected from the vicinity of the root systems of bahiagrass, bermudagrass (*Cynodon dactylon*), goosegrass (*Eleusine indica*), bush bean, purple nutsedge (*Cyperus rotundus*), smooth pigweed (*Amaranthus hybridus*), soybean, and tropical spiderwort (*Commelina benghalensis*). The population densities of other nematode genera in soil samples surrounding weeds were low.

Key words: broccoli, cover crops, bush beans, *Helicotylenchus*, *Meloidogyne*, *Mesocriconema*, oats, organic production, *Paratrichodorus*, *Rotylenchulus*, rye, soybeans, *Trichodorus*.

RESUMEN

Andersen, P. C., B. V. Brodbeck, C. M. Bliss, y R. McSorley. 2016. Influencia de la rotación de cultivos y años previos en pasto de bahía sobre las densidades de nematodos parásitos de plantas en un sistema de producción hortícola ecológica. Nematropica 46:60-70.

Se evaluaron las densidades de población de seis géneros de nematodos en un sistema de cultivo ecológico con rotaciones de avena, *Avena sativa*, centeno, *Secale cereale* (invierno); frijol, *Phaseolus vulgaris*, (primavera); soja, *Glycine max* (verano); y brécol, *Brassica oleracea* (otoño) como función de los años previos con pasto de bahía (*Paspalum notatum*) y laboreo. Ni el laboreo convencional ni el laboreo de conservación afectaron significativamente las poblaciones de nematodos. Se cuantificaron los nematodos formadores de agallas en las raíces (*Meloidogyne* spp.), reniformes (*Rotylenchulus* spp.), espirales (*Helicotylenchus* spp.), de la raíz rechoncha (*Trichodorus* and *Paratrichodorus* spp.), anillados (*Mesocriconema* spp.), y daga (*Xiphinema* spp.) desde 2011 a 2013 en parcelas que habían tenido previamente pasto de bahía durante 2 o 25 años o donde el pasto de bahía no había crecido. En 2011, la densidad de población de los nematodos formadores de agallas en las raíces fue menor tras la avena de invierno y el centeno, sin tener en cuenta si las parcelas estuvieron en rotación 0-, 2-, o 25-años con pasto de bahía. Tras la rotación con el frijol y soja, hubo un incremento en la abundancia de nematodos formadores de agallas en las raíces en el régimen de 0-años con pasto de bahía, comparado con los 2 o 25 años con pasto de bahía. Las densidades de nematodos formadores de agallas en las raíces fueron bajas en el segundo y tercer año de la rotación de cultivos. Los nematodos reniformes y espirales se afectaron a menudo por los años previos con pasto de bahía. La abundancia de nematodos reniformes fue más alta para el cultivo de frijol en el tratamiento 0-años con pasto de bahía desde 2011 a 2012. En el caso de la soja, la abundancia de nematodos reniformes fue mayor para 0-años con pasto de bahía solo durante el primer año de estudio. Los nematodos formadores de agallas en las raíces se mantuvieron a niveles muy bajos en brécol, y los de nematodos reniformes fueron bajos excepto en 2011 para el tratamiento 0-años con pasto de bahía. Se evaluó la influencia de las malezas en las densidades de los géneros de nematodos en campo. Las poblaciones de nematodos espirales fueron las mayores de todos los géneros en las muestras de suelo recolectadas en la vecindad de los sistemas radicales de pasto de bahía, gramas (*Cynodon dactylon*) y (*Eleusine indica*), frijol, castañuela (*Cyperus rotundus*), amaranto (*Amaranthus hybridus*), soja, y (*Commelina benghalensis*). Las densidades de población de otros géneros de nematodos en las muestras de suelos alrededor de las malezas fueron bajas

Palabras claves: brécol, cultivos de cobertura, frijoles, *Helicotylenchus*, *Meloidogyne*, *Mesocriconema*, avena, producción ecológica, *Paratrichodorus*, *Rotylenchulus*, centeno, soja, *Trichodorus*.

INTRODUCTION

The demand for organically-produced agricultural goods has increased faster than any other segment of agriculture in recent years. Growth has been estimated at between 15 and 25% for the last three decades, with the current value exceeding $30 billion U.S. (Hallmann *et al*., 2007; USDA Economic Research Service, 2013). About 60% of the U.S. organic vegetable acreage is located in California (USDA Economic Research Service, 2013). The Southern Coastal Plain (northern Florida, Alabama, Georgia, and South Carolina) has lagged behind the rest of the nation in organic production, and collectively accounts for less than 5% of the total organic production. There is a paucity of information concerning organic vegetable production and the number of growers that are transitioning to organic production in this region. Intense pest pressures and hot, humid growing conditions make organic production in this region particularly challenging.

Plant-parasitic nematodes are the most abundant animals in the soil (Knox *et al*., 2004), and may be the most common soil-borne pest problem facing organic vegetable production (Hallmann *et al*., 2007). Root-knot (*Meloidogyne* spp.) and reniform (*Rotylenchulus reniformis* Linford & Oliveira) nematodes are usually considered the most problematic (Sasser and Freckman, 1986; McSorley *et al*., 1994b; Koenning *et al*., 1995). Root-knot nematodes can account for a 10 to 30% reduction in the yield of vegetables depending on the crop species (Collange *et al*., 2011).

Primary control for plant-parasitic nematodes includes resistant plant cultivars (when available), crop rotations (Gallaher *et al*., 1988; Govaerts *et al*., 2007; Bhan *et al*., 2010; McSorley, 2011), the addition of organic soil amendments (Abawi and Widmer, 2000; Widmer and Abawi, 2000; Widmer *et al*., 2002; Zazada and Ferris, 2004; Briar *et al*., 2007; Oka, 2010), natural control by microbial and fungal organisms (Kerry, 2000; Knox et al., 2004; Dong and Zhang, 2006), and nematicides (Murphy *et al*., 1974; Dickson and Hewlett, 1989). Bahiagrass has been shown to reduce root-knot and reniform nematode populations compared to continuous cropping (Murphy *et al*., 1974; Tedford and Fortnum, 1988). The benefits of bahiagrass on reducing nematode populations have been examined mostly on *Meloidogyne arenaria* Chitwood on peanut-cotton rotations and in soybean (Brodie *et al*., 1970; Rodríguez-Kabána *et al*., 1988, 1991, 1994; Johnson *et al*., 1999; Katsvairo *et al*., 2006). Bahiagrass suppresses certain nematodes more than others (Brodie *et al*., 1969). The bahiagrass cultivars, Argentine, Pensacola, and Tifton-9 were non-hosts of *Meloidogyne incognita* Kofoid & White (Chitwood) and *M. arenaria* (Rodríguez-Kabána *et al*., 1988), and in Alabama, bahiagrass culture was as effective as aldicarb in reducing *M. arenaria* and increasing yield of peanut compared to the untreated control. The benefit of bahiagrass in suppressing nematode populations is temporary. Rodríguez-Kabána *et al.* (1991) found that positive economic returns of soybean culture in Alabama were limited to 2 yr after a bahiagrass rotation. Fallowing may also reduce plant-parasitic nematode populations, although it may also decrease soil fertility and greatly increase weed populations and soil erosion (Rodríguez-Kabána *et al*., 1991). Rich *et al.* (2008) conducted an exhaustive survey of the impact of weeds on *Meloidogyne* spp. and concluded that inadequate weed control may negate nematode control strategies such as fallow cropping or cover cropping.

Soil tillage has been associated with soil erosion, a loss of soil fertility, and a reduction in soil biodiversity (Porazinska *et al*., 1999; Widmer and Abawi, 2000). There have been conflicting results pertaining to the effect of conventional and conservation soil tillage on nematode populations. Thomas (1978) evaluated seven tillage treatments and found that the highest densities of plant-parasitic nematodes occurred in no-till ridge plots. Tillage reduced the population of plant-parasitic nematodes and increased bacterivorous and fungivorous nematodes (Freckman and Ettma, 1993), yet Briar *et al.* (2007) found that excessive tillage may restrict the buildup of tillage-sensitive omnivorous and predatory nematode feeding guilds. Govaerts *et al.* (2007) evaluated 12 yr of management treatments and found that both plant-parasitic and non-plant-parasitic nematodes increased in corn, but not wheat, under zero tillage compared to conventional tillage. A 1-yr (Baird and Bernard, 1984), a 5-yr (Gallaher *et al*., 1988), and a 15-yr (McSorley and Gallaher, 1993) study showed little effect of tillage on most nematode species examined. By contrast, Ito *et al.* (2015) examined a 3 × 3 factorial involving moldboard plow-rotary harrow, rotary cultivation, and no-till treatments with fallow, rye, and hairy vetch cover crops and found that tillage treatments influenced the population density of all nematode-feeding guilds.

In this study, we evaluated the population density of plant-parasitic nematodes in an organic crop rotation of oats and rye (winter), bush beans (spring), soybean (summer), and broccoli (fall) as a function of prior years in bahiagrass and tillage treatment. This crop rotation was examined for 3 yr to determine the duration of any positive or negative impacts of bahiagrass on nematode abundance. Also, since the density and diversity of weed species in this organic cropping system were substantial, we examined the nematodes in soil surrounding the roots of selected weed and crop species.

MATERIALS AND METHODS

Description of experimental plots

This study was conducted from 2011 to 2013 at the University of Florida North Florida Research and Education Center-Quincy, FL. Soil type was a Dothan sandy loam (fine loamy siliceous, thermic Plinthic Kandiuldult). The long-term history of the study area was a conventional peanut, cotton, corn, and soybean production system. Two years prior to the initiation of the experiment, one half of the study area remained in conventional soybean and peanut rotation, and the other half was planted in bahiagrass (*Papsalum notatum* Flugge) cv. Tifton-9. This plot design was to evaluate the length of rotation time in bahiagrass on the density of plant-parasitic nematodes. There were four replications (plots) for each treatment. A long-term, 25-yr bahiagrass treatment was also utilized in this study. This treatment was included to examine the potential degradation of soil quality over time (with respect to plant-parasitic nematode populations) with vegetable production. Soil organic matter averaged 1.3% at the beginning of the study in the conventional soybean, cotton, and peanut plots, and in the 25-yr bahiagrass treatment, soil organic matter was up to 2.3%. Soil pH averaged 5.5.

The crop rotation used exclusively was: cover crops of oats (*Avena sativa* L.) cv. Horizon 270 and rye (*Secale cereale* L.) cv. Horizon 401 in the winter; bush beans (*Phaseolus vulgaris* L.) cv. Valentino in the spring; soybeans (*Glycine max* (L.) Merrill) cv. Hinson Long Juvenile in the summer, and broccoli (*Brassica oleracea* L.) cv. Major in the fall. Planting dates were: late March-early April (bush beans), early June (soybeans), early September (broccoli), and early December (oats and rye). The seeding rates were as follows: oats (70 kg/ha) plus rye (50 kg/ha), bush beans (53 kg/ha), soybeans (112 kg/ha), and broccoli (39,850 plants/ha).

New plots were brought into the crop rotation during early December each year from 2011 to 2013. In 2011, the three treatments were: two previous years in conventional soybean (0-yr bahiagrass treatment), previous 2 yr in bahiagrass (2-yr bahiagrass treatment) and the long-term bahiagrass treatment (25-yr bahiagrass treatment). In 2012, additional plots were initiated into bahiagrass so the treatments consisted of 0-, 1-, 2-, 3-, and 25-yr bahiagrass treatments. The comparisons in 2013 were 0-, 1-, 2-, 3-, 4- and 25-yr bahiagrass treatments. All plots at the initiation of the crop rotation were harrowed three times, and tilled with a rotovator (Bush Hog rototiller; Bush Hog Co., Selma, AL) twice to prepare the plots for the winter cover crop in early December. Each plot was divided in half with one plot receiving conventional tillage and the other strip tillage. Plot size was 9.1-m long and 7.3-m wide. Conventional tillage entailed the total plot tilled with a rotovator. Strip tillage entailed plots tilled with a rip/strip implement (Kelley Manufacturing

Co., Tifton, GA), leaving the remaining plot not tilled. Bush beans were planted using a Monosem planter (Monosem Co., Edwardsville, KS) at a 15.2-cm spacing, soybeans were planted with a Tye drill (The Tye Company, Lockney, TX) and broccoli was hand planted at a 22.9-cm spacing from transplants grown in a greenhouse. The rows of bush bean and broccoli were spaced 0.9-m apart. Organic Nature Safe (Darling Ingredients Inc., Irving, TX) (8-5-5) was applied at 135 kg N/ha before final tillage (within 1 wk of planting). Two weeks after planting, bush beans, and broccoli were fertilized with organically certified sodium nitrate (16-0-0) at a rate of 34 kg N/ha. After harvest of bush beans and broccoli, standing plant residue was mowed to allow planting of the oats and rye and the soybean cover crops using a Great Plains no-till drill (Great Plains, Salinas, KS). Plots were not tilled for cover crop preparation. The oat and rye winter cover crop was fertilized with Nature Safe (8-5-5) before planting.

The abundance of plant-parasitic nematodes was determined in 100 cm^3 soil collected in the root zone of long-term (25-yr) bahiagrass, and from the soil around the root system of bermudagrass (*Cynodon dactylon* (L.) Pers., purple nutsedge (*Cyperus rotundus* L.), pigweed (*Amarantus hybridus* L.), and bush bean. Soil cores were collected directly over the base of the plant. This sampling occurred May 2013 in the plot of 25 yr of bahiagrass. These plots had been transitioned into organic vegetables for 3 yr (except for bahiagrass sampling that remained in bahiagrass for 25 yr). Additional soil samples were collected during June 2013 from the root zone of bahiagrass, goosegrass (*Eleusine indica* (L.) Gaert.), purple nutsedge, soybean, and tropical spiderwort (*Commelina benghalensis* (L.)) plots that had been transitioned from soybean to our organic crop rotation for 3 yr.

Data collection, analysis, and statistics

Soil was sampled from each plot after each cover crop and vegetable crop. The specific dates of collection were: 28 Feb, 10 June, 28 Aug, and 1 Dec 2011; 7 Mar, 11 June, 27 Aug, and 27 Nov 2012; 20 Feb, 10 June, 30 Aug, and 1 Dec 2013. Six soil cores (2.54-cm diam.) were collected at a depth of 20 cm at random locations in each plot, and samples were combined to form a composite sample. Nematodes were extracted from a 100 cm^3 subsample by a sieving and centrifugal flotation method (Jenkins, 1964). There were four replications.

The experiment was designed as a factorial with tillage and years in bahiagrass as the main factors. Nematode counts were log-transformed [$\log_{10}(x + 1)$] to help normalize data and to allow the inclusion of zero counts. Analysis of variance was performed on transformed values using the GLM procedure of the Statistical Analysis System. *P* values are reported for each statistical analysis. Means were separated by the Duncan-Waller test, 5% level. The data reported are mean ± standard error of actual nematode counts per 100 cm^3 soil.

RESULTS

Tillage did not have a significant effect ($P < 0.10$) on the population density of any of the nematode genera detected. Thus, the tillage treatments were combined, and the experiment was analyzed as a randomized block with eight replications. Root-knot, reniform, spiral, stubby-root, ring, and dagger nematodes were detected in the site.

Root-knot nematode population densities were relatively high for the 0-yr treatment after bush beans and soybean, and low after oats and rye and broccoli (Table 1). The 0-yr treatment was transitioned from a conventional soybean crop in 2010. In 2011, root-knot nematode density was generally higher in the 0-yr bahiagrass treatment than either the 2- or 25-yr bahiagrass treatments. There were no significant differences between treatments in 2012 and 2013, with the exception of soybeans in 2013, although nematode counts were very low. The four crop rotation sequence was sufficient to reduce the density of root-knot nematodes over time regardless of prior culture in bahiagrass. For the second (2012) and third (2013) year, the only appreciable root-knot nematode populations occurred in bush beans. The maximum mean number of root-knot nematodes during 2012 or 2013 after 2 or more yr in bahiagrass was 17 per 100 cm^3 soil.

The density of reniform nematodes was higher than that seen for root-knot nematodes, and significant differences occurred among treatments throughout the experiment (Table 2). The highest nematode population density for any genus was reniform nematodes for the 2011 soybean crop. In 2011, the 0-yr bahiagrass treatment produced the highest reniform nematode counts. The highest reniform nematode densities usually occurred in the bush bean or soybean crop, although high numbers were also recorded for the oats and rye rotation, especially for the 0-yr bahiagrass treatment in 2011. The abundance of reniform nematodes in bush beans was consistently highest for the 0-yr bahiagrass treatment. In 2013, relatively high numbers of reniform nematodes were recorded after 1, 2, 3, 4 or 25 yr of bahiagrass. In fact, some of the highest numbers of reniform nematodes in 2012 and 2013 occurred in the 25-year bahiagrass treatment.

Spiral nematode counts were at least as high

Table 1. The number of root-knot nematodes (*Meloidogyne* spp.) in 100 cm^3 soil at the end of each crop rotation from 2011 to 2013 as a function of consecutive years in bahiagrass.

	No. of Prior Years in Bahiagrass						
Date/crop rotation	0 Years	1 Year	2 Years	3 Years	4 Years	25 Years	Significance $P\leq$
2011							
Oats/Rye	6 ± 4 a[z]		4 ± 1 ab			0 ± 0 b	0.046
Bush Beans	360 ± 174 a		7 ± 4 b			26 ± 9 ab	0.072
Soybeans	397 ± 203 a		154 ± 86 ab			51 ± 15 b	0.044
Broccoli	17 ± 7 a		1 ± 1 b			1 ± 1 b	0.001
2012							
Oats/Rye	0 ± 0	1 ± 1	4 ± 4	0 ± 0		0 ± 0	NS
Bush Beans	67 ± 27	43 ± 18	17 ± 16	6 ± 3		8 ± 4	NS
Soybeans	0 ± 0	0 ± 0	0 ± 0	0 ± 0		0 ± 0	NS
Broccoli	3 ± 2	1 ± 1	4 ± 1	7 ± 3		2 ± 1	NS
2013							
Oats/Rye	4 ± 2	2 ± 1	2 ± 1	11 ± 7	5 ± 2	1 ± 0	NS
Bush Beans	0 ± 0	4 ± 4	1 ± 1	0 ± 0	0 ± 0	0 ± 0	NS
Soybeans	10 ± 2 a	5 ± 1 ab	7 ± 2 ab	6 ± 1 ab	4 ± 1 b	0 ± 0 c	0.001
Broccoli	5 ± 3	3 ± 2	2 ± 1	5 ± 2	4 ± 3	1 ± 0	NS

[z]Data are mean ± 1 standard error of eight replications. Means in rows followed by the same letter do not differ ($P \leq 0.05$) according to the Waller-Duncan test performed on $\log_{10}$-transformed data. No letters indicate no differences ($P \leq 0.10$) among bahiagrass treatments.

Table 2. The number of reniform nematodes (*Rotylenchulus* spp.) in 100 cm^3 soil at the end of each crop rotation from 2011 to 2013 as a function of consecutive years in bahiagrass.

	No. of Prior Years in Bahiagrass						
Date/crop rotation	0 Years	1 Year	2 Years	3 Years	4 Years	25 Years	Significance $P\leq$
2011							
Oats/Rye	293 ± 215[z]		22 ± 4			31 ± 6	NS
Bush Beans	143 ± 137 a		0 ± 0 b			0 ± 0 b	0.059
Soybeans	1319 ± 519 a		5 ± 5 b			28 ± 9 b	0.014
Broccoli	135 ± 75		94 ± 92			28 ± 13	NS
2012							
Oats/Rye	49 ± 26	25 ± 17	11 ± 8	3 ± 1		7 ± 4	NS
Bush Beans	217 ± 102 a	114 ± 77 ab	0 ± 0 c	17 ± 12 bc		0 ± 0 c	0.001
Soybeans	142 ± 48 ab	148 ± 102 ab	36 ± 8 ab	52 ± 29 b		337 ± 146 a	0.054
Broccoli	47 ± 15 a	43 ± 14 b	49 ± 12 a	27 ± 6 ab		14 ± 3 b	0.057
2013							
Oats/Rye	47 ± 20 b	30 ± 21 b	51 ± 31 b	8 ± 2 b	16 ± 7 b	149 ± 23 a	0.001
Bush Beans	219 ± 60 a	199 ± 47 a	132 ± 19 abc	78 ± 12 c	96 ± 12 abc	135 ±71 bc	0.044
Soybeans	32 ± 7	25 ± 10	16 ± 3	16 ± 2	12 ± 2	31 ± 11	NS
Broccoli	12 ± 4 ab	5 ± 3 abc	11 ± 4 abc	2 ± 2 c	3 ± 2 bc	15 ± 5 a	0.022

[z]Data are mean ± 1 standard error of eight replications. Means in rows followed by the same letter do not differ ($P \leq 0.05$) according to the Waller-Duncan test performed on $\log_{10}$-transformed data. No letters indicate no differences ($P \leq 0.10$) among bahiagrass treatments.

Table 3. The number of spiral nematodes (*Helicotylenchus* spp.) in 100 cm^3 soil at the end of each crop rotation from 2011 to 2013 as a function of consecutive years in bahiagrass.

Date/crop rotation	No. of Prior Years in Bahiagrass						Significance
	0 Years	1 Year	2 Years	3 Years	4 Years	25 Years	$P\leq$
2011							
Oats/Rye	14 ± 4 b[z]		37 ± 11 ab			73 ± 15 a	0.005
Bush Beans	54 ± 11		32 ± 9			39 ± 8	NS
Soybeans	63 ± 11 b		227 ± 83 a			65 ± 11 b	0.003
Broccoli	100 ± 37		70 ± 21			28 ± 13	NS
2012							
Oats/Rye	55 ± 26 a	31 ± 7 a	48 ± 14 a	28 ± 8 a		4 ± 3 b	0.001
Bush Beans	51 ± 12 b	50 ± 11 b	161 ± 30 a	131 ± 22 a		17 ± 6 c	0.001
Soybeans	140 ± 27 ab	95 ± 12 c	211 ± 37 a	164 ± 25 ab		44 ± 7 d	0.001
Broccoli	48 ± 7	79 ± 10	66 ± 18	58 ± 13		34 ± 3	NS
2013							
Oats/Rye	65 ± 27	78 ± 26	72 ± 22	40 ± 6	37 ± 10	108 ± 10	NS
Bush Beans	46 ± 16 ab	68 ± 12 a	54 ± 6 ab	50 ± 7 ab	35 ± 4 ab	31 ± 4 b	0.057
Soybeans	106 ± 11 a	95 ± 14 ab	70 ± 6 b	67 ± 9 b	71 ± 8 ab	40 ± 9 c	0.001
Broccoli	44 ± 7	44 ± 7	54 ± 8	65 ± 10	74 ± 12	65 ± 12	NS

[z]Data are mean ± 1 standard error of eight replications. Means in rows followed by the same letter do not differ ($P \leq 0.05$) according to the Waller-Duncan test performed on $\log_{10}$-transformed data. No letters indicate no differences ($P \leq 0.10$) among bahiagrass treatments.

in the 2- and 25-yr bahiagrass treatments as in 0-yr bahiagrass plots (Table 3). For example, in 2011 the highest density of spiral nematodes was observed in the 25-yr bahiagrass treatment for the oats and rye cover crop, and the 2-yr bahiagrass treatment for the soybean crop. In 2012, the highest nematode counts were observed for the bush bean and soybean rotation after 2 or 4 yr of bahiagrass. There were significant differences as a function of years in bahiagrass for the soybean crop from 2011-2013.

Stubby-root nematode counts were low (maximum mean 22 per 100 cm^3 soil) for the entire experiment (Table 4). Significant differences were only recorded for the oats and rye crop in 2011 (higher for 2-yr of bahiagrass) and for the bush bean crop in 2012 (lowest for 3 yr of bahiagrass). Ring nematodes were influenced by the number of years in bahiagrass for the oats and rye crop in 2011, for all crop rotations in 2012, and for the oats and rye and bush beans crops in 2013 (Table 5). However, nematode abundance was relatively low (range 1 to 61 per 100 cm^3 soil), and there were no patterns in relation to prior years in bahiagrass. The density of dagger nematodes was low in all treatments (0 to 4 per 100 cm^3 soil), although significant differences did occur in 2011, and after the broccoli crop in 2012 (highest in 25 yr of bahiagrass) (data not shown).

Weed density in this study was high, and the influence of some of the most abundant weed species on nematode density and diversity was examined. Nematode abundance in the vicinity of the root zone of long-term (25 yr) bahiagrass, and from the soil around the root system of bermudagrass, purple nutsedge, pigweed, and bush bean is shown in Table 6. These plots had been transitioned into organic vegetables for 3 yr (except for bahiagrass sampling that remained in bahiagrass for 25 yr). None of these plant species appeared to be a good host of any of the plant-parasitic nematodes examined, with the possible exception of spiral nematodes. Spiral nematodes were highest in bahiagrass and lowest in bush bean, and ring nematode abundance was highest on bermudagrass and lowest on pigweed and bush bean. In June 2013, additional samples were collected from the vicinity of the root zone of bahiagrass, goosegrass, purple nutsedge, soybean, and tropical spiderwort in plots that had been transitioned from soybean to organic crop rotation for 3 yr. Only root-knot, reniform, spiral, and ring nematodes were detected, and there were no significant differences in nematode abundance (data not shown). The density of spiral nematodes

Table 4. The number of stubby-root nematodes (*Trichodorus and Paratrichodorus* spp.) in 100 cm^3 soil at the end of each crop rotation from 2011 to 2013 as a function of consecutive years in bahiagrass.

Date/crop rotation	No. of Prior Years in Bahiagrass						Significance $P\leq$
	0 Years	1 Year	2 Years	3 Years	4 Years	25 Years	
2011							
Oats/Rye	1 ± 0 b[z]		9 ± 2 a			3 ± 1 ab	0.005
Bush Beans	10 ± 6		8 ± 4			0 ± 0	NS
Soybeans	10 ± 5		22 ± 7			11 ± 4	NS
Broccoli	3 ± 3		3 ± 1			4 ± 2	NS
2012							
Oats/Rye	5 ± 2 a	3 ± 2	4 ± 3	2 ± 1		1 ± 0	NS
Bush Beans	6 ± 2 a	9 ± 2 a	9 ± 4 ab	1 ± 1 b		10 ± 2 a	0.013
Soybeans	8 ± 3	10 ± 2	11 ± 3	10 ± 2		7 ± 1	NS
Broccoli	1 ± 0	1 ± 1	1 ± 1	3 ± 1		1 ± 0	NS
2013							
Oats/Rye	2 ± 1	3 ± 1	2 ± 1	5 ± 2	1 ± 1	1 ± 0	NS
Bush Beans	2 ± 1	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	NS
Soybeans	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	NS
Broccoli	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	NS

[z]Data are mean ± 1 standard error of eight replications. Means in rows followed by the same letter do not differ ($P \leq 0.05$) according to the Waller-Duncan test performed on $\log_{10}$-transformed data. No letters indicate no differences ($P \leq 0.10$) among bahiagrass treatments.

Table 5. The number of ring nematodes (*Mesocriconema* spp.) in 100 cm^3 soil at the end of each crop rotation from 2011 to 2013 as a function of consecutive years in bahiagrass.

Date/crop rotation	No. of Prior Years in Bahiagrass						Significance $P\leq$
	0 Years	1 Year	2 Years	3 Years	4 Years	25 Years	
2011							
Oats/Rye	13 ± 4 b[z]		61 ± 10 a			19 ± 5 b	0.001
Bush Beans	5 ± 2		6 ± 2			6 ± 2	NS
Soybeans	13 ± 4		12 ± 4			26 ± 8	NS
Broccoli	8 ± 3		10 ± 2			9 ± 3	NS
2012							
Oats/Rye	5 ± 2 a	11 ± 3 a	6 ± 4 ab	3 ± 1 ab		1 ± 0 b	0.016
Bush Beans	23 ± 6 a	26 ± 3 a	10 ± 2 b	11 ± 3 b		6 ± 2 b	0.001
Soybeans	41 ± 6 a	25 ± 3 ab	11 ± 3 b	17 ± 7 b		23 ± 8 ab	0.020
Broccoli	18 ± 7 ab	43 ± 14 a	7 ± 2 b	11 ± 3 b		9 ± 2 b	0.011
2013							
Oats/Rye	7 ± 4 ab	7 ± 2 ab	2 ± 1 b	10 ± 3 a	3 ± 1 ab	3 ± 2 b	0.064
Bush Beans	4 ± 2 ab	7 ± 2 a	3 ± 1 ab	1 ± 1 b	1 ± 0 b	14 ± 9 a	0.021
Soybeans	17 ± 5	19 ± 4	14 ± 3	9 ± 3	10 ± 3	31 ± 10	NS
Broccoli	6 ± 3	11 ± 3	10 ± 1	10 ± 3	15 ± 3	14 ± 5	NS

[z]Data are mean ± 1 standard error of eight replications. Means in rows followed by the same letter do not differ ($P \leq 0.05$) according to the Waller-Duncan test performed on $\log_{10}$-transformed data. No letters indicate no differences ($P \leq 0.10$) among bahiagrass treatments.

Table 6. The number of root-knot (*Meloidgyne* spp.), reniform (*Rotylenchulus* spp.), spiral (*Heliocotylenchus* spp.), ring (*Mesocriconema* spp.), and dagger (*Xiphinema* spp.) nematodes in 100 cm^3 of soil surrounding the roots of five weed species.[z]

	Nematodes per 100 cm^3 soil				
Plant species	Root-knot	Reniform	Spiral	Ring	Dagger
Bahiagrass	8 ± 5[z]	9 ± 8	144 ± 20 a	17 ± 9 bc	4 ± 4
Bermudagrass	0 ± 0	9 ± 7	113 ± 24 ab	40 ± 5 a	1 ± 0
Purple nutsedge	0 ± 0	13 ± 6	85 ± 16 ab	30 ± 5 ab	1 ± 0
Pigweed	6 ± 5	7 ± 2	85 ± 16 ab	6 ± 3 c	0 ± 0
Bush Bean	8 ± 5	9 ± 7	67 ± 11 b	8 ± 3 c	0 ± 0
Significance ($P\leq$)	NS	NS	0.060	0.002	NS

[z]Data are means ± standard error of four replications. Means in columns followed by the same letter did not differ significantly ($P\leq0.05$) based on the Waller-Duncan test. Non-significant (NS) and no letters indicate no significant differences ($P\leq0.10$).

was highest (30 to 85 per 100 cm^3 soil), and the population of other nematodes varied from 0 to 13 per 100 cm^3 soil.

DISCUSSION

There was no significant tillage effect on the plant-parasitic nematodes surveyed in this study. The variable effects of tillage on nematode density in the literature have been previously addressed (Thomas, 1978; Baird and Bernard, 1984; Gallaher *et al*., 1988; Freckman and Ettna, 1993; McSorley and Gallaher, 1993; Briar *et al*., 2007; Govaerts *et al.*, 2007; Ito *et al*., 2015).

Root-knot and reniform nematodes are considered the most important nematode parasites of many crop plant species (Sasser and Freckman, 1986; McSorley *et al*., 1994a,1994b; Koenning *et al.*, 1995). The relatively high density of root-knot nematodes after the bush bean and soybean crop in 2011 was likely due to high residual populations associated with the soybean crop of 2010. In 2012 and 2013, the second year of the organic crop rotation sequence, the abundance of root-knot nematodes fell to low levels with or without prior years in bahiagrass. Our data confirm that bahiagrass is not a good host for root-knot nematodes commonly found in agronomic and horticultural crops (Rodríguez-Kabána *et al*., 1988, 1991, 1994; Rich *et al*. 2008), and clearly nematode abundance was suppressed after the first year transitioning from conventional soybean to our crop rotation. The precipitous decline in root-knot nematode abundance for our organic crop rotation, with or without prior culture in bahiagrass, suggests that the crop rotation alone was sufficient to reduce the density of these important plant-parasitic nematodes.

The winter crop of oats/rye was associated with low root-knot population densities, although oats and rye are potentially good hosts of *Meloidgyne* spp. (Johnson and Motsinger, 1989). Wang *et al.* (2004) found that winter cover crops of oats, rye, wheat (*Triticum aestivum*), hairy vetch (*Vicia villosa*), or crimson clover (*Trifolium incarnatum*) did not sufficiently suppress plant-parasitic nematodes, especially *M. incognita*, on corn in north Florida. Although our organic crop rotation resulted in a root-knot suppression after 1 yr, suppression would likely depend on the specific rotation system chosen (Rodríguez-Kabána *et al*. 1988, 1991, 1994; Johnson *et al.*, 1999), the crops grown prior to the initiation of an experiment, and soil characteristics (Brodie *et al.*, 1969, 1970).

Significant differences in the population of reniform nematodes usually occurred following multiple years in bahiagrass. However, reniform nematodes were not always suppressed by bahiagrass, and in 2013 the abundance of nematodes was sometimes highest in the 25-yr bahiagrass treatment. Bahiagrass was not a good host for reniform nematodes, but it was a moderately suitable host for spiral nematodes. The abundance of spiral nematodes suggests that our organic crop rotation was favorable for the growth and reproduction of this genus. Ring nematodes remained at low to moderate levels for the duration of the experiment. The reason for the suppression of ring nematodes with 2 or more years of bahiagrass in 2012 is not known. Lewis *et al*. (1993) conducted an extensive survey of plant-parasitic nematodes in soybean in South Carolina and detected spiral, stubby-root and ring nematodes in 70, 60, and 40% of fields. In our study, stubby-root and dagger nematode populations remained low, and although significant differences occurred in

2011 and 2012, they likely had no substantial impact on our crop species.

Damage thresholds depend on the virulence of the nematode species and biotype, the resistance or tolerance of the host plant species and cultivar, and the soil type. For example, Mueller (2009) proposed an action threshold for *M. incognita* of 300, 100, and 75 nematodes per 100 cm^3 soil for corn, cotton, and soybean, respectively, in the Coastal Plains soils of South Carolina. The action thresholds for reniform nematodes for soybeans in a sandy soil of South Carolina (Mueller, 2009), and for snap bean in Rockdale soils of Dade County, Florida (Noling, 2009) have been estimated at 200 per 100 cm^3. The density of root-knot nematodes on bush bean and soybean for the 0-yr bahiagrass treatment in 2011 could potentially be problematic. Similarly, the density of reniform nematodes was close to the action threshold for bush beans for the 0-yr bahiagrass treatment from 2011 to 2013. However, their abundance was also high in the 1-, 2-, 3- and 25-yr bahiagrass treatments in 2013, indicating that the suppression of reniform nematodes by bahiagrass did not exceed 2 yr. The abundance of root-knot nematodes on broccoli was low for the duration of the experiment. Action thresholds for root-knot in broccoli could not be found in the literature.

Tedford and Fortnum (1988) characterized the host status of 32 common weed species for both *M. arenaria* and *M. incognita* in South Carolina based on reproductive rating, egg mass index, and galling index. They rated pigweed as a moderate host of *M. arenaria* and a poor host of *M. incognita*, and rated bermudagrass, yellow nutsedge, goosegrass, and bahiagrass as poor hosts of both *Meloidogyne* species. Our data on total *Meloidogyne* spp. counts were consistent with these assessments. There are much less data concerning the other plant-parasitic nematode genera on weed species.

We avoided the term rhizosphere when describing the collection and analysis of soil surrounding the roots of specific crop and weed species. The plant rhizosphere has been defined as a dynamic and complex soil habitat surrounding the plant roots, and may extend up to several millimeters from the root surface (Kerry, 2000). The rhizosphere is substantially different than bulk soil in respect to chemistry and micro- and macro-community structure. Clearly, our collection of bulk soil in the vicinity of the plant roots contains only a fraction of the "true rhizospere". Nevertheless, there were differences in spiral and ring nematodes as a function of plant species using our collection protocol. We hypothesize that much of the within-treatment variability of nematode density in our crop rotation system was due to the random collection of soil in plots with high weed density and diversity. However, there were low population densities associated with weed species, and generally less variation between weed species compared to those collected at random in our rotation plots. Thus, we have no evidence that the high within-treatment variability in nematode density was influenced by weed heterogeneity. Johnson *et al.* (1975) also found that the application of herbicides (thereby killing most weeds) in corn, cotton, and soybean fields did not significantly impact the population of any nematode species examined.

In conclusion, prior culture in bahiagrass suppressed root-knot nematodes in bush beans and soybeans for the first year of transition to our organic crop rotation system. However, our crop rotation was associated with reduced population density of root-knot nematodes for all treatments the second and third year of the study. Reniform nematodes were reduced for bush beans with prior years in bahiagrass, especially for the 25-yr bahiagrass treatment; however, reniform-suppression did not last beyond 2 yr. For soybean, the population density of reniform nematodes was reduced the first, but not the second year after bahiagrass culture. Oats and rye and broccoli supported relatively low populations of root-knot and reniform nematodes. Bahiagrass appears to be a moderate host of *Heliocotylenchus* (spiral) nematodes, but supported very low populations of other nematode genera. The weed species examined were not good hosts of any nematode genera, with the possible exception of spiral nematodes.

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