RESEARCH/INVESTIGACIÓN

THE INFLUENCE OF IRRIGATION, CROP ROTATION, AND FLUOPYRAM NEMATICIDE ON PEANUT YIELD AND THE NEMATODE COMMUNITY

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ABSTRACT

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Peanut (*Arachis hypogaea*) is an important cash crop in the southeastern United States and suffers from yield losses due to plant-parasitic nematodes. Peanut is rotated with two years of cotton (*Gossypium hirsutum*) or one year of cotton and two years of sod (*Paspalum notatum*) in conventional and sod-based crop rotation, respectively. Little is known about how three common agronomic practices – irrigation, crop rotation, and fluopyram nematicide application – collectively influence peanut yield and nematode community structure. Therefore, objectives of this research were to determine effects of irrigation (with or without), crop rotation (conventional or sod-based peanut), and fluopyram nematicide application (with or without) on various nematode feeding groups, ecological indices, and peanut yield. Soil samples were collected before planting, at midseason, and at harvest in 2018-2019 at a long-term research site in Quincy, FL, USA. Free-living and ring nematodes (*Mesocriconema ornatum*) were extracted from a subsample using sucrose-centrifugation and nematode ecological indices (structure, maturity, channel, enrichment, and basal) were calculated. Overall, ring nematode population densities were greater in sod-based peanut than conventional peanut. Conventional peanut had greater yield than sod-based peanut plots. Fluopyram nematicide application did not improve peanut yield compared to untreated plots. We observed consistent trends with sod-based peanut increasing fungivores relative to conventional peanut. Yet, other nematode feeding groups and ecological indices were not consistently impacted by our factors. Therefore, nematode ecology based on feeding groups was not heavily influenced by irrigation, crop rotation, or fluopyram nematicide in this research.

Key words: *Arachis hypogaea*, crop rotation, fluopyram, irrigation, *Mesocriconema ornatum*, nematicide, nematode community, peanut, ring nematode

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RESUMEN

Schumacher, L. A., I. M. Small, and Z. J. Grabau. 2024. La influencia del riego, la rotación de cultivos y el nematicida fluopiram en el rendimiento del maní y la comunidad de nematodos. Nematropica 54:96-110.

El maní (*Arachis hypogaea*) es un cultivo comercial importante en el sureste de los Estados Unidos y sufre pérdidas de rendimiento debido a los nematodos parásitos de las plantas. El maní se rota con dos años de algodón (*Gossypium hirsutum*) o un año de algodón y dos años de césped (*Paspalum notatum*) en la rotación de cultivos convencional y basada en césped, respectivamente. Poco se sabe acerca de cómo tres prácticas agronómicas comunes (riego, rotación de cultivos y aplicación de nematicida fluopiram) influyen colectivamente en el rendimiento del maní y la estructura de la comunidad de nematodos. Por lo tanto, los objetivos de esta investigación fueron determinar los efectos del riego (con o sin), la rotación de cultivos (maní convencional o de césped) y la aplicación de nematicida fluopiram (con o sin) sobre varios grupos alimentación de nematodos, índices ecológicos y rendimiento de maní. Se recolectaron muestras de suelo antes de la siembra, a mitad de temporada y en la cosecha en 2018-2019 en un sitio de investigación a largo plazo en Quincy, FL, EE. UU. Se extrajeron nematodos de vida libre y en anillo (*Mesocriconema ornatum*) de una submuestra mediante centrifugación de sacarosa y se calcularon los índices ecológicos de nematodos (estructura, madurez, canal, enriquecimiento y basal). En general, las densidades de población de nematodos anulares fueron mayores en el maní de césped que en el maní convencional. El maní convencional tuvo mayor rendimiento que las parcelas de maní con césped. La aplicación del nematicida fluopiram no mejoró el rendimiento de maní en comparación con las parcelas no tratadas. Observamos tendencias consistentes en el aumento de fungivoros del maní a base de césped en comparación con el maní convencional. Sin embargo, nuestros factores no afectaron consistentemente a otros grupos alimentación de nematodos e índices ecológicos. Por lo tanto, la ecología de los nematodos basado en grupos de alimentación no estuvo fuertemente influenciada por el riego, la rotación de cultivos o el nematicida fluopiram en esta investigación.

Palabras clave: *Arachis hypogaea*, comunidad de nematodos, fluopiram, maní, nematicida, nematodo anular, riego, rotación de cultivos, *Mesocriconema ornatum*

INTRODUCTION

In 2022, peanut (*Arachis hypogaea*) was grown in 11 US states on nearly 600,000 ha and a total value of $1.5 billion (USDA-NASS, 2023a, 2023b). A conventional rotation sequence in the southeast US consists of peanut followed by two years of cotton (*Gossypium hirsutum*). However, pests and pathogens may become problematic in conventional rotations due to reduced biodiversity. In peanut specifically, nematode damage may present itself in the form of above-ground symptoms such as stunted, chlorotic plants (Grabau and Dickson, 2018). To solve these problems without the use of chemicals, cultural management is a preferred method (Lawrence and McLean, 2001; Koenning *et al.*, 2004). Crop rotation is one form of cultural management shown to be successful in managing plant-parasitic nematodes (Stetina *et al.*, 2007; Leach *et al.*, 2012; Neher *et al.*, 2019; Schumacher *et al.*, 2020). A sod-based crop rotation utilizes two years of bahiagrass (*Paspalum notatum*) followed by one year each of peanut and cotton to improve pathogen management (Schumacher *et al.*, 2020, 2022; Zhang *et al.*, 2022) as well as a variety of agronomic traits like water infiltration and soil fertility (Katsvairo *et al.*, 2006; Katsvairo *et al.*, 2007; Maltais-Landry *et al.*, 2023). Yet, examining how conventional and sod-based rotations affect the nematode community in the peanut portions of the rotation has not been well-studied.

Rotating peanut with two years of cotton in a conventional rotation helps alleviate certain root-knot nematode (*Meloidogyne arenaria*) problems (Rodriguez-Kabana *et al.*, 1987), but exacerbates other plant-parasitic nematodes such as reniform nematode (*Rotylenchulus reniformis*) due to the ideal host status of cotton for reniform nematode (Schumacher *et al.*, 2020). Sod-based rotation has been shown to decrease densities of plant-parasitic nematodes like *R. reniformis* because peanut and bahiagrass are non-hosts (Tsigbey *et al.*, 2009; Grabau *et al.*, 2020; Schumacher *et al.*, 2020, 2022). These lower *R. reniformis* population densities can be attributed to three out of four years without a host crop for *R. reniformis* in the sod-based rotation. However, if bahiagrass is to be used in a peanut-cotton rotation, the sod must be kept free of weeds as these may serve as alternate hosts for various plant-parasitic nematodes (Davis and Webster, 2005). Typically, two years of a poor or non-host is enough to reduce nematode population densities, but longer rotations with bahiagrass may be needed due to poor weed suppression in year one (Rodriguez-Kabana *et al.*, 1988).

Another plant-parasitic nematode commonly encountered in southeast US peanut production is the ring nematode (*Mesocriconema ornatum*) (Tsigbey *et al.*, 2009). This nematode has a wide host range including both peanut and bahiagrass (Minton and Bell, 1969; Tsigbey *et al.*, 2009; Schumacher *et al.*, 2020). Ring nematodes are ectoparasites with relatively long stylets, which allow them to feed deep in root tissue near the tips of roots. This feeding behavior may stop root growth and result in plant stunting. However, any damage caused to peanut is thought to be minor (Minton and Bell, 1969; Wheeler and Starr, 1987). Because ring nematodes have such broad host ranges, rotation and cover crops may not be successful in their management. Therefore, investigating the effects of fluopyram nematicide on this nematode was a component of this research.

Free-living nematodes (omnivores, predators, fungivores, and bacterivores) are often abundant in the soil environment. These nematodes regulate nutrient cycling in the soil and are a useful reference to assess environmental quality (Bongers, 1990; Ferris *et al.*, 1998; Chen and Ferris, 1999; Porazinska *et al.*, 1999; Coleman and Wall, 2015). Furthermore, there is potential for regulating population densities of other species through predation by predatory nematodes, indicating the need to understand how this feeding group persists in different agronomic environments (Wang *et al.*, 2015). Free-living nematodes are also used to calculate various ecological indices that can be used to evaluate the health of a soil ecosystem (Bongers and Ferris, 1999; Ferris et al, 2001). The Channel Index (CI), Enrichment Index (EI), Structure Index (SI), Basal Index (BI), and Maturity Index (MI) were developed to estimate levels of soil health, disturbance, and enrichment, as well as decomposition pathways. For instance, high values of the CI indicate fungal decomposition while low values indicate bacterial decomposition (Ferris *et al.*, 2001; Wilson and Kakouli-Duarte, 2009). Bacterivores and fungivores are measured in the EI to indicate if an environment is resource enriched. The MI excludes plant-parasitic nematodes and instead measures community structure via colonizer (bacterivore/fungivore) and persister (omnivore/predator) abundances, making it a good indicator of agroecosystem succession (Bongers and Bongers, 1998; Ferris, 2010). A high value of the MI indicates a stable and/or enriched environment where a high value of the BI indicates a stressed and/or degraded environment. Finally, the stability of an ecosystem based on position in the food chain and relative abundance of omnivores/predators is measured by the SI, of which a high value indicates greater food web complexity. One would expect that a sod-based rotation would lead to greater SI and MI than a conventional rotation due to less disturbance and increased stability exhibited by the system.

Non-fumigant nematicides are frequently used to manage plant-parasitic nematodes (Moore and Lawrence, 2012; Grabau *et al.*, 2020). Some non-fumigants disrupt chemoreception and nervous system function (Haydock *et al.*, 2006). One such product – fluopyram – is used in crop production systems to alleviate yield losses caused by plant-parasitic nematodes (Faske and Hurd, 2015). Unfortunately, non-target impacts may be associated with the use of nematicides, decreasing population densities of beneficial, free-living nematodes (Yeates, 1999; Neher, 2010; Hodson *et al.*, 2019). Fluopyram reduced numbers of free-living nematodes after repeated applications in turfgrass (Waldo *et al.*, 2019) and tomato (Grabau *et al.*, 2021); however, in other studies, fluopyram had fewer non-target impacts than other nematicides (Watson and Desaeger, 2019; Grabau *et al.*, 2020; Schumacher *et al.*, 2022).

Observing population densities of various plant-parasitic nematodes allows us to quantify damage potential and yield loss (Blasingame, 2007). Meanwhile, facilitating a healthy soil ecosystem involves the reduction of plant-parasitic nematodes with minimal disruption to beneficial, free-living nematodes (Wilson and Kakouli-Duarte, 2009). If a sod-based rotation can aid in reducing plant-parasitic nematode populations while maintaining beneficial nematode populations, growers would spend less money on nematicides and still achieve their yield goals. Objectives for this work were to evaluate effects of irrigation, crop rotation, and fluopyram nematicide on peanut yield, ring nematode, nematode community structure, and ecological indices. This study was tangential to another study conducted in 2017-2018 that assessed nematode community structure in sod-based and conventional cotton (Schumacher *et al.*, 2020, 2022).

MATERIALS AND METHODS

Study site

Experiments were conducted in 2018 and 2019 at the University of Florida's North Florida Research and Education Center in Quincy, FL, USA (30°32.79'N, 84°35.50'W). The soil was a Dothan sandy loam (fine-loamy, kaolinitic, thermic Plinthic Kandiudult) with 85% sand-5% silt-10% clay, 2% organic matter, and a pH of 6.3 (Zhao *et al.*, 2010). The site was naturally infested with *M. ornatum* (Tsigbey *et al.*, 2009). The soil was strip tilled and planted to a winter cover crop of oats in December of each year (67 kg/ha) using a Great Plains drill (Great Plains Ag, Salina, KS, USA). On April 2, 2018, glyphosate at 1.6 l/ha was applied to all plots to kill the winter cover crop.

Experimental design

The experiment was arranged as a randomized complete block design with a modified split-split plot arrangement (irrigation by crop rotation by fluopyram nematicide) with three replicates. The research site included a four-year bahiagrass-bahiagrass-peanut-cotton (sod-based rotation) rotation and a three-year peanut-cotton-cotton (conventional) rotation where each crop phase of each rotation was present each year (Katsvairo *et al.*, 2007; Schumacher *et al.*, 2020, 2022). Of these, two peanut crop phases were sampled for this study in 2018 and 2019, one from the conventional rotation and one from sod-based rotation (Table 1). Irrigation (main plot treatment) was supplied via a lateral line overhead system and applied on June 26, July 12, and July 18 in 2018 and on May 2, June 4, June 26, August 8, and September 27 in 2019 at the rate of 1.5 cm per irrigation event versus rainfed-only main plots. Subplot treatments were conventional peanut and sod-based peanut. FloRun 331 peanuts inoculated with liquid inoculant were planted on April 27, 2018, and GA06G peanuts inoculated with liquid inoculant were planted on May 9, 2019, at a rate of 6 seeds per 0.3 m of row using a Monosem 450 planter (Monosem Co., Edwardsville, KS, USA). Fluopyram nematicide (Bayer Crop Science, St. Louis, MO, USA) was the sub-subplot treatment and both peanut crops received this treatment in 2018 and 2019. Fluopyram nematicide was formulated as Velum Total (Bayer Crop Science) which also included imidacloprid insecticide (0.34 kg a.i. per ha). Half the rows of both the conventional and sod-based rotation received fluopyram at 0.24 kg a.i. per ha (the maximum labelled rate) applied into the seed furrow at planting via the tractor-driven Monosem planter. Sub-subplots were 1.8 m by 9.1 m (10 rows of peanut). Sub-subplots planted to peanut (n=24) in 2018 and 2019 were assessed.

Yield

Peanut yield data were collected in 2018 and 2019. Each year, peanuts were inverted mechanically using a tractor-drawn peanut digger-inverter (Kelley Manufacturing Company, Tifton, GA) and harvested on the same day as inversion (to minimize predation by animals), which occurred on October 3, 2018, and October 21, 2019. All samples were weighed, and a 4.5 kg subsample was taken from each plot and dried for 72 hr at 45°C in a forced-aired dryer. Moisture in each sample was estimated based on subsample weight before and

Table 1. Crop sequence for bahiagrass, peanut, and cotton for conventional and sod-based rotation during 2016 to 2019.

Phase Number	Rotation	2016	2017	2018	2019
1	conventional	P ^{z}	C1	C2	P
2	conventional	C1	C2	P	C1
3	conventional	C2	P	C1	C2
4	sod-based	CS	B1	B2	PS
5	sod-based	B1	B2	PS	CS
6	sod-based	B2	PS	CS	B1
7	sod-based	PS	CS	B1	B2

^{z}C1 and C2 are first and second-year conventional cotton, respectively. CS is cotton in sod-based rotation. P and PS are conventional and sod-based peanut, respectively. B1 and B2 are first and second-year bahiagrass, respectively.

after drying, then yield at 10% moisture was calculated for reporting.

Soil sampling for nematode community

Twelve soil cores to a depth of approximately 20 cm were taken per plot using a 3.5 cm-diam. cone-shaped soil sampler with approximate volume of 200 cm^3 and the soil mixed to achieve one composite sample per plot. Soil samples from the two center rows of each plot (8 cm or less away from actively growing plants) were collected before planting (Pi) on April 19, 2018, and April 9, 2019. Midseason (Pm) soil samples (51 and 43 days after planting in 2018 and 2019, respectively) were collected on June 22, 2018, and June 21, 2019. Finally, harvest (Pf) soil samples (146 and 141 days after planting in 2018 and 2019, respectively) were collected on September 25, 2018, and September 27, 2019. Samples were put in plastic bags and stored at 4°C for less than three days before processing.

Nematode quantification

Prior to extraction, soil samples were dry sieved by gently rolling/pushing each soil core through a screen with 0.64-cm apertures to achieve a more uniform soil aggregate size. Nematodes were extracted from 100 cm^3 soil using a modified sucrose-centrifugation method (Jenkins, 1964) by volumetrically determining how many grams of soil was required to displace 100 ml water (205 g soil). Nematodes were fixed in 2% formalin prior to identification. Nematodes were counted from formalin-fixed samples using a 400x inverted microscope (Carl Zeiss Inc., Thornwood, NY, USA) and identified morphologically. Total nematode population density was recorded, the first 200 nematodes encountered identified to genus based on keys by Bongers (1994) and Mai and Mullin (1996), and then adjusted to the absolute abundance per 100 cm^3 soil. Of the plant-parasitic nematode genera encountered, only ring nematodes were statistically analyzed. For the free-living nematodes, statistical analysis was performed on population densities of bacterivores, fungivores, omnivores, and predators. Additionally, nematode ecological indices were calculated using the web-based NINJA (Nematode Indicator Joint Analysis) tool and statistical analysis performed on BI, SI, EI, CI, and MI (Sieriebriennikov *et al.*, 2014).

Statistical analysis

Yield, nematode, and ecological index data were subset according to irrigation regime (irrigated or rainfed) and analyzed separately for each season and pooled across years (2018 and 2019) using split-plot ANOVA (crop rotation by fluopyram nematicide) in R version 3.3.1 (The R Foundation for Statistical Computing, Vienna, Austria). Data were analyzed this way to account for more biologically meaningful interpretation of results based on common (i.e., irrigated) and less common (i.e., rainfed) peanut production practices as well as observing the nematode population density fluctuations within a season (Pi, Pm, and Pf). For example, after subsetting by irrigation regime, a reduced ANOVA model for a particular sampling date was as follows: Y = overall mean + effects of main plot (crop rotation) + effects of subplot (fluopyram nematicide) + interaction term of main and subplot (crop rotation × fluopyram nematicide) + replicate + residuals. Models were checked for homogeneity of variances using Levene's test and normality of residuals checked graphically (Levene, 1960; Cook and Weisburg, 1999). Year by crop rotation and year by fluopyram nematicide interactions were checked and were not significant ($P>0.05$), so data were combined and analyzed across years. Fluopyram nematicide effects for each crop rotation (conventional and sod-based) were analyzed separately if crop rotation by fluopyram nematicide interaction was significant ($P\leq0.05$). Treatment means were separated using Fisher's Least Significant Difference (LSD) test ($P\leq0.05$). Crop rotation and fluopyram nematicide were considered fixed effects while replicate and year were random effects.

RESULTS

Nematode genera

Thirty-nine genera were identified at the field site. These genera were divided into the following feeding groups: herbivores, fungivores, bacterivores, omnivores, and predators. For the herbivores, *Axonchium*, *Ecphyadophora*, *Helicotylenchus*, *Meloidogyne*, *Mesocriconema*, *Pratylenchus*, *Rotylenchulus*, *Trichodorus*, and *Xiphinema* were identified. The following fungivores were identified: *Aphelenchoides*, *Aphelenchus*, *Diphtherophora*, *Ditylenchus*, and *Filenchus*. The following bacterivores were identified: *Acrobeles*, *Alaimus*, *Bunonema*, *Cephalobus*, *Chronogaster*, *Diplogaster*, *Eucephalobus*, *Mesorhabditis*, *Panagrolaimus*, *Plectus*, *Prismatolaimus*, *Rhabditis*, and *Wilsonema*. The following omnivores were identified: *Epidorylaimus*, *Eudorylaimus*, *Mesodorylaimus*, *and Prodorylaimus*. Finally, the following predators were identified: *Aporcelaimellus*, *Clarkus*, *Discolaimus*, *Mylonchulus*, *Pristionchus*, *Thonus*, *Tobrilus*, and *Tripyla*.

Yield

Peanut yield was greater in conventional than sod-based peanut across both irrigation regimes (Table 2, $P \leq 0.03$). Fluopyram nematicide did not significantly affect peanut yield in either irrigated or rainfed plots (Table 2, $P \geq 0.58$).

Ring nematode

Ring nematode population densities were always greater in sod-based peanut than conventional peanut (Table 3, $P \leq 0.05$), save for midseason rainfed plots (Table 3, $P=0.19$). There were no significant fluopyram nematicide effects, except midseason fluopyram nematicide effects under irrigation varied by cropping regime (Table 3, $P=0.03$). At midseason, irrigated sod-based peanut with fluopyram nematicide had a greater number of ring nematodes (132 per 100 cm^3 soil) than irrigated conventional peanut with fluopyram nematicide (16 per 100 cm^3 soil). Irrigated conventional and sod-based peanut without fluopyram nematicide at midseason were not statistically different (80 and 77 nematodes per 100 cm^3 soil, respectively).

Fungivores and bacterivores

In both irrigated and rainfed preplant samplings, fungivore densities were greater in sod-based peanut than conventional peanut (Table 4, $P \leq 0.01$). Additionally, midseason irrigated sod-based peanut had greater densities of fungivores than conventional peanut (Table 4, $P=0.04$). Fluopyram nematicide had no effect on fungivores

Table 2. Effects of crop rotation and fluopyram nematicide application on peanut yield in irrigated and rainfed peanut in 2018 and 2019.

	Irrigated[x]		Rainfed	
Crop rotation				
Conventional	6613	A[y]	6013	A
Sod-based	5916	B	524	B
Nematicide				
Without fluopyram	6301		5586	
With fluopyram	6229		5666	
ANOVA (*P* values)[z]				
Crop rotation (C)	0.03	*	<0.01	**
Nematicide (N)	0.80		0.58	
C x N	0.89		0.70	

[x]Mean values at harvest (kg/ha).
[y]Values followed by different letters in the same column are significantly different according to Fisher's LSD at $P \leq 0.05$.
[z]* and ** represent significant effects at $P \leq 0.05$ and $P \leq 0.01$, respectively.

Table 3. Effects of crop rotation and fluopyram nematicide application on *Mesocriconema ornatum* in irrigated and rainfed peanut in 2018 and 2019.

	Irrigated						Rainfed					
	Pi[x]		Pm		Pf		Pi		Pm		Pf	
Crop rotation												
Conventional	54	B[y]	48	B	309	B	33	B	68		150	B
Sod-based	112	A	105	A	665	A	173	A	155		433	A
Nematicide												
Without fluopyram	96		79		451		98		130		296	
With fluopyram	70		74		524		109		94		287	
ANOVA (*P* values)[z]												
Crop rotation (C)	0.04	*	0.01	**	<0.01	**	0.05	*	0.19		<0.01	**
Nematicide (N)	0.56		0.84		0.49		0.65		0.42		0.84	
C x N	0.78		0.03	*	0.97		0.90		0.34		0.96	

[x]Pi, Pm, and Pf are mean nematode values (per 100 cm^3 soil) prior to planting, at midseason (51 and 43 days after planting in 2018 and 2019), and harvest (146 and 141 days after planting in 2018 and 2019), respectively.
[y]Values followed by different letters in the same column are significantly different according to Fisher's LSD at $P \leq 0.05$.
[z]* and ** represent significant effects at $P \leq 0.05$ and $P \leq 0.01$, respectively.

Table 4. Effects of crop rotation and fluopyram nematicide application on fungivores in irrigated and rainfed peanut in 2018 and 2019.

	Irrigated						Rainfed					
	Pi[x]		Pm		Pf		Pi		Pm		Pf	
Crop rotation												
Conventional	329	B[y]	214	B	306		351	B	254		217	
Sod-based	726	A	373	A	541		696	A	322		232	
Nematicide												
Without fluopyram	526		268		584		570		252		210	
With fluopyram	529		319		263		476		323		239	
ANOVA (*P* values)[z]												
Crop rotation (C)	<0.01	**	0.04	*	0.41		0.01	**	0.25		0.79	
Nematicide (N)	0.97		0.39		0.20		0.33		0.29		0.55	
C x N	0.72		0.24		0.22		0.67		0.79		0.77	

[x]Pi, Pm, and Pf are mean nematode values (per 100 cm^3 soil) prior to planting, at midseason (51 and 43 days after planting in 2018 and 2019), and harvest (146 and 141 days after planting in 2018 and 2019), respectively.
[y]Values followed by different letters in the same column are significantly different according to Fisher's LSD at $P \leq 0.05$.
[z]* and ** represent significant effects at $P \leq 0.05$ and $P \leq 0.01$, respectively.

(Table 4, $P \geq 0.2$). Bacterivore population densities in preplant samplings were greater in conventional peanut than sod-based peanut, regardless of irrigation (Table 5, $P \leq 0.04$). At harvest, bacterivore densities were greater in irrigated untreated plots than in fluopyram nematicide-treated plots (Table 5, $P<0.01$), but fluopyram nematicide did not affect bacterivore densities in rainfed plots or irrigated plots at preplant or midseason (Table 5, $P \geq 0.26$).

Omnivores and predators

In both irrigated and rainfed harvest samplings, omnivore densities were greater in sod-based peanut than conventional peanut (Table 6,

Table 5. Effects of crop rotation and fluopyram nematicide application on bacterivores in irrigated and rainfed peanut in 2018 and 2019.

	Irrigated					Rainfed				
	Pi[x]		Pm	Pf		Pi		Pm	Pf	
Crop rotation										
Conventional	942	A[y]	812	382		1306	A	953	544	942
Sod-based	609	B	815	457		699	B	929	513	609
Nematicide										
Without fluopyram	747		884	491	a	1037		1069	586	747
With fluopyram	805		743	348	b	968		813	471	805
ANOVA (*P* values)[z]										
Crop rotation (C)	0.04	*	0.97	0.36		<0.01	**	0.93	0.86	0.04
Nematicide (N)	0.68		0.38	<0.01	**	0.67		0.26	0.30	0.68
C x N	0.91		0.06	0.87		0.74		0.45	0.71	0.91

[x]Pi, Pm, and Pf are mean nematode values (per 100 cm^3 soil) prior to planting, at midseason (51 and 43 days after planting in 2018 and 2019), and harvest (146 and 141 days after planting in 2018 and 2019), respectively.
[y]Values followed by different letters in the same column are significantly different according to Fisher's LSD at $P \leq 0.05$.
[z]* and ** represent significant effects at $P \leq 0.05$ and $P \leq 0.01$, respectively.

$P \leq 0.03$). Additionally, omnivores were more abundant in midseason rainfed sod-based peanut than conventional peanut (Table 6, $P<0.01$). At midseason, omnivore population densities were greater in irrigated untreated plots than in fluopyram nematicide-treated plots (Table 6, $P=0.02$). Predator population densities were greater in irrigated sod-based peanut than conventional peanut at preplant and harvest (Table 7, $P \leq 0.05$). Fluopyram nematicide application did not affect predators, except that fluopyram nematicide application effects on predators at preplant in rainfed plots varied by cropping regime (Table 7, $P=0.04$). At preplant, rainfed sod-based peanut without fluopyram nematicide had greater densities of predators (21 nematodes per 100 cm^3 soil) than rainfed conventional peanut with fluopyram nematicide (0 per 100 cm^3 soil). Rainfed conventional and sod-based peanut with fluopyram nematicide were not statistically different (12 nematodes per 100 cm^3 soil).

Channel and enrichment indices

A consistent trend in preplant samplings occurred where sod-based peanut had greater CI values than conventional peanut (Table 8, $P \leq 0.05$). Fluopyram nematicide had no effect on CI (Table 8, $P \geq 0.13$). Rainfed plots were the only plots showing significant effects of crop rotation or fluopyram nematicide on EI. In both preplant and harvest samplings, EI was greater in sod-based peanut than conventional peanut (Table 9, $P \leq 0.04$). Furthermore, in rainfed harvest plots, EI was greater in fluopyram nematicide-treated plots than untreated plots (Table 9, $P<0.01$).

Basal, maturity, and structure indices

Overall, there were no consistent trends observed with the BI. In rainfed plots at harvest, BI was significantly greater ($P=0.04$) in conventional peanut than sod-based peanut (50.89 and 40.84, respectively). Additionally, plots without fluopyram nematicide had a significantly greater ($P=0.05$) BI than those with fluopyram nematicide (50.67 and 41.06, respectively). No overall trends were observed in the MI for any sampling or irrigation regime. The mean MI across crop rotation and fluopyram nematicide treatments under irrigated and rainfed conditions was 2.09 and 2.07, respectively. No overall trends were observed in the SI for any sampling or irrigation regime. The mean SI across crop rotation and fluopyram nematicide treatments under irrigation and rainfed conditions was 35.31 and 29.98, respectively.

DISCUSSION

Considering multiple factors – irrigation, crop rotation, and fluopyram nematicide – is warranted to understand how different agronomic practices

Table 6. Effects of crop rotation and fluopyram nematicide application on omnivores in irrigated and rainfed peanut in 2018 and 2019.

	Irrigated					Rainfed				
	Pi[x]	Pm		Pf		Pi	Pm		Pf	
Crop rotation										
Conventional	45	46		10	B[y]	79	38	B	0	B
Sod-based	37	62		32	A	40	95	A	17	A
Nematicide										
Without fluopyram	52	74	a	23		61	73		10	52
With fluopyram	30	34	b	19		58	59		8	30
ANOVA (P values)[z]										
Crop rotation (C)	0.79	0.52		0.03	*	0.23	<0.01	**	<0.01	**
Nematicide (N)	0.23	0.02	*	0.68		0.88	0.37		0.42	
C x N	0.70	0.26		0.15		0.34	0.95		0.42	

[x]Pi, Pm, and Pf are mean nematode values (per 100 cm^3 soil) prior to planting, at midseason (51 and 43 days after planting in 2018 and 2019), and harvest (146 and 141 days after planting in 2018 and 2019), respectively.
[y]Values followed by different letters in the same column are significantly different according to Fisher's LSD at $P \leq 0.05$.
[z]* and ** represent significant effects at $P \leq 0.05$ and $P \leq 0.01$, respectively.

Table 7. Effects of crop rotation and fluopyram nematicide application on predators in irrigated and rainfed peanut in 2018 and 2019.

	Irrigated					Rainfed			
	Pi[x]		Pm	Pf		Pi		Pm	Pf
Crop rotation									
Conventional	12	B[y]	9	8	B	6		12	13
Sod-based	42	A	24	19	A	17		21	15
Nematicide									
Without fluopyram	22		14	16		11		14	17
With fluopyram	33		19	11		12		19	11
ANOVA (P values)[z]									
Crop rotation (C)	0.02	*	0.72	0.05	*	0.34		0.58	0.64
Nematicide (N)	0.34		0.52	0.38		0.83		0.39	0.31
C x N	0.18		0.11	0.84		0.04	*	0.22	0.88

[x]Pi, Pm, and Pf are mean nematode values (per 100 cm^3 soil) prior to planting, at midseason (51 and 43 days after planting in 2018 and 2019), and harvest (146 and 141 days after planting in 2018 and 2019), respectively.
[y]Values followed by different letters in the same column are significantly different according to Fisher's LSD at $P \leq 0.05$.
[z]*represents significant effects at $P \leq 0.05$.

impact the nematode community and crop yields. In both irrigated and rainfed plots, peanut yields were greater in the conventional rotation than the sod-based rotation, a result that cannot be easily explained. Other studies support our observation of similar or greater yield of peanut following sod-based versus conventional rotations (Wright *et al.*, 2018). Additionally, bahiagrass increased water infiltration in the sod-based rotation (Katsvairo *et al.*, 2010; Zhao *et al.*, 2010), so one would expect any observed yield differences between the two rotations to be negligible. However, the addition of cover crops in the conventional rotation may have made it competitive with the sod-based rotation in terms of yield and agronomic benefits. Rainfed peanut had lower yields than irrigated peanut in years when soil moisture was a limiting factor (Lamb *et al.*, 2020), and our results also supported this observation.

There was inconsistency in the efficacy of

Table 8. Effects of crop rotation and fluopyram nematicide application on Channel Index (CI) in irrigated and rainfed peanut in 2018 and 2019.

	Irrigated				Rainfed			
	Pi[x]		Pm	Pf	Pi		Pm	Pf
Crop rotation								
Conventional	51.86	B	30.59	49.38	37.86	B	36.86	43.34
Sod-based	76.54	A	35.54	38.92	67.47	A	35.43	35.98
Nematicide								
Without fluopyram	67.58		29.11	49.53	56.10		31.60	40.43
With fluopyram	60.82		37.02	38.78	49.23		40.70	38.89
ANOVA (*P* values)[z]								
Crop rotation (C)	0.03	*	0.35	0.37	0.05	*	0.77	0.43
Nematicide (N)	0.49		0.13	0.20	0.39		0.31	0.90
C x N	0.69		0.16	0.86	0.79		0.30	0.72

[x]Pi, Pm, and Pf are mean nematode values (per 100 cm^3 soil) prior to planting, at midseason (51 and 43 days after planting in 2018 and 2019), and harvest (146 and 141 days after planting in 2018 and 2019), respectively.
[y]Values followed by different letters in the same column are significantly different according to Fisher's LSD at $P \leq 0.05$.
[z]* represents significant effects at $P \leq 0.05$ and $P \leq 0.01$, respectively.

Table 9. Effects of crop rotation and fluopyram nematicide application on Enrichment Index (EI) in irrigated and rainfed peanut in 2018 and 2019.

	Irrigated			Rainfed				
	Pi[x]	Pm	Pf	Pi		Pm	Pf	
Crop rotation								
Conventional	36.17	48.65	50.57	33.21	B	43.75	40.20	B
Sod-based	43.18	55.63	57.90	43.34	A	50.33	52.80	A
Nematicide								
Without fluopyram	40.60	52.40	52.52	39.88		48.02	40.52	b
With fluopyram	38.75	51.88	55.95	36.68		46.06	52.48	a
ANOVA (*P* values)[z]								
Crop rotation (C)	0.28	0.31	0.13	0.02	*	0.25	0.04	*
Nematicide (N)	0.69	0.87	0.40	0.40		0.72	<0.01	**
C x N	0.88	0.50	0.17	0.36		0.47	0.93	

[x]Pi, Pm, and Pf are mean nematode values (per 100 cm^3 soil) prior to planting, at midseason (51 and 43 days after planting in 2018 and 2019), and harvest (146 and 141 days after planting in 2018 and 2019), respectively.
[y]Values followed by different letters in the same column are significantly different according to Fisher's LSD at $P \leq 0.05$.
[z]* and ** represent significant effects at $P \leq 0.05$ and $P \leq 0.01$, respectively.

nematicide on peanut yield and nematode control. For example, no significant yield increase nor consistent *M. arenaria* control was achieved with fluopyram nematicide under severe *M. arenaria* pressure and a regular fungicide regime (Grabau *et al.*, 2024). In our study, there was no yield increase in either sod-based or conventional peanut due to fluopyram nematicide application. This result differed from fluopyram nematicide application in cotton in a similar study, where it increased yield inconsistently in conventional cotton but did not provide a yield increase in sod-based cotton (Schumacher *et al.*, 2020). Yet, the plant-parasitic nematode targeted by the fluopyram nematicide – *R. reniformis* – is a more significant pathogen of cotton than is ring nematode of peanut. In another study, fluopyram nematicide increased peanut yield relative to the non-treated control when

Meloidogyne arenaria was present (Grabau *et al.*, 2020). Additionally, Hagan *et al.* (2024) demonstrated a yield increase in peanut (most likely due to leafspot control) but no statistical control of *M. arenaria*. Since peanut is a poor host of *R. reniformis*, and *M. arenaria* was not detected at the study site, it is possible that fluopyram nematicide was less impactful in our experiment than in the aforementioned studies. If no nematode pressure was present, it should be no surprise that there was no nematicide effect.

Cultural management practices like crop rotation are widely adopted by farmers throughout the world. The goal of crop rotation in terms of nematode management is to rotate away from a host of the plant-parasitic nematode to reduce soil population densities before a susceptible crop is grown again (Wright *et al.*, 2018). While there are many different rotation schemes for managing plant-parasitic nematodes, unique rotation systems such as sod-based rotation requires further evaluation. In a similar study, sod-based cotton reduced *R. reniformis* population densities compared to conventional cotton (Schumacher *et al.*, 2020), but sod-based peanut increased ring nematode densities compared to conventional peanut in the present study. Bahiagrass is thus likely a better host for ring nematode than cotton (Tsigbey *et al.*, 2009; Schumacher *et al.*, 2020;). Additionally, reduced disturbance exhibited by this system (i.e., two years of pasture) may have contributed to the success of ectoparasites like ring nematode (Tsigbey *et al.*, 2009). This highlights that crop rotation may reduce densities of some plant-parasitic nematodes in one crop but exacerbate others. Therefore, it is important to determine the risk that different plant-parasitic nematodes pose to their respective host crops.

Many crops can tolerate significant levels of pest damage without a large yield reduction (Carlson and Main, 1976). The concept of an economic threshold was developed to define the critical level of pest damage that calls for crop protection measures as a function of treatment cost (Carlson and Main, 1976). This number varies regionally and does not guarantee that action will result in yield increase, but rather to protect against unwarranted production costs. While ring nematode was present at the site, the population densities were relatively low, rendering its damage potential low as well (Johnson *et al.*, 1999; Grabau and Dickson, 2018;). In a microplot study, 36 ring nematodes per 100 cm^3 soil suppressed peanut yields (Barker *et al.*, 1982). Even though our numbers exceeded this value, ring nematode was clearly not a major yield suppressor in peanut in our study. Our results were consistent with findings by Wheeler and Starr (1987) in which peanut crop damage was not observed.

Nematodes are important regulators of decomposition (Wall *et al.*, 2012). Up to 70% of bacterial and fungal-feeding nematodes occur in the rhizosphere, specifically in the soil located 1-2 mm from the rhizoplane, or root surface (Ingham *et al.*, 1985). Fungivores migrate to pockets of decomposing grass residue (which has a higher C:N ratio than broad-leaf plants) where the concentrations of labile substrates and food sources are high (Griffiths and Caul, 1993). Higher C:N ratios support fungal rather than bacterial decomposition. We saw this reflected by the CI, where both preplant rainfed and irrigated plots had a higher CI following two years in bahiagrass than in the conventional rotation. This was unsurprising since higher values of the CI indicate fungal decomposition and sod-based peanut also shown in this study contained more fungivores than conventional peanut.

Cock *et al.* (2012) suggested that soil invertebrates may be manipulated to benefit agriculture and enhance ecosystem services such as biological control and carbon sequestration. Generally, bacterivores and fungivores are characteristic of disturbed environments while omnivores and predators thrive in more stable environments (Bongers and Bongers, 1998). Environmental disturbance based on non-plant feeding nematode taxa is assessed via MI (Bongers, 1990). Lower values indicated disturbance and/or enrichment while higher values indicate stability. Enrichment stimulates the microbial community and succession and is reflected by a decreased MI followed by its slow increase (Bongers and Ferris, 1999). We did not observe any effects of irrigation, crop rotation, or fluopyram nematicide on the MI or SI in this study. While we expected to see an increased MI and decreased SI in the sod-based peanut due to less soil disturbance in the bahiagrass portion of the rotation, the data did not consistently reflect this.

Many agricultural practices, such as tillage, fertilizer, and pesticide use, may reduce nematode populations, but recovery may be rapid (Timper *et al.*, 2012; Coleman and Wall, 2015). These disturbances can affect nematode abundance and diversity. While not always statistically significant, there was an overall trend that predator population densities were greater in sod-based peanut than conventional peanut. This may be attributed to reduced levels of disturbance in the sod-based rotation (due to the presence of bahiagrass for two years) since predatory nematodes persist in areas without disturbance (Bongers and Ferris, 1999). In terms of fertilizer, Lumactud *et al.* (2010) showed that application of liquid hog manure caused food web enrichment through the addition of soluble carbon, therefore increasing bacterial growth. Like these other studies, the overall numerical trend of greater enrichment in sod-based peanut follows the relative abundance of the lower c-p nematodes (bacterivores and fungivores) on which the EI is based.

Fluopyram nematicide has been available to peanut growers for less than 10 years, and its continued assessment on nematode communities is warranted. Overall, fluopyram nematicide application did not reduce densities of plant-parasitic nor free-living nematodes in peanut plots of both sod-based and conventional rotations. We observed an overall numerical trend that there were fewer free-living nematodes in the fluopyram nematicide-treated plots, yet the results were inconsistent. Similar research demonstrated there were no non-target effects on free-living nematodes after fluopyram nematicide application in peanut production (Grabau *et al.*, 2020; Grabau *et al.*, 2024). However, in cotton plots at the same site as this study, omnivores were always negatively impacted by fluopyram nematicide application (Schumacher *et al.*, 2022). Interestingly, in peanut production, fluopyram use did not negatively impact omnivore population densities like it did in cotton production. This reinforces the idea that crop rotation system is an important factor influencing soil health in relation to nematode community stability and certain crops may be better than others in this regard.

Nematode community structure (i.e., nematode ecological indices) was generally unaffected by fluopyram nematicide application. Limited effects on nematode ecological indices indicate that the three factors evaluated in this study – irrigation, crop rotation, and fluopyram nematicide – had little overall effects on the free-living nematode community. The sod-based and conventional peanut systems had similar impacts on the composition of free-living nematodes. This result was counterintuitive to the thought that sod-based rotation would lead to greater MI and SI than a conventional rotation.

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