Root-knot Control and Yield Response of Corn with Seed Treatment and Granular Nematicides

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ABSTRACT

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In Coastal Plain soils of the southeastern United States, the root-knot nematode (RKN) *Meloidogyne incognita* race 3 causes significant yield loss in corn. Impact of abamectin + thiamethoxam and clothianidin + *Bacillus firmus* I-1582 nematicide seed treatments along with terbufos granular nematicide on RKN reproduction, plant populations, plant growth, and yield was assessed at two Alabama sites. Thiamethoxam and clothianidin insecticide seed treatments were included as controls. A factorial arranged as split-split plot with year as the main plot, seed treatment as the split plot, and granular nematicide as the split-split-plot treatment was used. Lower plant populations were noted for terbufos-treated corn at one study site. Reduced RKN reproduction was observed with terbufos granular nematicide at both study sites. Fresh seedling weights and yields were usually higher for the terbufos- than non-terbufos-treated corn. At both sites, both nematicide seed treatments and their insecticide seed treatment counterparts had similar plant populations, RKN reproduction rate, and fresh seedling weights. Yield differences were noted at both locations between abamectin + thiamethoxam and thiamethoxam but not clothianidin + *Bacillus firmus* I-1582 and clothianidin. With mean yield gains up to 13.5%, terbufos was superior to both of the nematicide seed treatments for managing RKN and protecting corn yields.

INTRODUCTION

Alabama's corn crop, which had a farm-gate value of $172 million on 115,300 ha in 2014 (NASS 2015), is commonly rotated with cotton (*Gossypium hirtsutum* L.), peanut (*Arachis hypogea* L.), and soybean (*Glycine max* (L.) Merr.). All four crops are hosts of one or more species of root-knot nematode (RKN) (*Meloidogyne* spp.) (Sassar and Carter 1982). Corn (*Zea mays* L.) is a host of *M. incognita* (Kofoid & White) Chitwood) race 3 (Davis and Timper 2000; Ibrahim et al. 1993) and race 4 (Williams and Windham 1988), but not race 1 or 2 of either *M. arenaria* or *M. incognita* (Ibrahim et al. 1993). Where cotton is produced in the United States on Coastal Plain soils, *M. incognita* race 3 is the dominant species of *Meloidogyne* (Davis and Timper 2000; Kirkpatrick and Sasser 1983). The 30% reduction of anticipated yield of corn attributed to RKN that was proposed by Gazaway et al. (1991) was confirmed by Bowen et al. (2008), who reported a 4 to 11% yield decline for every 100 (J2) juveniles/100 cc soil when soil assay juvenile counts from the preceding year ranged between 300 and 900. In greenhouse trials, Davis and Timper (2000) reported that a number of then-available commercial corn hybrids supported high levels of reproduction of *M. incognita* race 3. While significant differences in final juvenile counts were noted between multiple commercial hybrids in an Alabama field trial, all supported a high level of RKN reproduction (Hagan et al. 2012a).

Limited information is available concerning the impact of nematicides on RKN control and corn yield response. Johnson and Wright (1980) reported an increase in corn growth, but not a reduction in *M. incognita* juvenile counts or yield gains from in-furrow and banded applications of terbufos (Counter 15G) or aldicarb (Temik 15G). In contrast, significant yield gains and reduced root gall indices but not juvenile counts were observed in consecutive years with fenamiphos (Nemacur 15G) (Johnson et al. 1999). In recent years, yield gains up to 1.9 MT/ha (30 bu/acre) have been obtained in Alabama and Mississippi with terbufos on corn planted in *M. incognita* race 3-infested fields (Hagan et al. 2012a; Hagan et al. 2012b; Lawrence et al. 2009; Lawrence et al. 2010a; Lawrence et al. 2010b).

The seed treatment nematicide + insecticide abamectin + thiamethoxam (Avicta Duo Corn) gives early-season protection from plant-parasitic nematodes on corn. In Alabama (Lawrence et al. 2009) and Mississippi (Lawrence et al. 2010b), yield gains with this nematicide seed treatment matched those obtained with terbufos, but no reductions in *M. incognita* juvenile counts were noted in either study.

Selected soil bacteria, including *Bacillus firmus* I-1582, have antagonistic activity against plant-parasitic nematodes (Sikora 1988). Bioactive compounds in *B. firmus* I-1582 (VOTiVO) culture filtrates reduce egg hatching as well as cause paralysis and mortality of burrowing (*Radopholus similis* Cobb), stem (*Ditylenchus dipsaci* Kühn), and root-knot (*M. incognita* race 3) nematodes (Mendoza et al. 2008). Giannakou et al. (2007) noted that *B. firmus* destroyed *M. incognita* eggs in an egg mass, but proved most effective on cucumber (*Cucumis sativus* L.) when combined with soil solarization. On hybrid bermudagrass (*Cynodon dactylon* (L.) Pers.), Crow (2014) reported that *B. firmus* I-1582 enhanced root growth and decreased sting nematode (*Belonolaimus longicaudatus* Rau) populations compared with a non-treated control. While Jackson and Behm (2010) failed to see

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any reduction in lesion (*Pratylenchus scribneri* Steiner) nematode populations on corn with *B. firmus* I-1582 formulated as VOTiVO nematicide seed treatment, Guilhabert-Goya (2014) reported average yield gains of 0.25 to 0.31 MT/ha (4 to 5 bu/acre) with clothianidin + B. firmus I-1582 in corn.

The objective of these studies was to compare the effectiveness of terbufos (Counter 20G) granular nematicide with abamectin formulated with the insecticide thiamethoxam (Avicta Duo Corn) and the bionematicide *B. firmus* I-1582 formulated with the insecticide clothianidin (Poncho VOTiVO) seed treatments for the management of RKN and assess their impact on corn yield.

SEED TREATMENT AND GRANULAR NEMATICIDES FOR CORN COMPARED AT TWO ALABAMA SITES

Studies were conducted at the Brewton Agricultural Research Unit (BARU), which is located 72 km northeast of Pensacola, FL, and the Plant Breeding Unit (PBU), which is located 40 km northeast of Montgomery, AL. Soil fertility at both locations was adjusted according to the results of a soil fertility assay conducted by the Auburn University Soil Testing Laboratory. At BARU, weed control was obtained by a preplant-incorporated application of 0.63 liter/ha S-metolachor (Dual Magnum II, Syngenta Crop Protection, Greensboro, NC) followed by post-emergence applications of 0.5 gal/acre atrazine (Atrazine, Drexel Chemical Co., Memphis, TN) + 0.47 liter/ha S-metolachor, while a pre-plant-incorporated application of 0.47 liter/ha metolachor followed a broadcast application of 0.65 liter/ha glyphosate (Roundup WeatherMax, Monsanto Co., St. Louis, MO) at PBU. A fungicide seed treatment containing fludioxonil + mefenoxam + azoxystrobin + thiabendazole (Maxim Quattro, Syngenta Crop Protection) was applied to all seed at a rate of 15.8 ml/80,000 seed. The experimental design was a factorial arranged in a split-split plot with year as the whole plot, seed treatments thiamethoxam at 40 g a.i./80,000 seed (Cruiser 5FS, Syngenta Crop Protection), abamectin + thiamethoxam at 17.7 + 40 g a.i./80,000 seed (Avicta Duo Corn, Syngenta Crop Protection), clothianidin at 40 g a.i./80,000 seed (Poncho 600, Bayer CropScience, Research Triangle Park, NC), and clothianidin + *B. firmus* I-1582 at 40 g a.i. + 272 mg/80,000 seed (Poncho VOTiVO, Bayer CropScience) as the split-plot and terbufos (Counter 20G, AMVAC Chemical Corp., Los Angeles, CA) granular nematicide applied in-furrow at planting at 1.46 kg a.i./ha or non-terbufos treated control as the split-split plot treatments. Individual experimental units consisted of four 7.6-m rows on 0.76-m (PBU) or 0.9-m (BARU) centers in six replications. Yields were taken from the two center rows and are reported at 15.5% moisture.

The BARU study site [Benndale sandy loam (coarse-loamy, siliceous, semiactive, thermic Typic Paleudults)], which has a resident population of *M. incognita* race 3, was prepared for planting with a disk harrow and finished with a ripper bedder. A broadcast pre-plant application of 287 kg/ha (51 kg actual N per ha) of 20-60-60-10S analysis fertilizer on 15 March 2013 and 11 March 2014 was followed with applications of 200 kg/ha (67 kg actual N per ha) of 30-0-0 analysis fertilizer on 6 May and 20 May 2013; and 23 April, 6 May, and 19 May 2014. Armor 704 VT2 hybrid corn (Armor Seed Company, Fisher, AR) was sown at a rate of 71,955 seed/ha on 10 April 2013 and 26 March 2014. The study site received a total of 7.5 cm water/ha in 2013 and 2014 via a lateral irrigation unit. A broadcast application of 657 ml/ha pyraclostrobin (Headline 2.09SC, BASF Ag Products, Research Triangle Park, NC) + 292 ml/ha tebuconazole (Muscle 3.6F, SipcamAdvan, Durham, NC) was made on 1 July 2014 for southern rust (*Puccinia polysora* Underw.) management. Plots were mechanically harvested on 27 August 2013 and 26 August 2014.

The PBU study site [Independence (Cahaba) loamy fine sand (fine-loamy, siliceous, semiactive, thermic Typic Hapludults)], which has resident population of *M. incognita* race 3 (Bowen et al. 2008), was prepared for planting with a chisel and disk harrow. Augusta A0606GT hybrid corn (Augusta Seed, Staunton, VA), which was sown in 2012, was replaced with Armor 704 VT2 hybrid corn in 2013 and 2014. Planting dates were 10 April 2012, 9 April 2013, and 3 April 2014. Seeding rate was 70,800 seed/ha. Broadcast applications of 260 kg/ha (80 kg actual N per ha) of 33-0-0-10S analysis fertilizer were made on 9 April and 10 May 2012, 6 and 24 April and 28 May 2013, and 2 April and 28 May 2014. The study site received a total of 11.4 and 1.9 cm/ha water in 2012 and 2013, respectively, via a center-pivot irrigation system, but was not irrigated in 2014. Plots were mechanically harvested on 16 August 2012, 26 August 2013, and 20 August 2014.

Stand counts were taken in 2013 and 2014 at both study sites approximately 30 days after planting from one of two border rows. From the center two yield rows at PBU, initial ($P^{initial}$) soil samples consisting of ten 2.5-cm-diameter cores 10 cm in length for a nematode assay were collected on 16 May 2012, 8 May 2013, and 19 May 2014, while final (P^{final}) soil samples were taken on 23 August 2012, 23 August 2013, and 5 August 2014. Initial ($P^{initial}$) soil samples for a nematode assay were collected at BARU on 1 May 2013 and 23 May 2014 with final samples being taken on 22 August 2013 and 27 August 2014. For each sampling period, the reproduction ratio was calculated by dividing P^{final}/$P^{initial}$ *M. incognita* race 3 juvenile counts. Soil samples for a nematode assay were processed using the sugar flotation method (Jenkins 1964), where 50 cc of soil was added to 700 ml distilled water, poured through a #25 and #400 sieve into a test tube, and centrifuged for 5 min. The supernatant was then decanted, the pellet suspended in 40 ml of a 50% v/v sugar solution, and centrifuged for 2 min. After decanting the sugar solution through #40 and #400 sieves, the rinse material on the screens of both sieves was washed into a petri dish with sufficient water to cover the plate bottom and the nematodes were counted with a low-power microscope. On 3 July 2012, corn stalks at PBU were cut at tasseling from 1.5 m of row from a border row 2 cm above the soil surface, weighed wet, oven dried for 48 h at 80°C, and weighed to determine dry-weight yield. Fresh weights of 10 seedlings randomly collected from the border rows of each plot at each study site were recorded on 18 May 2013 and 19 May 2014 at PBU, and 6 May 2014 at BARU. Automated weather stations (Campbell Scientific, Logan, UT) at both study locations were used to collect weather data.

Analyses of interactions were done using the PROC GLIMMIX procedure in SAS v 9.2 (2013; SAS Institute Inc., Cary, NC) with the ddfm=satterthwaite option with year, seed treatment, and granular nematicide as fixed effects and year, replication-year, replication-seed treatment (year), and replication, seed treatment-granular nematicide (year) as random effects. Statistical analyses were done on rank transformations of plant population, root-knot reproduction rate, and plant/seedling weight data to normalize variances, which were back-transformed for presentation. Means were separated using Fisher's protected least significant difference (LSD) test at $P \leq 0.05$ unless otherwise indicated at $P \leq 0.10$.

YEAR AND TREATMENT EFFECTS ON PLANT POPULATIONS, SEEDLING WEIGHT, RKN REPRODUCTION, AND CORN YIELD BY STUDY SITE

BARU. In 2014, plant population was not impacted by seed treatment or granular nematicide (Table 1) with similar plant populations recorded for all insecticide seed treatments and nematicide seed treatments as well as the terbufos- and non-terbufos treated corn (Table 2). While year and seed treatment failed to impact RKN reproduction rate, a significant year × granular nematicide interaction segregates data by year and granular nematicide treatment. Similar levels of RKN reproduction were noted for all nematicide and corresponding insecticide seed treatments (Table 2). While the terbufos- and non-terbufos-treated controls had similar RKN reproduction values in 2013, a greater reproduction rate was recorded in 2014 for the latter than former treatment (Fig. 1). In both study years, RKN reproduction rate was similar for the non-terbufos and terbufos-treated corn.

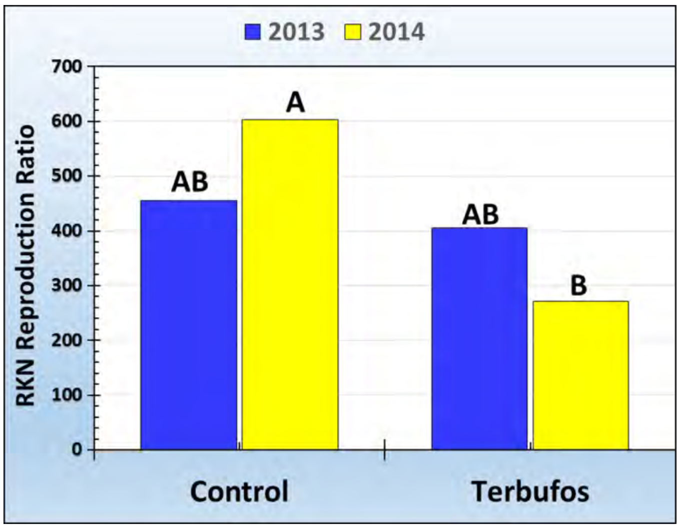

FIGURE 1

Year and nematicide impact RKN reproduction at BARU in 2013 and 2014. Different letters above bars indicate significant differences using Fisher's protected least significant difference test ($P \leq 0.05$).

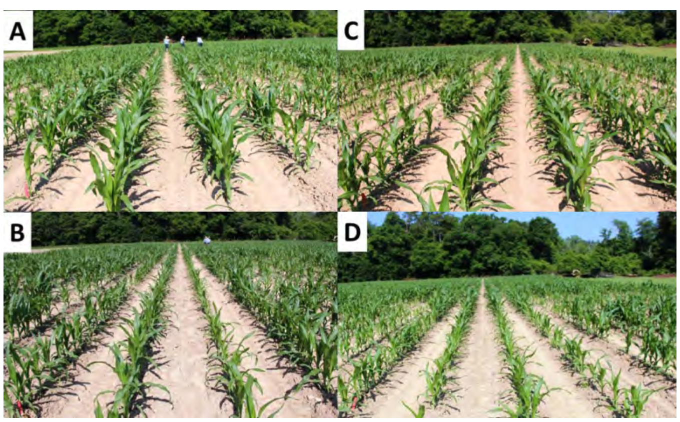

FIGURE 2

Illustration of growth response of corn at BARU in 2014 treated with (**A**) abamectin + thiamethoxam nematicide seed treatment + terbufos granular nematicide compared with (**B**) abamectin + thiamethoxam nematicide seed treatment alone and (**C**) clothianidin + B. firmus I-1582 nematicide seed treatment + terbufos granular nematicide compared with (**D**) clothianidin insecticide seed treatment alone.

In 2014, seedling fresh weight varied by granular nematicide, but not either nematicide and corresponding insecticide seed treatment (Table 1). With a non-significant seed treatment × granular nematicide interaction, data were pooled. Similar seedling fresh weights were recorded for the nematicide and corresponding insecticide seed treatments (Table 2). In contrast, seedling fresh weight values, which were significantly higher for the terbufos- than non-terbufos-treated controls, were reflected in increased plant size and darker-green foliage color (Fig. 2A-D).

The significant interaction for year, seed treatment, and granular nematicide ($P \leq 0.10$) showed that yields differed by seed treatment and granular nematicide over time (Table 1). In 2013, similar yields were recorded across the non-terbufos and terbufos-treated corn with each insecticide and corresponding nematicide seed treatment (Table 3). In contrast, significant yield gains were obtained with terbufos compared with the non-terbufos treated control with thiamethoxam and chlothiandin insecticide seed treatments as well as clothianidin + *B. firmus* I-1582, but not the abamectin + thiamethoxam nematicide seed treatments. Regardless of the seed and granular nematicide treatment, yield was greater in 2014 than 2013.

PBU. While plant populations were significantly impacted by year, seed treatment, and granular nematicide, no interactions between the above variables were noted, so data were pooled (Table 4). Despite similar seeding rates, greater plant populations were noted in 2013 than 2014 (Table 5). Mean plant populations for the thiamethoxam and chlothiandin insecticide seed treatments and abamectin + thiamethoxam and clothianidin + *B. firmus* I-1582 nematicide seed treatments were similar. However, lower plant populations were recorded for the terbufos granular nematicide than the non-terbufos treated control.

In 2012, dry stalk weight was not impacted by nematicide or insecticide seed treatments, or by granular nematicide (*data not presented*). In contrast, a significant year × seed treatment and seed treatment × granular nematicide interactions were recorded for seedling fresh weight (Table 4). In 2013, seedling fresh weight values were greater for clothianidin + *B. firmus* I-1582 than for either of the insecticide seed treatments but not abamectin + thiamethoxam, which also had higher seedling fresh weights than the thiamethoxam insecticide seed treatments (Fig. 3). Among the nematicide seed treatments in 2014, greater fresh weights were recorded for abamectin + thiamethoxam than clothianidin + *B. firmus* I-1582, while both insecticide seed treatments had intermediate seedling fresh weights. Over the two-year period, similar seedling fresh weights were recorded for both insecticide seed treatments and abamectin + thiamethoxam, while greater seedling fresh weights were noted for clothianidin + *B. firmus* I-1582 in 2013 than 2014. Greater mean seedling fresh weights were noted over both study years for terbufos granular nematicide compared with non-terbufos treated corn (Fig. 4).

RKN reproduction rate differed by study year and granular nematicide but not insecticide or nematicide seed treatments (Table 4). Similarly greater overall RKN reproduction rates were noted in 2012 and 2014 as compared with 2013 (Table 5). While the insecticide and nematicide seed treatments had similar RKN reproduction rates, lower reproduction rates were noted for the terbufos- than non-terbufos-treated corn ($P \leq 0.10$).

Yield at PBU was significantly impacted by year, seed treatment, and granular nematicide (Table 4). After peaking in 2012, a significant yield decline was noted in the following two years with the lowest yields recorded in 2014 (Table 5). Equally greater mean yields were noted for the abamectin + thiamethoxam

TABLE 1
***F* values for generalized linear models for effects of year, seed treatment, and granular nematicide on RKN reproduction, fresh seedling weight, and yield in 2013 and 2014 at BARU.**

Source of variation (*F* values)	Plant population[x]	RKN reproduction rate	Fresh seedling weight	Yield
Year	—	0.00	—	310.66***
Seed Treatment	1.66[y]	0.72	1.94	0.19
Year × Seed Treatment	—	0.28	—	2.50^
Granular Nematicide	2.68	7.52**	172.43***	23.57***
Year × Granular Nematicide	—	3.26*	—	4.99*
Seed Treatment × Granular Nematicide	1.47	1.01	1.15	2.02
Year × Seed Treatment × Granular Nematicide	—	0.94	—	2.23^

[x] Data collected in 2014 only.
[y] Significance at 0.10, 0.05, 0.01, and 0.001 levels is indicated by ^, *, **, and ***, respectively.

TABLE 2
Impact of seed and granular nematicide treatments on plant populations, RKN reproduction, and seedling fresh weight at BARU.

Treatments	Plant population (plants/ha)[w]	RKN reproduction ratio[x]	Seedling fresh weight (g)[wy]
Seed treatment and rate per 80,000 seed			
Thiamethoxam 40 g a.i.	60,037 a[z]	428 a	82 a
Abamectin + thiamethoxam 17.7 + 40 g a.i.	61,116 a	374 a	88 a
Clothianidin 40 g a.i.	62,193 a	581 a	82 a
Clothianidin + *B. firmus* I-1582 40 g a.i. + 272 mg	65,790 a	369 a	74 a
Granular nematicide and rate/ha			
Non-terbufos treated control	63,990 a	—	57 b
Terbufos 1.46 kg a.i.	61,116 a	—	105 a

[w] Data collected in 2014 only.
[x] RKN reproduction ratio = $(P^{final}+1)/(P^{initial}+1)$.
[y] Corn seedlings collected on 6 May 2014.
[z] Means in each column that are followed by the same letter are not significantly different according to Fisher's protected least significance (LSD) test ($P \leq 0.05$).

Table 3
Interaction of year, seed treatment, and granular nematicide on corn yield at BARU.

	Yield (MT/ha)			
	2013		2014	
Seed Treatment and rate/80,000 seed	Control	Terbufos	Control	Terbufos
Thiamethoxam 40 g a.i.	7.44 cd[x]	7.44 cd	9.30 b	9.86 a
Abamectin + thiamethoxam 17.7 + 40 g a.i.	7.38 cd	7.87 cd	9.24 b	9.24 b
Clothianidin 40 g a.i.	7.38 cd	7.75 c	8.80 b	10.17 a
Clothianidin + *B. firmus* I-1582 40 g a.i. + 272 mg	7.07 d	7.38 cd	9.05 b	10.42 a

[x] Means that are followed by the same letter are not significantly different according to Fisher's protected least significance (LSD) test ($P \leq 0.10$).

TABLE 4 F values for generalized linear models for effects of year, seed treatment, and granular nematicide on stand count, root-knot reproduction, seedling weight, and yield in 2012, 2013, and 2014 at PBU.					
Source of variation (*F* values)	Plant population[x]	Root-knot reproduction rate	Dry stalk weight[y]	Fresh seedling weight[x]	Yield
Year	7.90**[z]	13.38***	—	177.72***	200.01***
Seed Treatment	2.25^	0.31	0.28	3.42*	3.38*
Year × Seed Treatment	0.19	0.56	—	3.07*	0.38
Granular Nematicide	12.73***	3.16^	0.06	27.05***	33.52***
Year × Granular Nematicide	1.98	2.32	—	3.31	0.03
Seed Treatment × Granular Nematicide	0.79	0.12	0.31	0.63	1.22
Year x Seed Treatment × Granular Nematicide	0.05	0.73	—	0.85	0.73

[x] Data collected in 2013 and 2014.
[y] Data collected in 2012.
[z] Significance at 0.10, 0.05, 0.01, and 0.001 levels is indicated by ^, *, **, ***, respectively.

TABLE 5 Stand count, RKN reproduction rate, and yield of corn as impacted by seed treatments and a granular nematicide at PBU.			
	Population (plants/ha)[w]	RKN reproduction ratio[x]	Yield (MT/ha)[y]
Year			
2012	—	245 a	9.91 a
2013	68,662 a[z]	42 b	8.22 b
2014	65,049 b	211 a	6.14 c
Seed dressing, rate per 80,000 seed			
Thiamethoxam, 40 g a.i.	65,393 a	145 a	7.65 b
Abamectin + thiamethoxam, 17.7 + 40 g a.i.	67,630 a	154 a	8.15 a
Clothianidin, 40 g a.i.	69,178 a	184 a	8.22 a
Clothianidin + *B. firmus* I-1582, 40 g a.i. + 272 mg	65,049 a	180 a	8.28 a
Granular nematicide and rate/ha			
Non-terbufos treated control	69,178 a	196 a	7.65 b
Terbufos, 1.46 kg a.i.	64,533 b	135 b	8.53 a

[w] Plant population = number of plants per hectare.
[x] RKN reproduction ratio = $(P^{final}+1)/(P^{initial}+1)$.
[y] Mean yields presented at 15.5% moisture.
[z] Means in each column that are followed by the same letter are not significantly different according to Fisher's protected least significance (LSD) test ($P \leq 0.05$), except for the reproduction ratio for the granular nematicide ($P \leq 0.10$).

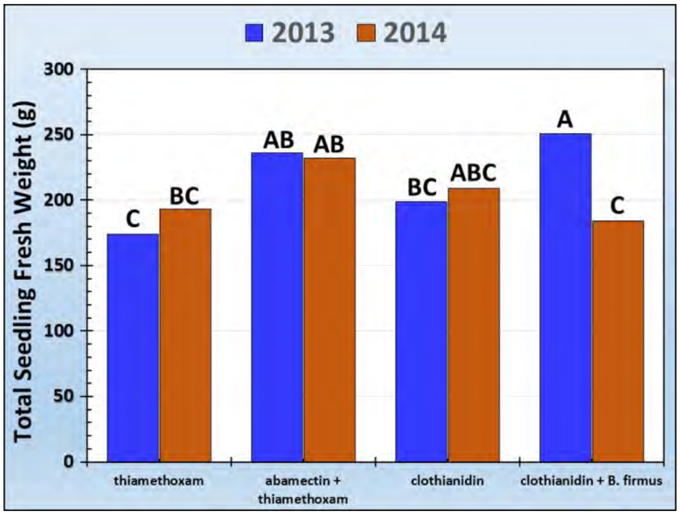

FIGURE 3

Total seedling fresh weight as influenced by year and seed treatment in 2013 and 2014 at PBU. Different letters above bars indicate significant differences using Fisher's protected least significant difference test ($P \leq 0.05$).

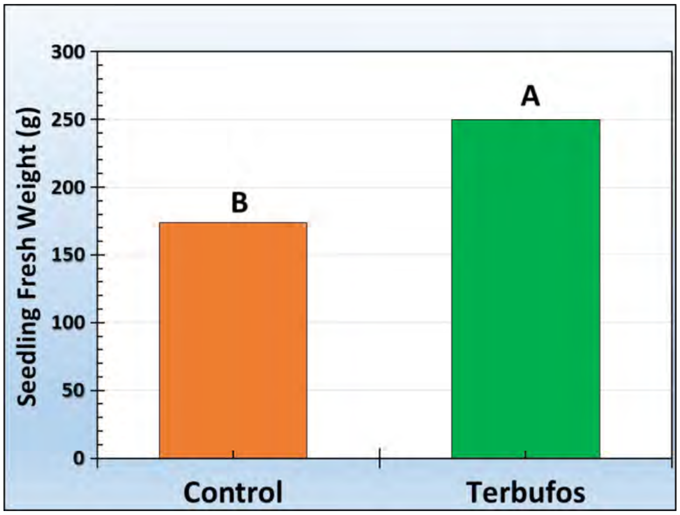

FIGURE 4

Total seedling fresh weight as influenced by granular nematicide treatment at PBU. Different letters above bars indicate significant differences using Fisher's protected least significant difference test ($P \leq 0.05$).

and clothianidin + *B. firmus* I-1582 along with the clothianidin compared with thiamethoxam. A significant yield gain was also obtained with terbufos than for the non-terbufos treated control.

IMPLICATIONS FOR RKN MANAGEMENT ON CORN IN THE SOUTHERN COASTAL PLAIN

While corn has long been recognized as a reproductive host for *M. incognita* race 3 (Davis and Timper 2000; Ibrahim et al. 1993), Bowen et al. (2008) only recently established that RKN significantly reduces yield, when corn is rotated with cotton on Coastal Plain soils found across much of the southern U.S. cotton belt (Koenning et al. 1996). As a result, limited information has been available concerning the efficacy of nematicides for managing RKN in corn. We showed that terbufos granular nematicide reduced the rate of *M. incognita* reproduction on corn, which was reflected in greater seedling fresh weights ranging up to 45% and yield gains of 0.9 to 1.4 MT/ha in studies at two Alabama locations in 2012, 2013, and 2014. While several studies (Hagan et al. 2012b; Lawrence et al. 2009; Lawrence et al. 2010a; Lawrence et al. 2010b) previously reported similarly high yield gains in corn in *M. incognita* race 3-infested fields with terbufos, Johnson and Wright (1980) also noted increases in the stalk weight of corn treated with this nematicide. Additionally, Lawrence et al. (2009) reported an increase in fresh root weight with terbufos. A reduction in plant population was, however, noted here at one of two study locations with terbufos. Phytotoxic effects on seedling emergence were previously reported with terbufos on pearl millet (Kennedy 2002) and reduced plant growth for no-till, non-irrigated grain sorghum (Matocha 1990), as well as a phytotoxic interaction with in-furrow applications of this insecticide to corn following the broadcast application of a sulfonylurea herbicide (Biediger et al. 1992). However, neither of the soil-applied residual herbicides (S- metolachlor or atrazine) used in this study were observed to have a phytotoxic interaction such as reduced top fresh weights or leaf chlorosis with terbufos, so the cause of the reduced plant populations in terbufos-treated corn is unknown.

In contrast to terbufos, abamectin + thiamethoxam and clothianidin + *B. firmus* I-1582 nematicide seed treatments failed to increase seeding fresh weight, or limit RKN reproduction when compared with their respective companion insecticide seed treatments thiamethoxam and clothianidin. Plant populations also were similar for all of the above seed treatments. Greater yields obtained with abamectin + thiamethoxam compared with thiamethoxam alone were noted at PBU but not BARU, where lower yields were recorded for the former nematicide seed treatments than the latter insecticide seed treatments. In contrast, Lawrence et al. (2010a) reported significant yield gains in corn with abamectin + thiamethoxam compared with thiamethoxam as well as terbufos, both of which had similarly lower yields. The erratic yield response observed with abamectin + thiamethoxam in corn has also been observed in cotton (Erwin et al. 2008). Early-season soil moisture levels may influence abamectin + thiamethoxam efficacy on corn. Wheeler et al. (2013) noted that abamectin + thiamethoxam nematicide seed treatments efficacy improves with increasing soil moisture, thereby enhancing abamectin redistribution from the seed coat, where toxicant concentrations are highest, to the radical of the cotton seedling (Faske and Starr 2007). Here, however, abamectin + thiamethoxam nematicide seed treatments failed to boost corn yields regardless of early-season moisture levels (Fig. 5) at both study sites over multiple years. The absence of any yield increase with clothianidin + *B. firmus* I-1582 over clothianidin alone demonstrates that the former nematicide seed treatments also has little value in managing RKN on corn. Jackson and Behn (2010) also did not observe a reduction in the *Pratylenchus* spp. reproduction rate or yield gains with chlothiandin + *B. firmus* I-1582 on corn. While Guilhabert-Goya (2014) reported average yield gains of 4 to 5 bu/acre with clothianidin + *B. firmus* I-1582 over clothianidin alone in corn, neither the target nematode nor the trial locations were reported.

Efficacy of terbufos granular nematicide was superior to the nematicide seed treatments for managing RKN and protecting corn yield. Significant yield gains were obtained with terbufos in combination with the nematicide seed treatments clothianidin + *B. firmus* I-1582 as well as chlothiandin and thiamethoxam insecticide seed treatments as compared with the latter seed treatments alone. Absence of a significant year × seed treatment × granular nematicide interaction at PBU illustrates that terbufos granular nematicide provided similar yield gains across all nematicide and insecticide seed treatments. Previously, similar yield gains were obtained in Alabama (Lawrence et al. 2009) and Mississippi (Lawrence et al. 2010b) studies with terbufos and abamectin + thiamethoxam on corn. No prior comparisons of terbufos and the seed treatment nematicide chlothiandin + *B. firmus* I-1582 for RKN management on corn have been published.

The most effective and sustainable strategy for managing RKN in corn is a peanut or other non-host crop-rotation partner alone or in combination with a RKN-resistant hybrid (Bowen et al. 2008; Davis and Timper 2000; Sassar et al. 1982; Williams and Windham 1988). Unfortunately, peanut or one of a handful of other non-host crops of *M. incognita* Race 3 often are not viable rotation options, nor are known RKN-resistant corn hybrids currently available (Hagan et al. 2012a), so a nematicide option is needed for RKN management in corn. Of the nematicides screened, terbufos granular nematicide consistently reduced RKN juvenile populations and increased seedling growth as well as provided yield gains of up to 13.5%, while the nematicide seed treatments products failed to match the growth or yield response obtained with terbufos. Based on our results, terbufos is the nematicide treatment of choice for managing RKN in corn, and can provide sufficient yield gains to cover product and application costs as well as a substantial income boost at current depressed corn prices.

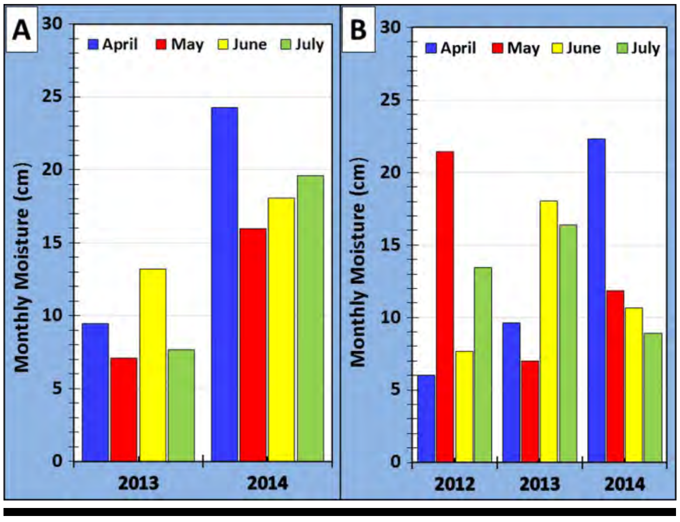

FIGURE 5

Total monthly moisture (rainfall + irrigation) at (**A**) BARU and (**B**) PBU study sites.

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