RESEARCH/INVESTIGACIÓN

MANAGEMENT OF *MELOIDOGYNE ARENARIA* IN PEANUT PRODUCTION USING RESISTANCE OR NEMATICIDES

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ABSTRACT

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Peanut cultivars resistant to *Meloidogyne arenaria* (peanut root-knot nematode, PRKN), a major plant-parasitic nematode in peanut production, are available, but assessment of modern resistant cultivars relative to nematicide application is needed. In field trials in 2021 and 2022, the PRKN-resistant cultivar TifNV-High O/L [TifNV] was compared with a PRKN-susceptible cultivar in combination with no nematicide [UTC], fluopyram or aldicarb nematicide treatments. TifNV significantly increased peanut yield 39% and 125% relative to UTC in 2021 and 2022, respectively. TifNV also managed PRKN abundances and symptoms, including significantly reducing root system galling at harvest 80% and 99.5% relative to UTC in 2021 and 2022, respectively. Nematicide treatments did not improve yield or consistently manage PRKN abundances or root system galling. Total free-living nematode soil abundances at harvest were significantly reduced by TifNV, with 47% and 49% decrease relative to UTC in 2021 and 2022, respectively. Aldicarb and fluopyram had inconsistent negative impacts on free-living nematodes. In summary, the resistant cultivar TifNV-High O/L was highly effective and better than fluopyram or aldicarb application for managing PRKN and maintaining yield in an environment with severe PRKN pressure.

Key words: Arachis hypogaea, free-living nematode, management, nematicide, *Meloidogyne arenaria*, *Mesocriconema* spp., peanut, peanut root-knot nematode, resistance, ring nematode

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RESUMEN

Z. J. Grabau, R. Sandoval-Ruiz, and C. Liu. 2024. Manejo de *Meloidogyne arenaria* en producción de maní utilizando resistencia o nematicidas. Nematropica 54:1-14.

Cultivares de maní resistentes a *Meloidogyne arenaria* (nematodo agallador del maní, PRKN), un importante nematodo parásito en la producción del maní, están disponibles, pero es necesaria la evaluación de cultivares resistentes modernos relativa a la aplicación de nematicidas. En ensayos de campo en el 2021 y el 2022, el cultivar TifNV-High O/L [TifNV] fue comparado con un cultivar susceptible a PRKN en combinación con no nematicida [UTC] y con los nematicidas fluopyram o aldicarb. TifNV aumentó significativamente el rendimiento de maní en 39% y 125% en relación con UTC en 2021 y 2022, respectivamente. TifNV también manejó la abundancia y los síntomas del PRKN, incluida una reducción significativa del agallamiento radicular en el momento de la cosecha en 80 % y 99,5 % en relación con UTC en 2021 y 2022, respectivamente. Los tratamientos con nematicidas no mejoraron el rendimiento ni controlaron consistentemente la abundancia de PRKN o las agallas del sistema radicular. TifNV redujo significativamente la abundancia total de nematodos de vida libre en el suelo en el momento de la cosecha, con una disminución del 47% y 49% en relación con UTC en 2021 y 2022, respectivamente. Aldicarb y fluopyram tuvieron impactos negativos inconsistentes sobre los nematodos de vida libre. En resumen, el cultivar resistente TifNV-High O/L fue altamente efectivo y mejor que la aplicación de fluopyram o aldicarb para manejar PRKN y mantener el rendimiento en un ambiente con severa presión de PRKN.

Palabras clave: Arachis hypogaea, nematodos de vida libre, manejo, nematicida, *Meloidogyne arenaria*, *Mesocriconema* spp., maní, nematodo agallador del maní, resistencia, nematodo anillado

INTRODUCTION

Meloidogyne arenaria (Neal, 1889) Chitwood 1949, the peanut root-knot nematode (PRKN), is the plant-parasitic nematode that causes the most damage in peanut production in the Southeast United States (Grabau and Timper, 2022). In some field studies, PRKN suppressed yield by nearly 50% (Rodriguez-Kabana and Robertson, 1987; Rodriguez-Kabana *et al*., 1994b), and in one study damage thresholds were 1 egg/100 cm^3 soil, demonstrating its severe damage potential (McSorley *et al*., 1992). Management relies primarily on crop rotation to poor hosts of PRKN (Johnson *et al*., 1999; Davis and Timper, 2000), nematicide application (Grabau *et al*., 2020), and use of resistant cultivars (Holbrook *et al*., 2008, 2017). Adjusting crop rotation typically requires multi-year planning and, in addition to nematode control, involves many other considerations such as crop economics, disease management, and agronomy. In contrast, nematicide application and use of resistant cultivars are management options that can be implemented during a single season with few other changes to operations, making them relatively flexible options.

In peanut production, in-furrow application of non-fumigant nematicides, sometimes followed by an in-season broadcast nematicide application, is the primary chemical nematode management strategy as this method is less expensive than other options (*e.g.*, fumigation). Product cost is an important consideration in peanut production as it has a crop value of $2,606 per hectare based on 2022 United States crop prices and yield estimates (USDA-NASS, 2023a, 2023b). To compare to select high-value crops in the Southeast United States, crop values in 2022 were $16,829 and $19,922 per hectare for tomato (*Solanum lycopersicum*) and watermelon (*Citrullus lanatus*), respectively (USDA-NASS, 2023b, 2023c). Among non-fumigant, conventional nematicides available for application to peanut in the region, oxamyl and aldicarb are carbamate nematicides. Aldicarb has demonstrated some level of PRKN suppression in peanut, although efficacy varies somewhat by year and site, which is not uncommon for non-fumigant nematicides (Rodriguez-Kabana *et al*., 1995; Johnson *et al*., 1999). Oxamyl has some efficacy at managing various root-knot nematode (RKN) species (*Meloidogyne* spp.) in other crops (Grabau *et al*., 2021; Liu and Grabau, 2022), but peer-reviewed, published efficacy data for oxamyl against PRKN in peanut is scarce. Fluopyram is a succinate dehyrodogenase inhibitor nematicide that is also available in peanut and part of a newer generation of nematicides that is generally safer for handlers and the environment than older carbamate and organophosphate nematicides (Desaeger *et al*., 2020). Fluopyram can help manage root-knot nematodes (Dahlin *et al*., 2019; Ji *et al*., 2019), although typically not to the same level as fumigants (Desaeger and Watson, 2019; Grabau *et al*., 2021). In peanut, fluopyram has also had some efficacy at managing PRKN in one year of a field trial, but PRKN pressure was too low for robust evaluation in the other year of study, and more published information is needed (Grabau *et al*., 2020). Fluopyram and other nematicides are applied to a more narrow area, typically as an in-furrow application in peanut and other row crops than in vegetables, which typically receive broadcast, chemigation, or drench applications (Desaeger and Watson, 2019; Grabau *et al*., 2021). Therefore, crop-specific testing of these nematicides is needed.

As described previously, resistant cultivars are the main alternative to nematicide application that allows for flexible, short-term deployment for PRKN management in peanut. Modern resistance to RKN in peanut originates with the cultivar COAN, which derived resistance from *Arachis cardenasii*, and was released in 1999 by Texas Agricultural Experiment Station (Simpson and

Starr, 2001). Since that time, resistance from COAN has been introgressed into various commercial cultivars (Holbrook *et al*., 2008; Branch and Brenneman, 2015; Holbrook *et al*., 2017). Notably, recent RKN-resistant cultivars, starting with 'Tifguard' in 2008 (Holbrook *et al*., 2008), also have some resistance or tolerance to disease caused by Tomato spotted wilt tospovirus (TSWV), a major pathogen in peanut production in the Southeast (Culbreath *et al*., 2008). While resistant cultivars have generally been effective at reducing PRKN symptoms and improving yield relative to susceptible cultivars (Simpson and Starr, 2001; Holbrook *et al*., 2008; Branch and Brenneman, 2015), grower adoption of resistant cultivars has been somewhat limited. Yield potential of resistant cultivars has typically been less than high-performing susceptible cultivars based on grower experiences and variety trial reports (Mailhot *et al*., 2023), which is a barrier to grower adoption. Breeding efforts have sought to improve yield of resistant cultivars so they are more commercially acceptable. 'TifNV-High O/L' is a recent product of these efforts, introduced in 2017 (Holbrook *et al*., 2017) and is a common PRKN-resistant cultivar in the Southeast. Similar to other resistant cultivars, its parentage includes 'COAN' and resistance was confirmed using both molecular marker-assisted selection and phenotyping (Holbrook *et al*., 2017).

In registration release data, 'TifNV-High O/L' was documented to greatly reduce PRKN egg mass production and galling in the greenhouse at a level similar to 'Tifguard' (Holbrook *et al*., 2017). In a field heavily infested with PRKN, 'TifNV-High O/L' as well as 'Tifguard' had substantially greater yield than 'Georgia-06G', a common PRKN-susceptible cultivar (Holbrook *et al*., 2017). However, field data on PRKN reproduction on 'TifNV-High O/L' or management of PRKN soil populations, an important component of season-to-season control, was not included in that report (Holbrook *et al*., 2017) and peer-reviewed information on this topic for PRKN-resistant cultivars in general is needed. Furthermore, comparison of resistant to susceptible cultivars in combination with non-fumigant nematicides under field production conditions is important as these are the primary options for PRKN management during a peanut-growing season. While tests of this nature have been described in abstracts or single-year reports (Hagan *et al*., 2021; Brenneman, 2022), to our knowledge, there are no peer-reviewed, multi-year or multi-site reports comparing resistant cultivars with nematicides in peanut production.

In addition to plant-parasitic nematodes, free-living nematodes are a major constituent of soil communities in agriculture production. Free-living nematodes can provide various ecosystem services such as nutrient cycling (Trap *et al*., 2016), microbe redistribution (Jiang *et al*., 2018), and potentially pest management (Khan and Kim, 2005). Therefore, assessing the impacts of plant-parasitic nematode management practices on non-target free-living nematodes can provide useful information to guide adoption of management practices. Typically, carbamate nematicides such as aldicarb have negative effects on free-living nematodes (Smolik, 1983; Grabau and Chen, 2016; Grabau *et al*., 2018), although aldicarb had minimal effects on free-living nematodes in an on-farm peanut study (Grabau *et al*., 2020). Fluopyram can negatively affect a wide range of free-living nematodes, such as with repeated applications in turfgrass (Waldo *et al*., 2019) or in tomato production (Grabau *et al*., 2021), although in other studies, fluopyram had fewer impacts (Watson and Desaeger, 2019; Grabau *et al*., 2020).

Resistant cultivars, regardless of crop, are presumed to have minimal impacts on free-living nematodes, and other non-target organisms, based on their mechanism of action, but field testing is scarce. In one field study, while either aldicarb application or a resistant soybean cultivar helped manage *Heterodera glycines*, aldicarb, but not the resistant cultivar, reduced free-living nematode abundances (Grabau and Chen, 2016). Field data on non-target effects of non-fumigant nematicides relative to resistant cultivars would provide more information to guide management decisions to minimize environmental impacts. The objectives of this study were to assess a PRKN-resistant peanut cultivar relative to non-fumigant nematicides in combination with a susceptible cultivar for: (1) PRKN management in peanut production, and (2) impacts on non-target, free-living nematodes.

MATERIALS AND METHODS

Field site

To investigate these objectives, field trials were conducted from May to October in 2021 and 2022 at the University of Florida North Florida Research and Education Center-Suwannee Valley near Live Oak, FL (30.304812, -82.897027). The soil is a Chipley-Foxworth-Albany complex (91% sand, 6.8% silt, 2.4% clay, and 1.7% organic matter). The site was naturally infested with PRKN and had been in peanut monoculture with winter small grain cover crops for a number of years. An overhead center-pivot system supplied irrigation for the site.

Experimental design

The experiment was a randomized complete block design with six replicates and five nematicide-cultivar treatments as the single experimental factor. The first 4 treatments were PRKN-susceptible cultivar Georgia-06G in combination with various nematicides: 1) no nematicide (UTC), 2) in-furrow fluopyram (FP), 3) in-furrow and in-season fluopyram (FP+FP) and 4) in-furrow aldicarb (AC). The fifth treatment was the resistant cultivar 'TifNV-High O/L' without nematicide (TifNV). Nematicide rates, timing, and products are described in Table 1. Experimental units were field plots 3.05 m wide by 9.14 m long. Each plot had 4 rows at 76-cm row spacing. Peanuts were planted at 26 seeds/m of row.

Nematicide application

As a liquid, fluopyram was delivered in-furrow via tubes directly onto the seed in the open planting furrow at a total solution application rate of 140 l/ha via a ground wheel-driven system mounted on the planter (John Deere 1706 planter, Deere & Company, IL, USA). Press wheels were located immediately behind the liquid nematicide delivery tubes on the planter and sealed the furrow with soil. As described in Table 1, all treatments except the one containing aldicarb—which has insecticidal activity—received in-furrow imidacloprid for insect control as standard in the region. Granular aldicarb was delivered through tubes into the open furrow as described for fluopyram, except it was dispensed by tractor-chain-driven paddles in the planter-mounted granular box. The day after planting, in both 2021 and 2022, the trial was irrigated (0.76 cm) to facilitate peanut growth and nematicide efficacy. Midseason fluopyram application was done manually using a backpack sprayer at 48 and 41 days after planting in 2021 and 2022, respectively (Table 2). Fluopyram was applied in a band approximately 38.1-cm wide over each row at 108 l/ha total solution application rate. Within 12 hr of application, fluopyram was watered into the soil via 0.76 cm of overhead irrigation. Environmental conditions from before planting until 2 wk after in-season fluopyram application are listed in Table 3 from information recorded by the Florida Automated Weather Network station (https://fawn.ifas.ufl.edu/) at the study site.

Trial establishment and maintenance

Peanuts were planted using the equipment described above in the middle of May each year (Table 2). Peanut seed was pre-coated with fungicides ipconazole, carbathiin, and metalaxyl as standard in the industry for protection against seedling disease. The crop was grown for approximately five months and exact dates for all agronomic and data collection events are provided in Table 2. The crop was managed conventionally

Table 1. Nematicide and peanut cultivar treatments.

Treatment	Peanut cultivar	Nematicide	Nematicide a.i.[x]	Rate (g a.i./ha)	Timing
1. UTC	Georgia-06G	-	-	-	-
2. FP	Georgia-06G	Velum[y]	Fluopyram	237	At planting
3. FP+FP	Georgia-06G	Velum	Fluopyram	237	At planting
		Propulse[y]	Fluopyram	199	Midseason
4. AC	Georgia-06G	AgLogic 15GG[z]	Aldicarb	1,180	At planting
5. TifNV	TifNV-High O/L	-	-	-	-

[x] All treatments except AC received imidicloprid in-furrow at planting (363 g a.i./ha) for insect control. Aldicarb has insecticidal activity, so AC did not receive imidicloprid.
[y] Velum and Propulse are manufactured by Bayer CropScience (St. Louis, MO). Propulse also contains prothioconazole fungicide, and FP+FP received 199 g a.i. prothioconazole/ha.
[z] AgLogic 15GG (AgLogic Chemical Company, Research Triangle Park, NC).

Table 2. Schedule for data collection and trial establishment. Numbers in parentheses are days after planting.

Event	2021	2022
Planting/in-furrow nematicide application	26 May	17 May
Stand count	4 June (9)	2 June (17)
Midseason soil/root sampling	6 July (41)	29 June (44)
Midseason fluopyram application	13 July (48)	27 June (42)
Harvest soil sampling	19 Oct (145)	12 Sep (119)
Harvest root galling rating	19 Oct (145)	3 Oct (139)
Peanut digging	22 Oct (148)	3 Oct (139)
Peanut harvest	26 Oct (152)	5 Oct (141)

according to standard practices in the region (Wright *et al*., 2021) and all fertilizers, fungicides, herbicides, and insecticides were applied uniformly across the entire trial. Strip tillage was used on the field, and small grain cover crops were grown in the winter at the site. Irrigation was supplied as needed via an overhead center-pivot.

Stand and yield assessment

After plants emerged (Table 2), plant stand was assessed by counting all plants in a 3.05-m section of each of the central 2 rows in each plot. At harvest, peanut yield was measured. First, peanut plants were dug and inverted using a tractor-pulled peanut digger-inverter implement (Kelley Manufacturing Company, GA, USA). Peanuts were left in the field to dry for 3-5 days (Table 2). Then peanuts were harvested using a mechanical 2-row KMC combine (Kelley Manufacturing Company, GA, USA) and in-shell peanut yield for each plot was weighed at field moisture. In addition to yield, change in income relative to the mean for untreated control was calculated for each plot and subjected to statistical analysis. This represents the change in income if a grower were to adopt a given practice relative to undertaking no management for PRKN. For each plot, net return (n) was calculated as $n = r – c$, where r was revenue per hectare based on plot yield and peanut price of $0.479/kg, and c was the treatment cost per hectare based on local estimates. In turn, mean net return for UTC (u) was calculated as average n for all plots with UTC treatment. Finally, change in income for each plot (i) was calculated as $i = n – u$.

Quantification of nematodes from roots and root system galling at midseason

At midseason (approximately 6 wk after planting, Table 2), PRKN populations from peanut roots were quantified. From each plot, four plants were dug manually from the outer rows (1st and 4th row of 4-row plots) to avoid compromising central yield rows. Plant roots were covered in soil and stored in bags until transported to a cold storage room to preserve roots and nematodes until extraction the next day. To prepare for extraction, roots were gently washed and laid on paper towels to remove excess moisture. Shoots were cut from roots, and the fresh weight of both parts was recorded. Root galling was also rated on each plant as a visual estimate of the percent root surface covered by galling for each plant (Grabau *et al*., 2021). Nematodes were extracted from roots using a bleach extraction method using a VWR 3500 STD orbital shaker (VWR International, PA, USA) modified from Hussey and Barker (Hussey and Barker, 1973) as described by Sandoval-Ruiz and Grabau (2023).

Soil collection and soil nematode quantification

At midseason, approximately 6 wk after planting, and before harvest (Table 2), soil samples were collected for nematode quantification. At each timing, 12 soil cores of 2-cm diam. were collected intersecting roots in the central two rows of each plot. Samples were homogenized by mixing gently, which was sufficient for the sandy soil at the site. For each plot, nematodes were extracted from 100 cm^3 soil using the sucrose-centrifugation method (Jenkins, 1964). Plant-parasitic nematodes were identified morphologically and quantified using a Zeiss Primovert (Carl Zeiss AG, NY, USA) inverted microscope. In addition to PRKN, ring nematode (*Mesocriconema ornata*) was also present at the field site and was included in analysis. Total free-living nematode abundances were also quantified,

Table 3. Environmental conditions from two weeks before planting to the week after midseason nematicide application 2021 and 2022.

	2021			2022		
		Temperature[w] (°C)			Temperature (°C)	
Time Period[x]	Rainfall[y]	Soil	Air	Rainfall	Soil	Air
2 WBP	0.64	24.9	20.1	1.80	28.3	23.7
1 WBP	0.00	29.1	24.2	3.40	27.6	22.2
Day of planting	0.15	31.6	26.1	0.00	29.2	26.7
1 WAP	0.00	31.2	25.2	2.95	29.6	25.6
2 WAP	1.63	30.7	26.3	1.75	28.7	25.2
3 WAP	1.93	29.6	26.4	4.11	30.7	25.8
4 WAP[z]	7.80	28.8	26.0	2.87	30.7	27.0
5 WAP	1.57	27.1	24.9	0.58	33.5	28.4
6 WAP	11.18	27.7	25.2	2.59	33.3	27.8
7 WAP	1.91	28.8	26.4	2.87	32.3	27.2
8 WAP	1.32	32.2	26.8	1.65	32.2	27.1

[w]Temperatures are mean for the week or day.

[x]WBP and WAP are weeks before and after planting, respectively.

[y]Rainfall (cm) is total for the respective week or day.

[z]Midseason nematicide application was on 48 days after planting (end of 7 WAP) and 42 days after planting (end of 6 WAP) in 2021 and 2022, respectively.

but no taxonomic-level identification was performed.

Statistical analysis

Initially, within each season, each variable was analyzed using a modified 2-way ANOVA for combining experiments. However, because there were important year by treatment interactions, analysis was done separately for each year. For final analysis, variables were analyzed separately for each season and year using a one-way ANOVA. Before analysis, models were checked for homogeneity of residual variances using Levene's Test (Levene, 1960) and for normality graphically (Cook and Weisburg, 1999) to ensure model assumptions were met. Variables were transformed if necessary to meet model assumptions. When there were main effects of treatment ($P < 0.05$), treatment means were separated using Fisher's protected LSD (α=0.05).

RESULTS

PRKN abundances and galling management

In 2022, TifNV ('TifNV-High O/L' PRKN-resistant cultivar) significantly reduced midseason PRKN egg abundances on roots (Fig. 1) relative to UTC or FP. There was a similar, but not statistically significant, trend in 2021 (Fig. 1). At midseason in both years, root surface galling was low (1% or less) and not affected by treatments (Table 4). In 2021 and 2022, TifNV significantly reduced root system galling at harvest relative to all other treatments (Fig. 1), with an 80% and 99.5% reduction relative to UTC in 2021 and 2022, respectively. In 2022, root system galling at harvest was also significantly less for FP+FP than UTC. Treatments did not significantly affect PRKN soil abundances at midseason in 2021 or 2022 (Fig. 2). TifNV, AC, and FP significantly reduced PRKN soil abundances relative to UTC at harvest in 2021 and abundances were also less for TifNV than FP or FP+FP at that time (Fig. 2). In 2022, TifNV significantly reduced PRKN soil abundances at harvest relative to all other treatments, except FP+FP, to which it had similar soil abundances (Fig. 2). TifNV reduced harvest PRKN soil abundances by 87% and 75% relative to UTC in 2021 and 2022, respectively.

Ring nematode abundances

Ring nematode soil abundances were not consistently affected by treatments (Fig. 3). At midseason in 2021, AC significantly reduced ring nematode soil abundances relative to any other treatment. At harvest in 2022, FP+FP or AC significantly reduced ring nematode soil

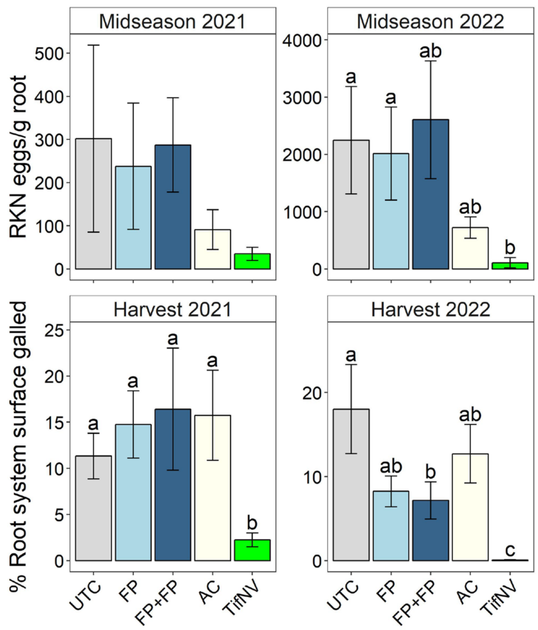

Figure 1. Midseason (41-44 days after planting) and harvest peanut root-knot nematode (RKN) egg population densities on roots and visual rating of percent root surface galled at harvest. Treatment abbreviations: UTC is untreated control, FP is in-furrow fluopyram, FP+FP is fluopyram in-furrow and at midseason (42-48 days after planting), AC is in-furrow aldicarb, and TifNV is 'TifNV-High O/L' root-knot nematode resistant cultivar. Treatment means that have different letters are significantly different based on Fisher's protected LSD (α=0.05). Subfigures without letters did not have significant treatment effects (ANOVA, *P*>0.05).

abundances relative to UTC or TifNV, with FP intermediate. Treatments did not significantly affect ring nematode soil abundances at harvest 2021 or midseason 2022.

Peanut yield and other growth parameters

Peanut yield and income change were significantly greater for TifNV than any other treatment in 2021 and 2022 and there were no other significant differences among treatments (Fig. 4). TifNV increased yield by 39% and 125% relative to UTC in 2021 and 2022, respectively. Plant stand was significantly greater for TifNV than any other treatment in 2021, but least for TifNV and greatest for AC in 2022 (Table 4). Root and shoot weights at midseason were not significantly affected by treatments (Table 4).

Free-living nematode soil abundances

Treatment effects on free-living nematode soil abundances at midseason were not consistent. In 2021, AC significantly decreased midseason free-living nematode soil abundances compared with UTC, FP, or FP+FP with TifNV intermediate (Fig. 5). In 2022, free-living nematode soil abundances at midseason were not significantly affected by treatments. At harvest of both years, free-living nematode soil abundances were significantly less for TifNV than many other treatments (Fig. 5). In 2021, abundances were less for TifNV than UTC or FP and in 2022, abundances were less for TifNV than any other treatment. TifNV decreased free-living nematode soil abundances at harvest by 47% and 49% relative to UTC in 2021 and 2022, respectively. AC also tended to decrease harvest free-living nematode abundances, as AC significantly decreased free-living nematodes abundances relative to UTC in 2021 and AC significantly decreased abundances relative to FP.

DISCUSSION

Using a resistant cultivar, specifically 'TifNV-High O/L', was highly effective for managing PRKN and maintaining yield in environments with severe PRKN pressure. Furthermore, resistance was more effective than fluopyram or aldicarb for managing PRKN. Resistance did not have a consistent statistical effect on management of soil or root PRKN populations at midseason, largely due to high variability in abundances as there were clear numerical trends. However, at harvest, all metrics clearly showed that resistance managed PRKN better than no treatment or the nematicides tested. Galling is often used as a rough measurement of season-long nematode damage, so the substantial reduction in galling by 'TifNV-High O/L' demonstrates its effectiveness against PRKN. Peanut root-knot nematode soil abundances at harvest also indicate that resistance may have carryover benefits for the following crop. Improvement in yield and corresponding income increase are the most important metrics for producers and reflect that the resistant cultivar greatly reduced damage from PRKN.

Consistent with this study, resistant cultivars, including 'TifNV-High O/L', were already reported to manage PRKN, protecting yield

Table 4. Peanut growth parameters and root galling at midseason[w] as affected by nematicide and cultivar treatments.[x]

Treatment[y]	Plants/30 cm	Root weight (g)	Shoot weight (g)	Root surface galling (%)[z]
		2021		
UTC	4.4 b	4.0	29.1	1.04
FP	4.5 b	3.8	29.8	0.83
FP+FP	4.5 b	3.5	26.7	0.38
AC	4.5 b	3.4	28.9	0.83
TifNV	5.1 a	3.7	26.9	0.42
		2022		
UTC	4.1 ab	2.7	29.5	0.42
FP	3.7 c	3.0	26.0	0.83
FP+FP	3.9 bc	3.0	24.2	0.63
AC	4.3 a	2.6	25.3	0.00
TifNV	3.4 d	2.7	26.1	0.00

[w]Plant stand was assessed 9 and 17 days after planting in 2021 and 2022, respectively. All other parameters were assessed 41 and 44 days after planting in 2021 and 2022, respectively.
[x]Values are means of 6 replicates. Letters within a crop, parameter, and run indicate significant differences (Fisher's protected LSD, P<0.05). Values with no letters are not significantly different (ANOVA, P<0.05).
[y]Treatment abbreviations: UTC is untreated control, FP is in-furrow fluopyram, FP+FP is fluopyram in-furrow and at midseason (42-48 days after planting), AC is in-furrow aldicarb, and TifNV is 'TifNV-High O/L' resistant cultivar.
[z]Visual rating of percent root surface galled, mean of 4 plants.

relative to susceptible cultivars without a nematicide (Holbrook *et al.,* 2008, 2017). Comparison of PRKN-resistant peanut cultivars to nematicide application in combination with a susceptible cultivar had not been reported among peer-reviewed sources to our knowledge. However, there are a number of non-peer-reviewed, single-year reports on the subject (Hagan *et al*., 2020; Brenneman, 2021a, 2021b, 2022). Similar to this study, 'TifNV-High O/L' and other resistant cultivars have consistently managed PRKN populations and symptoms, particularly root system galling, in non-peer-reviewed reports, which include two trials in Alabama and five trials in south Georgia (Hagan *et al*., 2020; Brenneman, 2021a, 2021b, 2022). In contrast to this study, in non-peer-reviewed reports, 'TifNV-High O/L' and other resistant cultivars have had mixed impacts on yield. In three trials in south Georgia, 'TifNV-High O/L' increased peanut yield relative to a susceptible cultivar with either fluopyram or no nematicide (Brenneman, 2021b, 2022). However, in two other trials in south Georgia and two trials in Alabama, 'TifNV-High O/L' yielded no better than a susceptible cultivar (Hagan *et al*., 2018, 2020; Brenneman, 2021a, 2021b). Inconsistent yield reports may be due to varying growing conditions in different regions, varying levels of PRKN pressure, and variation in the aggressiveness of PRKN isolates among locations. Further investigation of agronomic performance of resistant cultivars relative to nematicide application in a wider range of environments and under different levels of PRKN pressure would help improve PRKN management decisions in peanut.

There were few differences in efficacy at managing PRKN among nematicides and minimal benefit from the nematicides tested relative to foregoing nematicide. Aldicarb tended to demonstrate better control of PRKN abundances than other nematicides, although this was not consistently statistically significant. Fluopyram did not consistently manage PRKN abundances. None of the nematicides significantly improved yield, although a combination of in-furrow and midseason fluopyram application tended to numerically increase yield and income relative to forgoing nematicide application. In general, this study suggested that under severe PRKN pressure,

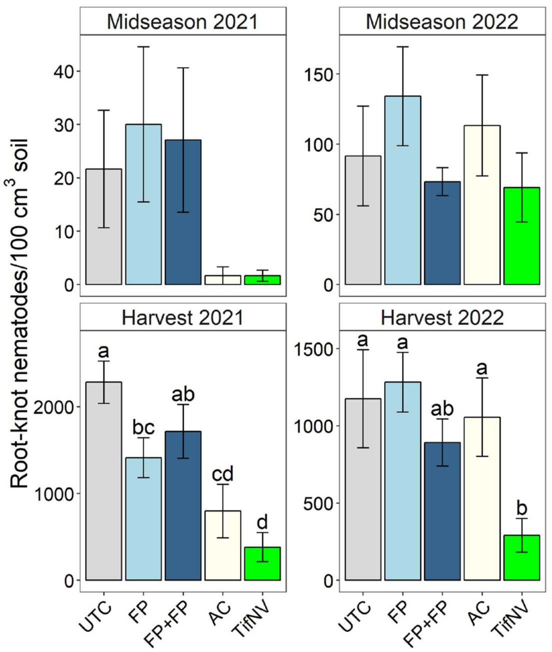

Figure 2. Peanut root-knot nematode soil population densities at midseason (41-44 days after planting) and harvest in 2021 and 2022. Treatment abbreviations: UTC is untreated control, FP is in-furrow fluopyram, FP+FP is fluopyram in-furrow and at midseason (42-48 days after planting), AC is in-furrow aldicarb, and TifNV is 'TifNV-High O/L' root-knot nematode resistant cultivar. Treatment means that have different letters are significantly different based on Fisher's protected LSD (α=0.05). Subfigures without letters did not have significant treatment effects (ANOVA, *P*>0.05).

aldicarb and fluopyram do not provide adequate PRKN management in peanut. As discussed above, resistance is a better option than nematicide application under severe pressure. In prior studies, aldicarb has had some efficacy at managing PRKN populations and yield, but results were inconsistent (Rodriguez-Kabana *et al.*, 1994a, 1994b, 1995; Timper *et al.*, 2001). For example, even in continuous peanut, across four studies in Alabama, aldicarb application increased yield in only 9 of 17 site-years (Rodriguez-Kabana and Robertson, 1987; Rodriguez-Kabana *et al.*, 1994a, 1994b, 1995). In more diverse rotations with lower PRKN pressure, aldicarb has generally had even fewer benefits (Johnson *et al.*, 1999; Timper *et al.*, 2001). Peer-reviewed research on fluopyram management of PRKN in peanut is scarce, but fluopyram has been inconsistently effective in non-peer-reviewed reports (Hagan *et al.*, 2018, 2020; Brenneman, 2021a, 2022).

While this study tested some common nematicides in peanut production in the Southeast, it was not completely comprehensive, and results suggest future research directions. In addition to testing other nematicide chemistries, such as oxamyl, further testing of in-furrow combined with post-plant nematicide application is of interest. In this study, a combination of fluopyram in-furrow and in-season was numerically the most effective nematicide for improving peanut production (increased income by nearly $100/ha), although there were no consistent statistical benefits. This suggests that further testing with other combinations of nematicide chemistries at in-furrow and post-plant timings (*e.g.*, in-furrow aldicarb followed by fluopyram) to improve

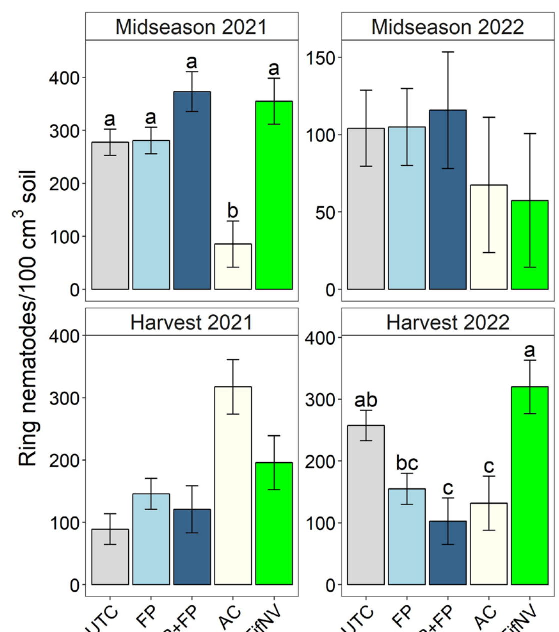

Figure 3. Ring nematode soil population densities at midseason (41-44 days after planting) and harvest in 2021 and 2022. Treatment abbreviations: UTC is untreated control, FP is in-furrow fluopyram, FP+FP is fluopyram in-furrow and at midseason (42-48 days after planting), AC is in-furrow aldicarb, and TifNV is 'TifNV-High O/L' root-knot nematode resistant cultivar. Treatment means that have different letters are significantly different based on Fisher's protected LSD (α=0.05). Subfigures without letters did not have significant treatment effects (ANOVA, P>0.05).

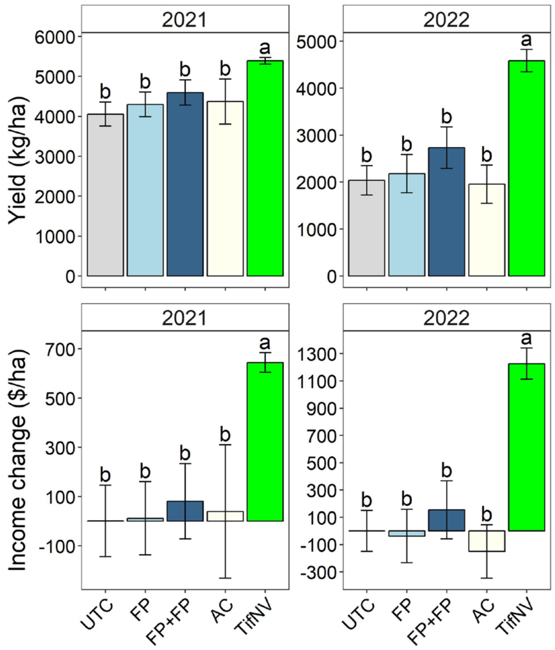

Figure 4. Peanut yield and income change in 2021 and 2022. Income change is difference in income (crop value-product cost for given treatment) from grand mean of UTC. Treatment abbreviations: UTC is untreated control, FP is in-furrow fluopyram, FP+FP is fluopyram in-furrow and at midseason (42-48 days after planting), AC is in-furrow aldicarb, and TifNV is 'TifNV-High O/L' root-knot nematode resistant cultivar. Treatment means that have different letters are significantly different based on Fisher's protected LSD (α=0.05).

management would be warranted. In this study nematicides were applied primarily in-furrow at planting because preventing nematode infection early in the season is typically the most effective method of managing crop damage by nematodes (Liu and Grabau, 2022). However, in some cases, post-plant nematicide application can improve nematode control, such as foliar oxamyl applications to cotton (Lawrence and McLean, 2000, 2002). Peanut pods are initiated in the soil a few weeks after planting, so post-plant nematicide application could be an opportunity to protect new plant growth. Further research in search of an effective post-plant chemistry or methodology is warranted.

In contrast to PRKN management, neither nematicides nor resistance were consistently effective at managing ring nematode. Resistance is typically genera or species specific for a given target nematode (Bendezu and Starr, 2003; Khanal *et al*., 2018), so PRKN-resistant cultivars were not expected to confer resistance to ring nematodes. Aldicarb showed the most efficacy at managing ring nematode populations, with some efficacy in each year, although at different timings (midseason in 2021 and harvest in 2022). There are few studies on ring nematode in peanut, but it is considered a minor parasite of peanut and neither nematicides nor cultivars have consistently managed ring nematode abundances in single-year reports (Brenneman, 2021b, 2022). In this study, there was no clear impact of ring nematode on yield, although the severe pressure from PRKN may have obscured ring nematode impacts.

Final free-living nematode abundances were consistently lower for the resistant cultivar 'TifNV-High O/L' than the susceptible cultivar 'Georgia-

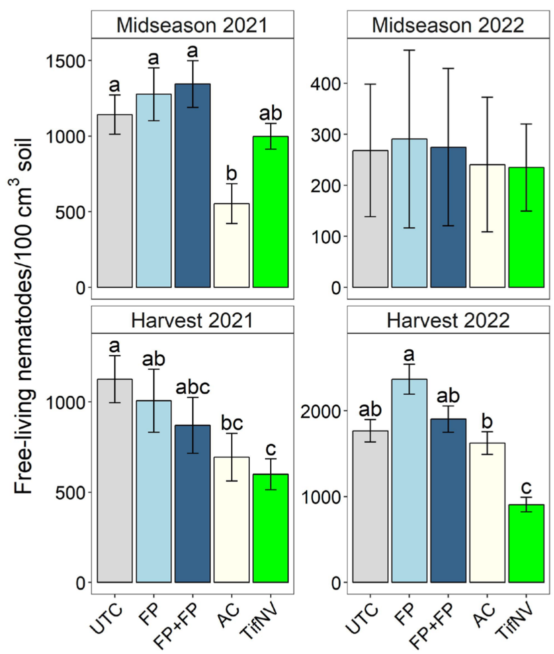

Figure 5. Free-living nematode soil population densities at midseason (41-44 days after planting) and harvest in 2021 and 2022. Treatment abbreviations: UTC is untreated control, FP is in-furrow fluopyram, FP+FP is fluopyram in-furrow and at midseason (42-48 days after planting), AC is in-furrow aldicarb, and TifNV is TifNV-High O/L root-knot nematode resistant cultivar. Treatment means that have different letters are significantly different based on Fisher's protected LSD (α=0.05). Subfigures without letters did not have significant treatment effects (ANOVA, P>0.05).

06G' without nematicide application. The mechanism by which this resistant cultivar negatively impacted free-living nematode abundances is not clear. Therefore, this result should be interpreted with caution and more investigation is warranted to support or refute this result and understand the underlying mechanism. A potential area of investigation is root exudates and related rhizosphere microbial community. It is plausible that a susceptible cultivar under PRKN infection would release root exudates of a different quality or quantity than a resistant cultivar. In turn, that could affect the soil microbial community and, the free-living nematode community. For example, peanut cultivars with varying levels of resistance to Fusarium pathogens differed in the components and contents of their root exudates (Li *et al*., 2013). Similarly, cotton cultivars with varying levels of susceptibility to *Verticillium dahlia* also varied in their rhizosphere and endosphere (inside of root) microbiomes (Wei *et al*., 2019). Classically, Van Gundy *et al*. (1977) demonstrated that infection by *Meloidogyne incognita* altered tomato root exudate chemical composite, and in turn these exudates can alter progression of disease caused by the fungus *Rhizoctonia solani*. So, from related systems, there is some evidence to support the proposed hypothesis, but investigation of this specific scenario (PRKN-resistant and susceptible peanut cultivars) would be needed and is beyond the scope of this study. Furthermore, only total free-living nematode abundances were measured in this study, but individual trophic groups and genera are known to vary in their responses to agronomic practices (Fiscus and Neher, 2002; Grabau and Chen, 2016; Grabau *et al*., 2020). Further investigation at more precise taxonomic and trophic resolution would be useful to better understand and interpret this phenomenon. From a practical perspective, short-term benefits of the resistant cultivar outweighed negative impacts on free-living nematodes as production was much improved by the resistant cultivar.

There were not consistent impacts of nematicides on free-living nematode abundances, although aldicarb negatively impacted abundances in 2021. Both fluopyram and aldicarb have been shown to have negative impacts on free-living nematodes in other studies (Smolik, 1983; Grabau and Chen, 2016; Waldo *et al*., 2019; Grabau *et al*., 2021), although the scope varies by situation (Watson and Desaeger, 2019; Grabau *et al*., 2020). Impacts may vary based on the rate, timing, and application method, and the total nematicide a.i. received and field area treated was relatively lower in this study, and row crops in general, than in other cropping systems. As discussed above, because free-living nematodes were not resolved taxonomically or trophically, there may have been unquantified nematicide impacts on free-living nematodes in this study.

In conclusion, under severe PRKN pressure, a resistant cultivar ('TifNV-High O/L') is highly effective for maintaining peanut production and is a more effective option than aldicarb or fluopyram nematicides in combination with a susceptible cultivar ('Georgia-06G'). Ring nematode was not consistently managed by either a resistant cultivar or nematicide application, and PRKN management was a much more important factor in peanut production. The resistant cultivar 'TifNV-High O/L' had negative impacts on free-living nematodes, which warrant further investigation for validation and to understand the underlying mechanism.

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