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Relationships among Soil Properties, Nematode Densities, and Soybean Yield in a Long-Term, Double-Crop System in Eastern Arkansas

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Abstract

The economic damage to soybean [*Glycine max* (L.) Merr.] production in the United States attributed to nematodes has increased in recent years. Understanding how soil properties affect nematodes will help to properly manage agroecosystems to minimize potential nematode damage to soybean crop and the associated economic impact. The objective of this study was to evaluate the relationships between near-surface soil properties and soybean yield and nematode densities across two years (2017 and 2018) in a long-term, wheat (*Triticum aestivum* L.)-soybean, double-crop production system on a silt-loam soil (Fragiudalfs) in eastern Arkansas. Soybean cyst nematode (SCN; *Heterodera glycines* Ichinohe) eggs and stage-2 juveniles (J2), lance (*Hoplolaimus* spp.), lesion (*Pratylenchus* spp.), spiral (*Helicotylenchus* spp.), stunt (*Tylenchorhynchus* spp.), total nematode numbers, and the total genera counts from early in the growing season (July), mid-season (August), and end of the season (October) were generally unrelated with soybean yield. Soybean cyst eggs population density in August was negatively correlated with soil pH ($r = -0.92$; $P \leq 0.05$). Total nematode numbers in July was negatively correlated with silt content ($r = -0.23$; $P \leq 0.05$), soil pH ($r = -0.27$; $P < 0.01$), and soil organic matter (SOM, $r = -0.24$; $P \leq 0.05$). Results suggested that soil properties influenced nematode population densities, indicating that nematodes can be at least partially managed and minimized through greater understanding of the variation of select near-surface soil properties in a wheat-soybean, double-crop production system on a silt-loam soil.

Keywords

Nematode, Tillage, Burning, Residue Level, Irrigation, Soybean

1. Introduction

The United States (US) is one of the leading producers of soybean [*Glycine max* (L.) Merr.], harvesting over 35.0 million ha in 2022 [1]. Arkansas, the tenth largest soybean-producing state in the US, harvested more than 1.2 million ha, producing 4.4 million metric tons of soybean in 2022 [2] Optimal soybean production is achieved with high-quality genetics and proper crop management. However, soybean production is also greatly influenced by several abiotic and biotic factors, such as weather, soil quality, weeds, and other pests [3], particularly plant-parasitic nematodes (PPNs). Between 1996 and 2016, PPNs were estimated to have caused $32 billion USD in economic losses in the US and Canada, with an average annual impact of $1.5 billion USD [4]. The soybean cyst nematode (SCN; *Heterodera glycines* Ichinohe) is considered the most damaging soybean pathogen in the US [5] [6] [7]. In Arkansas, the most common PPNs in 2015 were SCN, root-knot nematode (RKN; *Meloidogyne incognita*), lesion nematode (*Pratylenchus* spp.), and reniform nematode (*Rotylenchulus reniformis*) [8] [9].

Nematode abundance in the soil is influenced by numerous factors, such as soil properties, plant host, cropping sequence, and tillage practices [10] [11] [12] [13] [14]. Soil physical properties impact the abundance and survival of nematodes; for example, in Dubbs silt loam soil, SCN numbers are larger compared to Sharkey clay soils [15]. Nematodes can cause yield reductions in organic-rich soils with granular soil structure [16]. In addition to physical properties, soil chemical properties, including soil nutrient contents and pH, are associated with nematode distribution in the soil [17]. Changes in soil pH, electrical conductivity (EC), and nutrient levels, such as nitrogen (N), phosphorus (P), calcium (Ca), and magnesium (Mg), can affect soil nematodes [18] [14].

Effectively implementing soil conservation practices, such as no-tillage (NT), crop-livestock integration, and organic soil amendments, can reduce nematode population densities, minimizing the potential detrimental effects on crop production [19] [20]. However, the impact of previous crop residues and rotation sequences on nematode populations needs further evaluation [11] Being highly susceptible to lesion nematodes, corn (*Zea mays* L.) is often used in NT rotations with soybean in Brazil, which increased lesion, spiral, and total nematode abundances [19]. In the US, rotation sequences involving corn, soybean, and wheat (*Triticum aestivum* L.) decreased spiral nematode population density compared to continuous corn cultivation [14].

A previous study, in the same area, examined the impacts of agronomic practices on nematode populations in a long-term, wheat-soybean, double-crop system in eastern Arkansas [21]. Results showed that abundance of SCN egg in the soil was greater in October compared to July and August [21]. Combining conventional tillage (CT) with residue burning (B) increased SCN J2 densities; however, SCN J2 under CT with no-burn (NB) and NT-B did not differ [21]. Various nematode genera were affected by different field treatments [21]. Results also suggested that management practices can influence nematode populations, potentially impacting long-term soybean profitability [21].

Limited research exists on the relationships between soil properties, nematode densities, and soybean yield in the US and other soybean-producing countries in general, but more specifically in long-term, wheat-soybean, double-crop systems. However, similar studies have been conducted. Results from a study in Brazil, on generally sandy soils, reported that population densities of lesion, spiral, and total nematode numbers increased in a soybean-corn cropping system [19]. A study by Dias-Arieira *et al.* [19] observed that lesion nematode numbers were greater in sandy than in clay soils. Another study conducted in a Brazilian Ultisol reported that in medium-textured soils, soil potassium (K) and soil organic matter (SOM) were associated with low nematode densities in soybean roots [22]. In contrast, areas with large extractable soil Mg and sulfur (S) and soybean productivity were associated with large nematode abundances in the roots [22]. In a study encompassing northern and southern Illinois, central Iowa, and central Missouri, where resistant and susceptible soybean cultivars were planted under different tillage practices (*i.e.*, conventional tillage in Illinois and Iowa and no-tillage in Missouri), natural SCN infestations resulted in reduced plant height, leaf area, delayed pod and seed development in resistant cultivars, and decreased soybean yields, even without visible nematode damage symptoms [23].

The primary strategies for managing nematode infestations in soybean cultivation include crop rotation to disrupt the host-plant interactions, planting resistant cultivars, and using nematicides [6] [8] [24] [25]. Using nematode-resistant soybean cultivars is the most practical and cost-effective approach to managing nematode infestations [8]. However, for example, no agronomically accepted soybean cultivar is resistant to all the different types of SCN [16], thus additional strategies need to be used along with planting resistant cultivars. The objective of this study was to evaluate the relationships between near-surface soil properties and soybean yield and nematode densities across two years (2017 and 2018) in a long-term, wheat-soybean, double-crop production system on a silt-loam soil (Fragiudalfs) in eastern Arkansas. It was hypothesized that soybean yield would decrease as nematode population densities increase. It was also hypothesized that nematode population densities would be low when extractable soil nutrient concentrations (*i.e.*, P, K, Ca, and S) are large, as plants tend to grow optimally in fertile, healthy soils.

2. Materials and Methods

2.1. Site Description

In 2017 and 2018, field trials were conducted at the University of Arkansas, Division of Agriculture’s Lon Mann Cotton Branch Experiment Station near Marianna, AR [21]. The study site resides in Major Land Resource Area 134, the Southern Mississippi Valley Loess (90˚76W, 34˚73N) [26]. The soil throughout the study area was mapped as a Calloway silt loam (fine, mixed, thermic, Glossaquic Fragiudalfs; [27], with 16% sand, 73% silt, and 11% clay in the top 10 cm [28], which contains the majority of the soil's A horizon. A wheat-soybean, double-crop production system has been managed at the site since Fall 2001 [29]. According to the Koppen-Geiger climate classification system, the climate in the study region is classified as Humid Subtropical, Cfa [30]. The 30-year (*i.e.*, 1981-2010) mean monthly air temperature is 16.7˚C, with an average maximum air temperature of 32.6˚C in July and an average minimum of 0˚C in January [31]. The 30-year average annual precipitation in the study region is 4.3 in (107.0 mm) [31].

2.2. Treatments and Experimental Design

The study area consisted of 6 m-long by 3 m-wide plots. From Spring 2005 to spring 2018, to achieve different wheat residue levels,112 kg N·ha^{-1} was applied to 24 plots, while no N was applied to the other 24 plots, residue burning and non-burning, and tillage [*i.e.*, conventional tillage (CT) and NT]. The tillage treatment was stripped across the burn treatments. The residue-level treatment was split within tillage-burn treatment combinations in a randomized complete block (RCB) design with six replications [21]. Before the 2005 soybean growing season, an irrigation treatment was added by dividing the study area in half so that 24 out of the 48 plots remained flush-irrigated, while the other 24 plots were transformed to dryland production (*i.e.*, non-irrigated; [28]). Out of practical necessity, the irrigation-treatment plots directly corresponded with the burn-treatment plots. Consequently, for this study and following Amuri *et al.* [32], a completely random design was assumed, such that there were three replications of 16 residue-level-burn-tillage-water management treatment combinations.

2.3. Field Management

Starting in Fall 2001 and for the following falls, usually between late October and mid-November, wheat was drill-seeded at a rate of 168 kg seed·ha^{-1} with a 19 cm row spacing [28] [33]). Beginning in March 2002, and for the following springs, wheat received N fertilization using urea (46% N), which was applied as a split application in early to mid-March and usually in early to mid-April [28] [33]. Between 2002 and 2004, for achieving the high and low-residue-level treatment, all wheat plots were fertilized with 101 kg N·ha^{-1} at the first spring application time and, at the second spring application time, the same rate of N was applied to only 24 plots to create the high-residue-level treatment [28] [32]. From Spring 2005 to Spring 2018, the residue level differences were achieved by applying N to only 24 plots with a split application of N at a rate of 56 kg N·ha^{-1}, for a total N application of 112 kg·ha^{-1}, while the other 24 plots received no fertilizer-N addition [28] [33]. In 2017, after 15 years of the same management, the wheat residue level was 1.2 times greater ($P = 0.05$) under a high residue level than the low residue level treatment. Similarly, [34] reported that wheat residue was 1.6 times greater under high residue levels compared to low residue levels.

The residue-burn treatment was achieved using propane flaming that was used to manually burn 24 plots, while the other 24 were left unburned [21]. After the burning treatment was imposed and prior to soybean planting in early June, the CT treatment was created with approximately three passes with a tandem disk to a 5 to 10-cm depth, followed by three passes with a field cultivator to disperse soil clumps and soften the seedbed, while the other 24 plots were not tilled (*i.e.*, NT; [28] [21]). A glyphosate-resistant maturity group (MG) 4 to 5 soybean cultivar was planted in early June for 2002 to 2013 growing seasons [28]. Between 2014 and 2018, a Liberty-Link soybean cultivar was drill-seeded with 19-cm row spacing. In early June 2017, Go Soy 4912LL, a Liberty-Link, MG 4.9, somewhat resistant to the SCN and moderately resistant to the southern RKN soybean cultivar [35], was drill-seeded with 19-cm row spacing. In 2018, P 5414 LLS, a Liberty-Link, MG 5, susceptible to SCN and moderately resistant to southern RKN soybean cultivar [36], was drill-seeded with 19-cm row spacing on 9 June and replanted on 27 June due to initially low soil moisture and poor stand establishment. Soybeans were drill-seeded without beds [28]. The Liberty-Link herbicide program was used twice during the study period from 2014 to 2018 after soybean planting to control pigweed (*Amaranthus palmeri* S.) and ryegrass (*Lolium perernne* L.), while the 24 irrigated plots were flush-irrigated as required three to four times annually. Soybeans were harvested yearly using a plot combine from early October to mid-November [21].

2.4. Soil Sample Collection, Processing, and Analyses

To determine sand, silt, and clay percentages, at wheat harvest in 2002, 10 composite soil samples were collected from the top 10-cm depth of individual plots, resulting in 48 samples (n = 48) [37]. Soil samples were oven-dried at 70˚C for 48 hours, crushed, and sieved through a 2-mm mesh screen for particle-size analysis using the hydrometer method described by Arshad *et al.* [38].

Before soybean planting in May 2017 and 2018, one composite soil sample per plot was manually collected using a 4.8-cm-diameter stainless steel core chamber and a slide hammer from the top 10 cm. In addition to encompassing most of the SOM concentration and A horizon, the top 10 cm is the typical zone of most significant microorganism activity. Soil samples were oven-dried at 70˚C for 48 hours, weighed for bulk density (BD) determination, and then crushed and sieved through a 2 mm mesh screen for chemical analyses. Soil pH and electrical conductivity (EC) were determined potentiometrically on a 1:2 soil-mass-to-distilled-water-volume paste. Subsamples were extracted with Mehlich-3 extraction solution in a 1:10 soil-mass-to-extractant-volume ratio. Extracted solutions were analyzed for P, K, Ca, Mg, S, Na, Fe, Mn, Zn, Cu, and B by inductively coupled, argon-plasma spectrometry (CIROS CCD model, Spectro Analytical Instruments, MA). Total carbon (TC) and nitrogen (TN) concentrations were determined by high-temperature combustion (Vario MAX Total C and N Analyzer, Elementar Americas Inc., Mt. Laurel, NJ). The soil C: N ratio was calculated using measured TC and TN concentrations. Soil organic matter concentration was determined by weight-loss-on-ignition (LOI) after 2 hours at 360˚C. Soil nutrient contents (*i.e.*, P, K, Ca, Mg, S, Na, Fe, Mn, Zn, Cu, and B) were calculated from measured concentrations and measured BD, while TC and SOM concentrations from the top 10 cm of each plot were used for subsequent correlation analyses. Table 1 summarizes the soil property minima and maxima across the two years of data included in this study.

2.5. Nematode Sampling and Assessment

In 2017 and 2018, each treatment plot was sampled approximately 1 and 2 months after planting and near soybean harvest (*i.e.*, on 7 July, 15 August, and 12 October 2017 and on 9 July, 10 August, and 15 October 2018). At each

Table 1. Summary of soil property minima and maxima in the top 10 cm in 2017 and 2018 after 15 complete wheat-soybean cropping cycles on a silt-loam soil in eastern Arkansas.

Soil property	Minimum	Maximum
Sand (%)	11.2	20.6
Silt (%)	67.8	78.8
Clay (%)	3.6	16.6
pH	5.5	7.1
Electrical conductivity ($dS \cdot m^{-1}$)	0.1	0.3
Bulk density ($g \cdot cm^{-3}$)	1.1	1.5
P ($kg \cdot ha^{-1}$)	19.7	54.7
K ($kg \cdot ha^{-1}$)	53.4	231.5
Ca ($kg \cdot ha^{-1}$)	1205	2207
Mg ($kg \cdot ha^{-1}$)	240	599
S ($kg \cdot ha^{-1}$)	11.7	40.5
Na ($kg \cdot ha^{-1}$)	9.9	47.1
Fe ($kg \cdot ha^{-1}$)	195	433
Mn ($kg \cdot ha^{-1}$)	167	331
Zn ($kg \cdot ha^{-1}$)	1.4	4.7
Cu ($kg \cdot ha^{-1}$)	0.9	2.5
B ($kg \cdot ha^{-1}$)	0.4	1.5
Total carbon (%)	0.7	1.8
C:N ratio	8.6	18.8
Soil organic matter (%)	1.7	3.4

sampling, 10 soil cores (2-cm diameter × 10-cm depth) were manually collected using a push probe from within the planted soybean row in a criss-cross pattern, combined for one sample per plot, and placed in a plastic bag [28]. After soil sample collection, soil samples were kept in the dark and at room temperature until being sent within three days to the Arkansas Nematode Diagnostic Laboratory located in Hope, AR for nematode population density analysis and genus identification [28]. The population density of 10 different genera of plant-parasitic nematodes [*i.e.*, SCN second-stage juveniles (J2), SCN eggs, dagger (*Xiphinema americanum*), reniform, lance, lesion, spiral, ring nematode (*Criconemella* spp.), stubby-root nematode (*Trichodorus* spp.), stunt, and RKN] was determined for each soil sample.

Similar to procedures described by Monfort *et al.* [39] and Brye *et al.* [28] nematodes were extracted from 100 cm^3 of fresh soil using a semi-automatic elutriator [40] and SCN cysts were collected on 60-mesh sieves followed by centrifugal flotation [41]. Nematodes genus identification and determination of population density were conducted under a stereoscope with 40 to 60× magnification. The SCN cysts that were trapped on the 60-mesh sieves of the elutriator were collected and crushed in a glass-tissue homogenizer to free eggs, which were subsequently counted at 40× magnification with a stereoscope [42]. For statistical analysis, the total nematode numbers and the count of nematode genera associated with plants were determined for each plot between the 10 identified and quantified nematode genera.

2.6. Statistical Analyses

Combined across years and field treatments, linear correlation analyses were performed (version 16, Minitab, Inc., State College, PA) between soybean grain yield and soil properties (*i.e.*, sand, silt, clay, pH level, P, K, Ca, Mg, S, Na, Fe, Mn, Zn, Cu, and B contents; TC and SOM concentration; and C:N ratio) and nematode genera (*i.e.*, SCN eggs, SCN J2, lance, lesion, spiral, and stunt densities, total nematode numbers, and total genera counts) separately for the July, August, and October measurement dates. Significance was judged at $P \leq 0.05$. Though quantified, there were insufficient data for dagger, reniform, ring, stubby-root, and RKN across the three measurement dates [21]; thus, were not included in the correlation analyses.

3. Results and Discussion

3.1. Correlations between Soybean Yield and Nematode Properties

Soil physical, chemical, and biological properties play a significant role in plant growth and production and influence soil microorganisms' development and behavior. Since crop yield variability is known to be affected by soil physical and chemical properties and pests, soybean yield variations were expected to be related to at least some nematode genera. However, combined across years, nematode genera from early in the growing season (July), mid-season (August), and the end of the season (October) at a 10 cm depth were mostly unrelated to soybean yield, with two exceptions (**Table 2**). Soybean yield was moderately negatively correlated ($r = -0.36$; **Table 2**) with mid-season spiral nematode density in the top 10 cm, indicating that the increase in spiral nematode density was related to a decrease in soybean yield. The decline in soybean yield is consistent with the ecology of the spiral nematode, which is an ectoparasite that feeds on soybean roots [43]. However, soybean yield was weakly positively correlated ($r = 0.26$; **Table 2**) with stunt nematode density in the top 10 cm, indicating that the increase in stunt nematode density might not affect soybean yield. The weak positive correlation between stunt nematode density and soybean yield was not surprising, as stunt nematode does not generally cause severe soybean injury [8].

Results only partially supported the hypothesis that soybean yield would decrease as nematode densities increase, as no consistent correlation between nematode densities and soybean yield resulted from the study. The absence of many correlations between nematode properties and soybean yield at any of the three points in the soybean growing season was likely at least partially due to the overall low nematode population densities throughout the entire study area in 2017 and 2018 (**Table 2**). Additionally, none of the nematodes assessed in this research surpassed the threshold levels that would pose a concern for soybean production in Arkansas. In Arkansas, the critical thresholds for soybeans in terms of RKN are 60, SCN are 500, and reniform nematode are 1000 nematodes per 6.1 in^3 (100 cm^3) of soil [8], which suggests the potential beneficial impacts of the long-term nature of consistent management with the various management practice combinations at the study site at controlling nematode densities in general. In addition to the nematode densities measured in this study being generally

Table 2. Summary of correlation coefficients (r) between nematode genera and soybean yield across 2017 and 2018 in a long-term, wheat-soybean, double-crop production system on a silt-loam soil in eastern Arkansas.

Nematode genera	July	August	October
		r	
Soybean cyst nematode (SCN) eggs	0.55	−0.82	0.27
SCN second-stage juveniles	0.33	0.02	0.31
Lance	0.42	0.60	−0.15
Lesion	−0.09	−0.66	0.28
Spiral	−0.35	−0.36*	0.16
Stunt	0.18	0.26*	−0.22
Total nematode numbers	0.14	0.17	−0.05
Total genera counts	0.08	0.04	−0.04

*$P \leq 0.05$.

below the level at which soybean injury would be expected, the soybean cultivars Go Soy 4912LL and P 5414LLS grown in the two years of this study (*i.e.*, Go Soy 4912LL and P 5414LLS) were also known to be at least partially resistant to the SCN and southern RKN. Similar results to the current study were reported in Brazil on sandy soils, where no correlations were observed between nematode numbers and soybean yield in a soybean-brachiaria (*Brachiaria* spp.) and soybean-sugarcane (*Saccharum officinarum* L.) cropping sequence [19].

3.2. Correlations between Near-Surface Soil Properties and Nematode Properties

In contrast to the few correlations between soybean yield and nematode properties, numerous significant correlations existed among nematode genera and soil properties in the top 10 cm. Combined across the two years (2017 and 2018), SCN egg density in July was uncorrelated with any soil properties, but in August and October was negatively correlated with soil Ca ($r = -0.92$) and total soil C ($r = -0.37$), respectively (**Table 3**). In contrast, SCN egg density in August was positively correlated with soil Zn (r = 0.94), while in October was positively correlated with soil P ($r = 0.42$) and Fe ($r = 0.44$; **Table 3**). Similar to SCN egg density, SCN J2 density in July and August was uncorrelated with any soil properties, while in October, and also similar to SCN egg density, the SCN J2 density was positively correlated with soil P ($r = 0.51$; **Table 3**).

In contrast to SCN genus, there were more correlations between lance nematode genus among all three times during the soybean growing season. Lance nematode density in July was negatively correlated with clay content ($r = -0.74$), while lance nematode density in August and October was also negatively correlated with soil pH ($r = -0.87$) and with sand content ($r = -0.35$) and soil Na ($r = -0.36$), respectively (**Table 3**). In contrast, lance nematode density in July was positively correlated with silt content ($r = 0.60$), while lance nematode density in August and October was positively correlated with soil BD ($r = 0.72$), soil Ca ($r = 0.73$), and SOM ($r = 0.72$) and with soil K ($r = 0.36$) and soil Ca ($r = 0.42$), respectively (**Table 3**).

Lesion nematode density in August was negatively correlated with silt content ($r = -0.95$), soil S ($r = -0.98$), and soil Mn ($r = -0.96$), while in October was negatively correlated with soil K ($r = -0.45$) and soil Cu ($r = -0.48$; **Table 3**). In contrast, lesion nematode density in July was positively correlated with soil Zn ($r = 0.85$), in August was positively correlated with soil Ca ($r = 0.97$), and in October was positively correlated with total C ($r = 0.72$) and SOM ($r = 0.67$; **Table 3**).

Spiral nematode density in October was negatively correlated with soil S ($r = -0.31$), soil Zn (r = −0.49), and the C: N ratio ($r = -0.35$; **Table 4**). In contrast, spiral nematode density in July was positively correlated with silt content ($r = 0.35$) and soil Zn ($r = 0.41$), in August was positively correlated with soil Ca ($r = 0.36$), soil S ($r = 0.45$), and soil Na ($r = 0.41$), and in October was positively correlated with soil pH ($r = 0.35$) and soil Mg ($r = 0.54$; **Table 4**).

Table 3. Summary of correlation coefficients (r) between nematode population densities and soil properties from the top 10 cm across 2017 and 2018 in a long-term, wheat-soybean, double-crop production system on a silt-loam soil in eastern Arkansas.

Soil property†	SCN eggs			SCN J2			Lance			Lesion		
	July	August	October	July	August	October	July	August	October	July	August	October
							r					
Sand	−0.48	0.2	−0.06	0.11	0.15	−0.25	0.11	−0.6	−0.35*	0.18	−0.65	0.04
Silt	0.34	0.69	−0.22	−0.4	−0.26	0.23	0.6**	−0.29	0.16	−0.14	−0.95*	0.35
Clay	0.28	−0.69	0.21	0.22	0.07	0	−0.74***	0.58	0.12	−0.12	0.94	−0.28
pH	−0.06	0.56	−0.27	−0.66	−0.16	−0.23	−0.12	−0.87*	0.09	0.17	−0.86	0.23
EC	−0.54	−0.14	0.21	0.12	−0.41	−0.03	−0.23	−0.12	0.08	0.37	−0.33	−0.08
BD	0.15	−0.73	−0.33	0.05	0.03	−0.17	−0.43	0.72*	0.01	–	0.82	−0.38
P	−0.16	0.53	0.42*	−0.17	−0.23	0.51*	−0.17	0.17	0.21	0.19	−0.39	0.19
K	−0.01	−0.34	0.01	−0.11	0.03	0.1	0.15	0.53	0.36*	−0.74	0.7	−0.45*
Ca	−0.81	−0.92*	−0.11	−0.16	0.38	0.09	−0.23	0.73*	0.42*	0.1	0.97*	0.19
Mg	−0.4	−0.83	−0.17	−0.41	0.3	−0.03	−0.26	0.05	0.05	−0.11	0.92	0.21
S	−0.3	0.48	0.28	0.24	−0.38	0.22	−0.27	0.15	−0.16	0.13	−0.98*	−0.06
Na	−0.37	−0.15	0.15	−0.15	−0.2	−0.14	−0.27	−0.23	−0.36*	0.27	−0.22	−0.27
Fe	−0.02	−0.45	0.44*	−0.15	0.33	0.37	−0.06	0.63	−0.1	−0.11	0.5	−0.34
Mn	0.61	0.52	−0.33	−0.3	−0.22	0.05	−0.35	0.14	0.2	0.04	−0.96*	0.19
Zn	−0.05	0.94*	0.2	−0.06	−0.43	0.14	−0.14	−0.07	0.29	0.85**	−0.82	0.13
Cu	0.57	0.58	0.02	−0.23	−0.14	0.22	−0.14	0.34	0.14	−0.33	0.65	−0.48*
B	−0.22	0.15	−0.05	0.16	−0.47	−0.08	−0.14	−0.47	−0.19	0.67	−0.32	−0.3
Total C	−0.21	−0.3	−0.37*	0.33	−0.08	−0.04	0.44	0.34	0.31	0.34	−0.87	0.72***
C:N ratio	−0.13	0.42	−0.1	0.46	−0.35	−0.04	−0.05	−0.11	0.31	0.56	−0.38	0.02
SOM	−0.21	−0.54	−0.27	0.25	0.09	0.05	0.39	0.72*	0.3	0.34	−0.82	0.67*

*$P \leq 0.05$; **$P < 0.01$; ***$P < 0.001$. †Electrical conductivity, EC; bulk density, BD; soil organic matter, SOM.

Stunt nematode density in July was negatively correlated with soil Mg ($r = -0.26$) and SOM ($r = -0.27$), but positively correlated with soil S ($r = 0.43$) and Cu ($r = 0.29$). In August, stunt nematode was negatively correlated with silt content ($r = -0.40$), soil pH ($r = -0.31$), soil Mn ($r = -0.29$), and TC ($r = -0.32$), but was positively correlated with soil S ($r = 0.31$). In October, stunt nematode density was negatively correlated with soil Mn ($r = 0.30$; Table 4).

In contrast to individual nematode densities, summing nematode densities across all individual genus resulted in a greater number of correlations among soil properties. Total nematode numbers in July were negatively correlated with silt content ($r = -0.28$), soil pH ($r = -0.27$), TC ($r = -0.28$), and SOM ($r = -0.24$), but was positively correlated with soil EC ($r = 0.28$), soil S ($r = 0.38$), and

Table 4. Summary of correlation coefficients (r) between nematode population densities and soil properties from the top 10 cm across 2017 and 2018 in a long-term, wheat-soybean, double-crop production system on a silt-loam soil in eastern Arkansas.

Soil property[†]	Spiral			Stunt			Total nematode numbers			Total genera counts		
	July	August	October	July	August	October	July	August	October	July	August	October
	r											
Sand	−0.15	−0.24	0.16	0.11	0.15	0	0.06	0.09	−0.01	0.08	0.01	0.05
Silt	0.35*	−0.14	−0.09	−0.34	−0.40***	−0.15	−0.23*	−0.32**	−0.16	0.01	0.08	−0.16
Clay	−0.13	0.27	−0.06	0.17	0.18	0.13	0.12	0.17	0.12	−0.07	−0.07	0.08
pH	0.23	0.04	0.35*	−0.4	−0.31**	−0.12	−0.27**	−0.23*	0.07	0.22*	0.11	−0.19
EC	0.26	0.34	−0.21	0.19	0.26	0.15	0.28**	0.32**	−0.26*	0.31	0.28**	−0.32**
BD	−0.29	−0.25	0.17	0.06	0.01	0.09	−0.02	−0.06	0.17	−0.09	−0.22*	0.03
P	0.16	0.2	−0.18	0.13	0.15	−0.16	0.21	0.2	−0.25*	0.2	0.22*	−0.25*
K	−0.25	−0.08	−0.14	0.11	−0.06	−0.01	0.08	−0.1	0.09	−0.08	−0.23*	0.1
Ca	−0.06	0.36*	0.14	−0.09	−0.09	0.01	−0.05	−0.07	0.21*	0	−0.28**	−0.03
Mg	−0.12	0.34	0.54***	−0.26*	−0.16	−0.05	−0.16	−0.1	0.39***	0.15	−0.12	0.03
S	0.23	0.45*	−0.31*	0.43***	0.31**	0.11	0.38***	0.34**	−0.31*	0.2	0.28	−0.22*
Na	0.22	0.41*	0.17	0.14	0.04	0.15	0.18	0.08	−0.13	0.32	0.03	−0.17
Fe	0	0.34	−0.19	0.37	0.22	−0.13	0.40***	0.27*	−0.28*	0.19	0.08	−0.19
Mn	0.31	−0.16	−0.01	−0.19	−0.29*	−0.30*	−0.13	−0.27*	−0.22	0.05	0.05	−0.23*
Zn	0.41*	−0.05	−0.49***	0.1	0.01	−0.08	0.18	0.05	−0.47***	0.17	0.26	−0.35**
Cu	−0.16	−0.32	0.04	0.29*	0.02	−0.16	0.22	−0.02	−0.03	−0.08	0	0.04
B	0.31	0.24	−0.18	−0.1	0.06	0.2	−0.01	0.12	−0.12	0.28**	0.26	−0.06
Total C	−0.07	0.13	−0.11	−0.31	−0.32**	0	−0.28*	−0.26*	−0.05	−0.13	−0.05	−0.01
C:N ratio	0.28	−0.08	−0.35*	−0.16	−0.02	0.03	−0.16	−0.11	0.02	−0.24*	−0.11	0.2
SOM	0.07	0.18	−0.17	−0.27*	−0.3	−0.07	−0.24*	−0.23*	−0.01	−0.15	−0.12	−0.03

*$P \leq 0.05$; **$P < 0.01$; ***$P < 0.001$. [†]Electrical conductivity, EC; bulk density, BD; soil organic matter, SOM.

soil Fe ($r = 0.40$; Table 4). Similar to July, total nematode numbers in August were negatively correlated with silt content ($r = -0.32$), soil pH ($r = -0.23$), soil Mn ($r = -0.27$), TC ($r = -0.26$), and SOM ($r = -0.23$), but was positively correlated with soil EC ($r = 0.32$), soil S ($r = 0.34$), and soil Fe ($r = 0.27$; Table 4). In contrast to July and August, in October, total nematode numbers was negatively correlated with soil EC ($r = -0.26$), soil P ($r = -0.25$), soil S ($r = -0.31$), soil Fe ($r = -0.28$), and soil Zn ($r = -0.47$), but was positively correlated with soil Ca ($r = 0.21$) and soil Mg ($r = 0.39$; Table 4).Total genera counts present in the top 10 cm in July were negatively correlated with the soil C: N ratio ($r = -0.24$), but was positively correlated with soil pH ($r = 0.22$) and soil B ($r = 0.28$; Table 3). In August, total genera counts were negatively correlated with soil BD ($r = -0.22$), soil K ($r = -0.23$), and soil Ca ($r = -0.28$), but were positively correlated with soil EC ($r = 0.28$) and soil P ($r = 0.22$; **Table 3**). In October, total genera counts were negatively correlated with soil EC ($r = -0.32$), soil P ($r = -0.25$), soil S ($r = -0.22$), soil Mn ($r = -0.23$), and soil Zn ($r = -0.35$; **Table 4**).

Though not formally compared across the three measurement times throughout the two soybean growing seasons, there were a total of 8 negative and 10 positive correlations with various soil properties from early season (July) nematode assessments, 16 negative and 15 positive correlations from mid-season (August) nematode assessments, and 18 negative and 11 positive correlations from late-season (October) nematode assessments (**Table 3**, **Table 4**). Though the specific soil properties varied, the number of positive correlations among soil properties and nematode genera was relatively stable over the soybean growing season from July to August to October. In contrast, the number of negative correlations among soil properties and nematode genera tended to increase over the soybean growing season from July to August to October.

While nematodes did not hinder soybean yield, early season soil properties affected numerous nematode genera in the top 10 cm. In this study, several correlations resulted among soil properties and nematode abundance, supporting the hypothesis that nematode densities would be low under high nutrient contents in the soil. Soil N, P, and potassium are essential nutrients for plant growth and likely influence belowground microorganism biodiversity, including nematodes. Nitrogen enrichment in the soil tends to increase soil hydrogen (H^+) and/or aluminum (Al^{3+}) concentrations, acidifying the soil, thus reducing nematode populations [44]. Phosphorus addition decreased total nematode density of N_2-fixing plants (*i.e.*, *Alnus cremastogyne*) [45] because P additions to the soil stimulate plant growth and increases photosynthate translocation [46], which is similar to results of the current study, where total nematode numbers and total genera counts were negatively correlated with soil P, but positively correlated with SCN eggs only. Potassium is essential to reduce nematode plant damage because K is necessary for developing thicker cell walls on plant roots, blocking nematode penetration, feeding, and reproduction; K also minimizes plant stress [47]. Furthermore, [22] measured lower nematode numbers when the soil had enough K in a soybean crop, thus supporting results of the current study, as lance and total genera counts were negatively correlated with extractable soil K.

Calcium is another macronutrient essential for plant growth. The numbers of SCN eggs and total genera counts in the soil are affected by soil Ca, indicating fewer SCN eggs at greater Ca levels. [48] also reported soil Ca was negatively correlated with nematode densities, specifically the lesion nematode. Previous research suggested that the exposure of *Caenorhabditis elegans*, a free-living nematode, to an increasing concentration of Ca reduced nematode development [49], which similar effects of soil Ca may be attributed to the relationships identified between soil Ca and SCN eggs and total genera counts in this study. In contrast, lance, lesion, spiral, and total nematode numbers were positively correlated with soil Ca.

The relationship observed between soil S and nematodes properties varied. spiral and total nematode numbers increased as soil S increased, which agreed with the positive correlation between soil S, total nematode numbers, and lesion nematodes in a < 4-year-old soybean-brachiaria crop rotation in Brazil [19]. However, in the current study, lesion nematode densities decreased as soil S increased, while the relationships among other micronutrients (*i.e.*, Cu, Mn, and Zn) and nematode genera were significant, but inconsistent.

Soil pH in the top 10 cm across plots in the current study ranged from 5.5 to 7.1 (**Table 1**), and most of the significant correlations among total nematode numbers and soil pH were negative, except with spiral and total genera counts, which were positive. Similarly, Norton *et al.* [50] reported a negative correlation between nematode populations and soil pH and a positive correlation with the spiral nematode. [14] also reported a positive correlation between soil pH and spiral nematode abundance. Another study suggested a positive correlation of soil pH with stunt nematodes in a pH range of 5.0 to 6.0 [51]. However, a study conducted in Mexico reported that soil pH in the range of 5.0 to7.6 did not affect PPNs in corn, sorghum (*Sorghum bicolor* L.), bean (*Phaseolus vulgaris* L.), squash (*Cucurbita pepo* L.), tomato (*Lycopersicum esculentum* L.), potatoes (*Solanum tuberosum* L.), alfalfa (*Medicago sativa* L.), and pepper (*Capsicum annum* L.), suggesting that soil pH likely has only a slight effect on nematode hatching [52].

In addition to improving soil physicochemical and biological properties, native SOM and organic amendments serve as a traditional approach for PPN management by releasing various nematicidal compounds during the degradation of organic matter, such as glucosinolate-derivative, organic acids, nitrogenous compounds, and glycoside-derivative [20], which matches with the negative correlation between SOM and stunt and total nematode numbers in July and August of the current study. A similar negative correlation between SOM and total nematode numbers and lesion nematode densities has also been reported in soybean fields in Brazil [19].

Soil EC is a crucial factor in the life cycle of PPNs [18] because microorganisms, including nematode activity, generally decrease on saline soils [18]. Even though the correlation of soil EC with total nematode numbers and total genera counts were significant, but not consistent, except for the positive correlation with stunt nematode density, soil EC in this study site varied from 0.1 to 0.3 $dS \cdot m^{-1}$ (**Table 1**), meaning that the study area had no salinity issues, which likely resulted in soil EC variations having little to no effect on soybean parasitic nematode densities and survival.

Soil texture is known to have a substantial effect on nematode population density. Sandy or loamy soils favor the development of most nematode genera [19]. Results of the current study showed that silt content positively influenced lance and spiral nematodes, both migratory, semi-endoparasitic PPNs. This observation suggested that silt-loam texture of the soil at the study site may provide favorable conditions for the survival and reproduction of lance and spiral nematodes. However, it is worth noting that results from another study reported an increase in population of lesion nematodes in a silt-loam soil in a corn-soybean rotation [53]. In the current study, lance nematode density was negatively correlated with sand and clay content, which is plausible since nematodes need pore space and enough soil moisture for migration towards plant roots, feeding, and reproduction. Thus, elevated sand and clay content may restrain the persistence of certain nematode genera in the soil. In contrast, lesion, stunt, and the total nematode numbers were negatively influenced by silt content. However, in a potato study, lesion nematode density was more numerous on a sandy loam and coarse-loamy Dystrochrept when potatoes were cultivated in rotation with rye [54].

Similar to soil texture, soil BD can influence nematode density, migration, and survival through control on soil pore space, where soils with increased bulk density have decreased pore space, which negatively affects microorganism survival [55]. Soil BD correlations with nematode genera were significant, but inconsistent among nematode genera and time of the soybean growing season. The current study showed a negative correlation between BD and the total genera counts, where soil BD averaged 1.3 $g \cdot cm^{-3}$ across the study site (**Table 1**). However, Gibson *et al.* [56] reported that total nematodes did not correlate with soil BD between 2 - 6 cm and 9 - 13 cm intervals after logging machinery traffic in a mixed conifer forest in New Mexico.

It was hypothesized that soybean yield would decrease as nematode population densities increase. It was also hypothesized that nematode population densities would be low when extractable soil nutrient concentrations (*i.e.*, P, K, Ca, and S) are large, as plants tend to grow optimally in fertile, healthy soils. Nematode management is challenging due to many factors, including the nematode's ability to form survival structures and adaptation strategies to subsist in adverse environments and nematode diversity, and every crop can be parasitized by at least one nematode species. However, management can be achieved by implementing an integrated nematode management plan (cultural control, use of resistant plant varieties, chemical control, monitoring, and regulatory control) that minimizes the nematode's negative effect on crops while considering environmental and economic impacts [8].

4. Conclusions

This study assessed the correlations between soybean yield and near-surface soil properties and various nematode genera, including several individual nematode genus densities, over the course of two consecutive soybean growing seasons after > 15 years in a long-term, wheat-soybean, double-crop production system on a silt-loam soil in eastern Arkansas. Unexpectedly and contradictory to the hypothesis, soybean yield was mostly unrelated with the majority of nematode genera, but numerous near-surface soil properties were both negatively and positively correlated with various nematode genera at various stages in the soybean growing season. However, even in various combinations of production practices after > 15 years of consistent management, which by themselves has likely contributed to limiting nematode densities and potential soybean damage, numerous significant correlations among soil properties and nematode genera were identified that can provide further guidance into future management practices adjustments that could be made to keep various nematode genera densities and potential soybean damage at a minimum.

Results of this study highlight the importance of considering crop sequence, soil characteristics, and nematode populations in crop management decisions. Managing soil nutrients and monitoring nematode populations, especially SCN, RKN, lesion, stunt, and spiral nematode, can be crucial for optimizing soybean yield in general, but particularly in wheat-soybean, double-crop systems in Arkansas and other locations. Based on results of this study, additional investigation is necessary to more fully understand the relationships among soil properties, soybean yield, and nematode genera in countries that produce soybeans, including the United States.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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