

Effects of soil mechanical resistance on nematode community structure under conventional sugarcane and remaining of Atlantic Forest

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Abstract Nematodes present high potential as a biological indicator of soil quality. In this work, it was evaluated relations between soil physical properties and nematode community under sugarcane cropping and remaining of Atlantic Forest areas in Northeastern Pernambuco, Brazil. Soil samples were collected from September to November 2009 along two 200-m transects in both remaining of Atlantic Forest and sugarcane field at depths of 0–10, 10–20, 20–30, 30–40, and 40–50 cm. For soil characterization, it was carried out analysis of soil size, water content, total porosity, bulk density, and particle density. The level of soil mechanical resistance was evaluated through a digital penetrometer. Nematodes were extracted per 300 cm³ of soil through centrifugal flotation in sucrose being quantified, classified according trophic habit, and identified in level of genus or family. Data were analyzed using Pearson correlation at 5% of probability. Geostatistical analysis showed that the penetration resistance, water content, total porosity, and bulk density on both forest and cultivated area exhibited spatial dependence at the sampled scale, and their experimental semivariograms were fitted to spherical and exponential models. In forest area, the ectoparasites and free-living nematodes exhibited spherical model. In

sugarcane field, the soil nematodes exhibited pure nugget effect. *Pratylenchus* sp. and *Helicotylenchus* sp. were prevalent in sugarcane field, but in forest, there was prevalence of Dorylaimidae and Rhabditidae. Total amount of nematode did not differ between environments; however, community trophic structure in forest presented prevalence of free-living nematodes: omnivores followed by bacterial-feeding soil nematodes, while plant-feeding nematodes were prevalent in sugarcane field. The nematode diversity was higher in the remaining of Atlantic Forest. However, the soil mechanical resistance was higher under sugarcane cropping, affecting more directly the free-living nematodes; especially Dorylaimidae which was the most sensible to changes in soil physical properties.

Keywords Soil strength · Biodiversity · Soil quality · Monoculture · Native vegetation

Introduction

Cultivation of sugarcane (*Saccharum* spp.) has great economic importance for Brazil, which holds the title of world's largest producer. The state of Pernambuco is currently the second largest producer of Brazil with 334,000 ha cultivated (CONAB 2010). With the expansion of the crop due to economic incentives in the 1980s, many undisturbed places have been incorporated to areas of the mills, fragmenting native vegetation areas of the Atlantic Forest (Silva and

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Tabarelli 2000). Besides the high waste generation, intensification of mechanization has intensified soil compaction mainly by machinery heavy traffic (Seixas and Oliveira Júnior 2001; Souza et al. 2010).

Soil compaction is a major cause of soil physical degradation. Determining the impact of management practices in the physical and biological soil attributes is imperative, because it alters the soil physical properties and reduces productivity by limiting microbial activities (Lanzanova et al. 2007). Among the soil physical attributes used to determine soil compaction, the mechanical resistance to penetration has been considered the most sensitive indicator, easy and quick application, widely used to assess management systems, because it is directly related to the growth of plants (Busscher et al. 2000; Serafim et al. 2008).

Conversely, the Atlantic Forest is considered one of the hotspots of global biodiversity, although there are only 11.73% of its original cover (Myers et al. 2000; Ribeiro et al. 2009). In the Northeast of Brazil, there are only 2% of the original area (Silva and Tabarelli 2000). As a result of intense exploitation of forest resources, it has now become fragmented and impoverished as its composition (Souza et al. 2002). Fact that makes relevant knowledge of soil physical and biological aspects of the few remaining still exists.

Nematodes constitute the group of invertebrates that are abundant and diverse, being found occupying almost all ecological niches. The structure and composition of their communities undergo change when changes occur in vegetation (Pattison et al. 2008), in soil (Gupta and Yeates 1997; Yeates and Pattison 2006), in environmental conditions, whether natural or triggered by human activities. In addition, studies related to nematode community show that the environmental disturbances will lead predominance of certain taxa (Wasilewska 1997; Yeates 1999; Goulart and Ferraz 2003; Pattison et al. 2008).

The soil properties can directly or indirectly affect the composition and structure of nematode communities (De Goede and Bongers, 1994; Yeates 1999). Specifically, changes in the soil physical properties directly influence the habitat and food chain of the nematodes (Neher 1999). Often the physical properties such as texture, water content, and soil structure are correlated with the nematodes communities (Yeates and Bongers 1999; Kandji et al. 2001; Gomes et al. 2003; Kimenju et al. 2009), presenting an important role in the abundance, distribution, and

structure of nematodes communities. This is one reason that validates the potential of nematodes as bioindicators of soil quality (Kandji et al. 2001; Qi and Hu 2007; Mondino et al. 2009). Due to the abundance, morphology, rapid response to environmental changes, and management actions of the soil, short reproductive cycle, and food specificity, the nematodes have great potential bioindicator. And, consequently, the analysis of the structure of their community could complement the conventional analysis of soil (Bongers 1990; Urzelai et al. 2000; Neher 2001, Pattison et al. 2008).

Geostatistical methods quantify and characterize the spatial variability. In a certain way, the use of these methods has become popular in soil science. Many studies have been conducted on the spatial patterns of soil properties (Goovaerts 1998; Utset and Cid 2001; Amirinejad et al. 2011) and of soil nematodes (Wallace and Hawkins 1994; Shi et al. 2008; Dinardo-Miranda and Fracasso 2010). Despite, more studies for characterization of the spatial variability of soil attributes is essential to a better understanding of complex relations between soil properties and other environmental factors.

Concern about the integrity of the environment necessitates the search for sustainable strategies that maximize productivity and minimize the impact to the environment. Thus, the aim of the present study was to characterize the trophic structure of nematodes communities in soil under sugarcane continuous cropping and remaining of Atlantic Forest areas in Northeastern Pernambuco, Brazil, correlating nematode community structure with mechanical compaction of the soil.

Material and methods

Study sites

This study was conducted in an area (19.14 ha, 7°36'48" S; 34°58'45.9" W) continuous cultivated with sugarcane managed under conventional tillage for over 20 years, and in a remaining area of Atlantic Forest (7°36'45.7" S; 35°00'47.6" W) both located in the Engenho Bujari owned by Usina Santa Tereza—CAIG, Municipality of Goiana, Pernambuco. The areas are characterized by sandy soils. Local climate, according to Köppen Climate Classification, is humid tropical type As' or pseudotropicalis, characterized by hot and humid, with

rains from autumn to winter, and temperature annual averages ranging around 24°C.

Soil sampling

Sampling points were established from September to November 2009 along two 200-m crossed transects in both forest fragment and sugarcane cultivation. Soil cores were taken every 20 m, with Uhland sampler modified of SONDATERRA[®]. At each point, it was sampled soil for physical analysis and soil cores collected at depth 0–10, 10–20, 20–30, 30–40, and 40–50 cm for nematodes' identification and density. Additionally, to verify the spatial variability, the sampling was made each 10 m at depth 0–10 cm.

Nematodes analyses

The samples for nematodes were processed from aliquots of 300 cm³ of soil by the method of centrifugal flotation in sucrose solution (Jenkins 1964). The suspensions obtained were placed in vials and stored under refrigeration until the moment of reckoning. The population estimate was obtained by counting on Peters' slides, under an optical microscope, with two replications, and results computed per 300 cm³ of soil. Nematodes were classified according to feeding habits in five trophic groups (plant-feeders, bacterivores, fungivores, predators, and omnivores), based on the morphology of the stoma and esophagus, according to Yeates et al. (1993). Plant-feeding nematodes were identified to genus level according to the May et al. (1996). Nematode community structure was described by trophic groups and the ratios fungivores/bacterivores (F/B) and omnivores+predators/bacterivores+fungivores+plant-feeders (O+P)/(B+F+PF) (Gomes et al. 2003).

Physical properties analyses

For measure of soil compaction, it was used digital record penetrometer PNT-2000 Soil Control[®]. The acquisition mode was vertical with measurement of soil compaction to 400 mm in both studied sites. The cone used was the type 2 (medium) with an area of 129 mm².

The following soil physical analyses were performed at the Laboratory of Soil Mechanics and Waste Utilization, according to EMBRAPA (1997):

1. Particle size analysis: carried out by the hydrometer method using sodium hydroxide as dispersant
2. Soil water content: determined by thermogravimetric method, which is to weigh the mass of moist soil and then dry it in an oven at 105–110°C for 24 h, and after, to determine their dry weight
3. Soil particle density: measured using 50-mL volumetric flask using 20 g of air-dried soil and alcohol as fluid to determine the volume occupied by the particles
4. Soil bulk density: checked after the assessment of water content and determined by the volumetric ring method, which relies on the use of a ring of sharp edges with known internal capacity
5. Total porosity: calculated from the values of soil particle density (Dp) and soil bulk density (Ds), according to the formula: $P = (Dp - Ds) \times \left(\frac{100}{Dp}\right)$

Statistical and spatial variability analysis

Through analysis of data generated by physical and nematodes analysis were made calculations of Pearson's correlation coefficients using the program Statistical Analytical System (SAS). For spatial variability analysis, the soil physical properties (penetration resistance, water content, total porosity, and bulk density), and nematodes communities (plant-feeders and free-living) were analyzed by descriptive statistic and geostatistical techniques. The normality hypothesis of data was tested by Kolmogorov–Smirnov Test using the software SAS (Schlotzhaver and Littell, 1997).

Concerning to variability of analyzed attributes was adopted the classification of Warrick and Nielsen (1980), where the variability is classified as low (CV<12%), mean (12≤CV≤62%), and high (CV>62%). For knowledge, the degree of spatial dependence was used criteria reported by Cambardella et al. (1994). In that, the parameters are computed by finding the percentage ratio of nugget to sill value of semivariogram, which if found less than 25% is considered as the indicator of strong spatial dependence and if between 26% and 75% is indicator of moderate spatial dependence; otherwise, the variable have a weak spatial dependence.

The spatial dependence was examined by geostatistical tools: GS+(Robertson 1998) and Geostatistical Environmental Assessment Software (Englund and

Sparks 1992), adopting the classic estimator of semi-variance (Journel and Huijbregts 1978), where γ is the estimated semivariance value since of experimental data, $N(h)$ is the pairs number of observation $Z(x_i)$ and $Z(x_i+h)$ separated by distances h (Landim 1998).

$$\gamma^*(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [Z(x_i) - Z(x_i+h)]^2$$

The parameters of theoretic semivariogram were represented in the graphics defined by the range (a), sill (C_1), and nugget effect (C_0), fitted so that the mean squared errors are minimized. The semivariogram models are spherical, linear, exponential, and Gaussian (McBratney and Webster 1986). The adjustments of the models were chosen on the parameters of semivariograms, coefficients of determination (R^2), and self-validation (“Jack-Knifing”).

The trend was verified and removed using the procedure described by Davis (1986), whereby one can fit a polynomial to the property values as a function of the coordinates and cause the residual to be obtained by difference between measured and estimated values by polynomial in each point.

Results and discussion

Soil nematodes

Total nematode abundance

The nematode community composition varied within studied environments (Table 1). In sugarcane field, it was identified seven genera of plant-feeders and five families: bacterivores (two families), fungivores (one family), omnivores (one family), and predators (one family). In the forest soil, it was identified, in addition to previous measurements, more five genera of plant-feeders (Table 1).

In this study, omnivores were more representatives in forest rather than sugarcane soil, with 30% of dominance followed by bacterivores Rhabditidae, with 19%. This group has been considered more sensitive to environmental changes, because they occupy higher levels in food chains. In stable environments, they are numerous and plentiful (Wasilewska 1997; Yeates 1999). Gomes et al. (2003) and Goulart and Ferraz (2003) pointed out the sensitivity of

Dorylaimidae to cultural practices, resulting in low densities in cultivated soils, whereas its presence is synonymous of stability in the ecosystem.

Plant-feeding nematodes tend to be favored by monocultures (Pattison et al. 2008). Sites with many stresses or environmental disturbances, such as the intensively cultivated agroecosystems, provide the prevalence of the plant-feeder communities (Cares and Huang 1991; Niles and Freckman 1998; Gomes et al. 2003; Mondino et al. 2006, 2009). Thus, the results hereby are consistent with this assertion; plant-feeders prevailed under monoculture with dominance of 81%, highlighting the genera *Pratylenchus* and *Helicotylenchus* with dominance of 39% and 25%, respectively. These ratios were similar to those found by Mondino et al. (2009) in experiments with pineapple, beans, maize-bean intercropping and arrowroot, as well those results of Kimenju et al. (2009) in crops with beans and corn, and Li et al. (2007) in maize cultivation.

In the forest, there was a predominance of free-living nematodes, which corresponded to 64% of total abundance, confirming the results found by Kimenju et al. (2009) also in the forest. This response must be linked to the fact that forests have a higher content of organic matter in soil, which favors microbial fauna, allowing dominance of free-living nematodes (Papatheodorou et al. 2004). However, bacterivores nematodes corresponded to 21%. These usually are associated with the decomposition of organic matter, which explains its prominence in the forest. Yeates (2003) observed that soil water content and soil organic matter provide a relative increase in the number of species in Rhabditidae. Yeates and Bongers (1999) emphasized bacterivores dominance in forest under temperate conditions also and found low contribution of predators and plant-feeders in that environment. According to Niles and Freckman (1998), the Rhabditidae family predominates in initial phases of organic matter decomposition and over time will be replaced by Cephalobidae family, which is predominating in a mature community. Thus, nematode communities have not reached the climax in the areas of study, since Rhabditidae was prevalent.

The plant-feeders in forest area accounted for 36%, in which the predominant genera were *Xiphinema* and *Tylosorus*, both with 12% of dominance. Mattos (2002) also noted the prevalence of *Xiphinema*, although in the native area of Savannah. Mattos et al. (2008) observed dominance of this genus in cultivation

Table 1 Abundance, average, and dominance of the nematode communities associated to area cultivated continuously with sugarcane and to Atlantic Forest area in Northeastern Pernambuco

Trophic groups/Taxon	Sugarcane area			Forest area		
	A	Means±SD	D (%)	A	Means±SD	D (%)
Bacterivores						
Cephalobidae	320	2.46±10.95	1.05	404	1.55±7.06	1.42
Rhabditidae	853	6.55±16.32	2.80	5,555	21.36±32.79	19.51
Fungivores						
Aphelenchidae	704	5.41±15.38	2.31	346	1.33±6.20	1.21
Omnivores						
Dorylamidae	2,382	18.32±35.37	7.83	8,439	32.45±44.23	29.65
Predators						
Mononchidae	1,545	11.88±47.00	5.08	3,341	12.85±25.14	11.74
Plant-feeders						
<i>Criconemella</i>	658	5.06±14.89	2.16	884	3.40±12.58	3.11
<i>Helicotylenchus</i>	7,774	59.80±81.43	25.56	704	2.70±11.95	2.47
<i>Hemicicliophora</i>	36	0.27±2.27	0.12	99	0.38±4.59	0.35
<i>Meloidogyne</i>	1,074	8.26±19.00	3.53	716	2.75±9.84	2.52
<i>Pratylenchus</i>	11,788	90.67±107.56	38.76	510	1.96±8.34	1.79
<i>Paratrichodorus</i>	0.00	0.00±0.00	0.00	20	0.07±1.24	0.07
<i>Rotylenchulus</i>	0.00	0.00±0.00	0.00	293	1.12±6.69	1.03
<i>Tylenchus</i>	0.00	0.00±0.00	0.00	75	0.28±3.28	0.26
<i>Trichodorus</i>	1,229	9.45±24.66	4.04	41	0.15±1.83	0.14
<i>Tylosorus</i>	0.00	0.00±0.00	0.00	3,321	12.77±27.33	11.67
<i>Xiphinema</i>	2,046	15.73±30.96	6.73	3,566	13.71±24.15	12.53
Total Nematodes	30,408	233.90±177.45		28,463	109.47±88.13	
F/B		0.30±0.78			0.04±0.18	
(O+P)/(B+F+PF)		0.16±0.27			0.86±1.15	

A (abundance) sum of nematodes number in 130 samples from each area by taxa per 300 cm³ of soil, Means±SD means number and standard deviation of nematodes per 300 cm³ of soil in each area, D (%) dominance of each trophic group and taxa expressed as a percentage, F/B mean ratio between fungivores and bacterivores, (O+P)/(B+F+PF) mean ratio between omnivores+predators and bacterivores+fungivores+plant-feeders

of *Eucalyptus* spp. and *Pinus caribaea*, associating it with cultural systems with minimum tillage corroborating Cadet et al. (2003).

Mononchidae accounted for 5% in sugarcane area and 12% in the forest. Regulating the food web by predation on other nematodes (Grewal et al. 2005), the low trophic dominance of predators is a characteristic feature of annual crops (Mattos 2002). On the other hand, the contrast of omnivore dominance on soil under sugarcane and forest (8% and 30%, respectively) corroborates with Gomes et al. (2003) that reported omnivore prevalence higher than 25% under low human intervention.

Nematode community structure

In the sugarcane area, the plant-feeders are correlated to the other trophic groups (Table 2). Gomes et al. (2003) found a strong correlation between plant-feeders and both fungivores and predators and also between predators and fungivores. In this study, *Meloidogyne* correlated negatively with *Pratylenchus*. Umesh and Ferris (1994) observed that species feeding the roots first inhibited penetration by the latter species. The free-living nematodes stood out, and Rhabditidae correlated with Dorylamidae, Mononchidae, Aphelenchidae, and plant-feeders. On forest, there was signif-

Table 2 Significant correlation coefficients between taxa on area cultivated with sugarcane in Pernambuco

	Acro	Aph	Rha	Cric	Dory	Heli	Hemi	Melo	Mon	Prat	Para	Roty	Tyle	Tric	Tylo	Xiph
Acro										0.28 ^a						
Aph			0.34 ^a													
Rha									0.39 ^a							
Dory			0.23 ^a			0.27 ^a		0.49 ^a								
Heli					0.27 ^a											
Melo					0.49 ^a											
Prat		0.26 ^a								-0.17 ^b						
Tric				0.28 ^a												
Xiph					0.20 ^b				0.39 ^a							
Trich				0.28 ^a												
Endo	0.27 ^a	0.28 ^a								0.98 ^a						
Ecto					0.29 ^a	0.86 ^a								0.25 ^a		0.49 ^a
PF	0.26 ^a		0.20 ^b		0.22 ^a	0.56 ^a				0.72 ^a				0.21 ^b		0.30 ^a
FL		0.40 ^a	0.65 ^a		0.54 ^a		0.23 ^a	0.23 ^a	0.75 ^a							0.35 ^a

Acro Acrobeles, *Aph* Aphelenchoides, *Rha* Rhabditidae, *Cric* Criconemella, *Dory* Dorylaimidae, *Heli* Helicotylenchus, *Hemi* Hemicycliophora, *Melo* Meloidogyne, *Mon* Mononchidae, *Prat* Pratylenchus, *Para* Paratrichodorus, *Roty* Rotylenchulus, *Tyle* Tylenchus, *Tric* Trichodorus, *Tylo* Tylodorus, *Xiph* Xiphinema, *Trich* Trichodoridae, *Endo* plant endoparasites, *Ecto* plant ectoparasites, *PF* plant-feeders, *FL* free-living

^aSignificant at 1%

^bSignificant at 5%

ificant correlation between Rhabditidae and plant ectoparasites and between *Helicotylenchus* and *Hemicycliophora*. *Tylo* correlated with *Meloidogyne*, *Pratylenchus*, and *Xiphinema* (Table 3).

Nematode community indices

The ratio of fungivores to bacterivores nematodes (F/B) is known to be an important indicator of the relative organic matter decomposition pathway in detrital food webs (Sohlenius and Sandor 1987). In this study, the F/B ratio was lower than 1 in both sugarcane (0.30 ± 0.78) and in forest (0.04 ± 0.18) areas. Liang et al. (2001) recorded similar values in peanut cropping; Tong et al. (2010) in forest and Steinberger et al. (2001) in desert. The low F/B ratio indicates decomposition of organic matter was based more on bacterial than fungal action. Bacterial population favors the bacterivore communities directly reflecting in the decomposition of organic matter (Freckman and Caswell 1985). Thus, the organic material decays faster (Porazinka and Coleman 1995), because the decomposition rate of bacteria-based food chain is faster than that based on fungi, reflecting the

structure of soil microbial communities (Liliana 2003).

The ratio O+P/B+F+PF reflected lower incidence of omnivores and predators in relation to other trophic groups, with higher value in forest (0.86) than in sugarcane area (0.16). This low value is reflection of annual crops (Neher and Campbell 1994).

Correlations between soil physical properties and nematode communities

The nematode communities associated with the study sites was correlated with soil physical properties (Table 4). The soils of the sites evaluated are characterized by sandy to sandy loam texture. In the forest, the positive correlations were expressed between the sand particle size fraction and the Rhabditidae and *Hemicycliophora*. This can be supported by the fact that bacterivores require larger pore spaces for their activities while the plant-feeders are favored in soils with sandy texture. Olabiyi et al. (2009), studying nematode communities in environments with different soil textures, found prevalence of plant-feeders in sandy soils also. Negative correlations were expressed between sand and the

Table 3 Significant correlation coefficients between taxa on remaining of Atlantic Forest in Pernambuco

	Acro	Rha	Cric	Dory	Heli	Hemi	Melo	Mon	Prat	Para	Roty	Tyle	Tric	Tylo	Xiph
Rha				0.12 ^b											
Dory															
Heli		0.16 ^a									0.22 ^a				
Hemi		0.14 ^b	0.21 ^a												
Melo										0.23 ^a					
Mon													0.15 ^b		
Prat			0.17 ^a									0.37 ^a			
Roty					0.22 ^a										
Tyle							0.13 ^a		0.37 ^a						
Tylo															0.28 ^a
Trich								0.16 ^a		0.55 ^a			0.82 ^a		
Endo			0.17 ^a				0.78 ^a		0.67 ^a	0.16 ^a		0.33 ^a			
Ecto		0.17 ^a	0.35 ^a		0.25 ^a	0.14 ^b					0.14 ^b		0.13 ^b	0.74 ^a	0.68 ^a
PF		0.19 ^a	0.38 ^a		0.22 ^a	0.16 ^a	0.20 ^a		0.22 ^a		0.14 ^b			0.69 ^a	0.64 ^a
FL	0.18 ^a	0.57 ^a		0.76 ^a				0.40 ^a						0.15 ^b	

Acro Acrobeles, *Aph Aphelenchoides*, *Rha Rhabditidae*, *Cric Criconemella*, *Dory Dorylaimidae*, *Heli Helicotylenchus*, *Hemi Hemicycliophora*, *Melo Meloidogyne*, *Mon Mononchidae*, *Prat Pratylenchus*, *Para Paratrichodorus*, *Roty Rotylenchulus*, *Tyle Tylenchus*, *Tric Trichodorus*, *Tylo Tylodorus*, *Xiph Xiphinema*, *Trich Trichodoridae*, *Endo* plant endoparasites, *Ecto* plant ectoparasites, *PF* plant-feeders, *FL* free-living

^aSignificant at 1%

^bSignificant at 5%

Acrobeles, silt and both *Aphelenchoide* and *Tylo*, clay and *Hemicycliophora*.

The positive correlation between soil water content and Mononchidae could be favored by higher water content in the soil, facilitating their movement in search of their prey. In contrast, the plant-feeder *Hemicycliophora* showed negative correlation. In the forest area, the correlation between soil water content and both Mononchidae and *Tylo* was negative. This behavior may be associated with greater competition among the representatives of other trophic groups.

Criconemella was the only taxon that showed positive correlation with soil depth; although Li et al. (2007) claim that the plant-feeders distribution in the soil profile is a reflection of the roots distribution. However, in forest area, there was a negative correlation between soil depth and the free-living nematodes: Rhabditidae, Dorylaimidae, and Mononchidae, showing that they are concentrated in the surface layers of soil, which agrees with the results of Tita et al. (2002) and Meng et al. (2006).

In the sugarcane area, the soil bulk density was positively correlated with the plant-feeders *Hemicycliophora* and *Pratylenchus*, and negatively with *Meloidogyne*, Mononchidae, and *Xiphinema*, although *Meloidogyne* and *Xiphinema* correlated positively with soil total porosity, demonstrating these genera are pore spaces dependent, essential for gas exchange taking place via the cuticle. Olabiyi et al. (2009) also observed the predominance these nematodes in sandy soils, whereas *Hemicycliophora* and *Pratylenchus* had negative correlations with the soil total porosity. These results agree with those on *Pratylenchus* observed by Li et al. (2007), highlighting the plight of this genus by pore spaces.

In the forest, just *Paratrichodorus* correlated negatively with soil total porosity, which shows the preference of this genus by pore spaces, unlike Rhabditidae and *Tylo* which presented negative correlation with soil bulk density. Moreover, Rhabditidae was positively correlated with soil total porosity, confirming that the free-living nematodes react negatively to the decrease of pore spaces in

which concentrate their activities (Jones and Thomasson 1976; De Goede and Bongers 1994; Bouwman and Arts 2000).

The free-living nematodes were negatively correlated with soil penetration resistance, which may have occurred due to the decrease of pore spaces by increasing of the soil bulk density. Cephalobidae inversely correlated with soil total porosity, which was also revealed by Yeates (2003), suggesting a possible relationship between soil degradation and this family. The positive correlation between *Criconemella* and penetration resistance agree with the results found by Bouwman and Arts (2000), revealing that the plant-feeders are influenced positively in more compacted soils, as well as by the greater soil bulk density.

Soil physical properties

Soil penetration resistance

The soil mechanical resistance correlated with the soil bulk density (Table 5). Similar results were obtained by Ribon et al. (2003), Araújo et al. (2005) and Serafim et al. (2008). In contrast, penetration resistance correlated negatively with soil water content, corroborating the claims of Imhoff et al. (2001), Utset and Cid (2001), Vaz et al. (2001), Castrignano et al. (2002), Cunha et al. 2002, Genro Júnior et al. (2004), and Kılıç et al. (2004).

Both the bulk density as the penetration resistance were correlated with depth (Table 5), as reported by Franzen et al. (1994) and Bouwman and Arts (2000).

Table 4 Significant correlation coefficients between soil physical properties and taxa distribution on area cultivated with sugarcane and remaining of Atlantic Forest in Pernambuco

	De	WC	BD	PD	Po	Sa	St	Cl	PR
Sugarcane									
Aph							-0.21 ^b		
Cric	0.26 ^a								
Dory	-0.28 ^a								
Heli	-0.29 ^a								
Hemi		-0.17 ^b	0.20 ^b		-0.22 ^a				
Melo	-0.23 ^a		-0.24 ^a		0.20 ^b				
Mon	-0.19 ^b	0.26 ^a	-0.21 ^b						
Prat			0.23 ^a		-0.21 ^b				
Xiph	-0.31 ^a		-0.23 ^a		0.17 ^b				
FL									-0.22 ^b
Forest Remaining									
Acro						-0.12 ^b			
Rha	-0.14 ^b		-0.21 ^a		0.23 ^a	0.12 ^b			
Cric									0.18 ^b
Dory	-0.16 ^a								
Hemi						0.13 ^b		-0.19 ^a	
Mon	-0.12 ^b	-0.17 ^a							
Para					-0.13 ^b				
Tyle				-0.16 ^a					
Tylo		-0.19 ^a	-0.13 ^b				-0.12 ^b		

Acro Acrobeles, *Aph* Aphelenchoides, *Rha* Rhabditidae, *Cric* Criconemella, *Dory* Dorylaimidae, *Heli* Helicotylenchus, *Hemi* Hemicycliophora., *Melo* Meloidogyne, *Mon* Mononchidae, *Prat* Pratylenchus, *Para* Paratrichodorus, *Roty* Rotylenchulus, *Tyle* Tylenchus, *Tylo* Tyloporus, *Xiph* Xiphinema, *FL* free-living, *De* depth, *WC* water content, *BD* bulk density, *PD* particle density, *Po* total porosity, *Sa* sandy, *St* silt, *Cl* clay, *PR* penetration resistance

^aSignificant at 5%

^bSignificant at 1%

Table 5 Significant correlation coefficients between physical properties in area cultivated with sugarcane and remaining of Atlantic Forest in Pernambuco

	De	WC	BD	PD	Po	Sa	St	Cl	PR
Sugarcane									
BD	0.28 ^a	-0.46 ^a							
PD	0.25 ^a								
Po		0.48 ^a	-0.76 ^a	0.58 ^a					
Sa		-0.34 ^a	0.34 ^a		-0.23 ^a				
St		0.31 ^a	-0.29 ^a		0.27 ^a	-0.81 ^a			
Cl		0.27 ^a	0.31 ^a				0.55 ^a		
PR	0.63 ^a		0.37 ^a		-0.26 ^a				
Forest Remaining									
De			0.24 ^a						
BD	0.24 ^a								
Po	-0.29 ^a		-0.86 ^a	0.30 ^a					
PR	0.77 ^a								

De depth, WC water content, BD bulk density, PD particle density, Po total porosity, Sa sandy, St silt, Cl clay, PR penetration resistance

^a Significant at 1%

Consequently, both were negatively correlated with the soil total porosity. This result resembles that of Lopes et al. (2007). Soil penetration resistance was higher in areas under sugarcane, showing higher levels of compaction when compared to the native area (Fig. 1). According to Bouwman and Arts (2000), penetration resistance is higher in areas more compact. Costa et al. (2003) showed that conventional tillage compared with native vegetation, increased penetration resistance due to degradation of properties related to the shape and stability of soil structure, also shown by the increase in soil bulk density. Results also correlated with the observations of Valpassos et al. (2001) and Araújo et al. (2004), which show that the soil bulk density was lower in the native area when compared with agricultural systems managed or not.

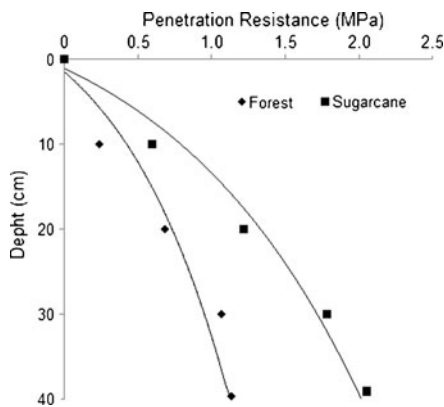


Fig. 1 Soil penetration resistance evaluated at different depths in two environments: conventional sugarcane compared to the Atlantic Forest remaining in Pernambuco

Soil water content

In sugarcane area, the soil water content was negatively correlated with soil bulk density and sand. And there was positive correlation with total porosity, silt, and clay. This result emphasizes that the increase in soil water content decreases the soil bulk density, and consequently also decreases total porosity, corroborating to Timm et al. (2006) that claims that the soil water content influences important process in the soil, such as: soil compaction, water movement, soil aeration, and roots development.

Soil bulk density

In both studied sites, the soil bulk density showed positive correlation with the depth, sand, clay, and penetration resistance. The bulk density typically increases with the depths because the subsurface layers have reduced organic matter compared surface layer. Thus, the organic matter has been used to improve soil conditions, consequently, preventing the soil compaction. On the other hand, the soil bulk density had negative correlation with the water content, total porosity, and silt.

Soil total porosity

In both areas, the particle density had positive correlation with the soil total porosity and bulk density negative. However, penetration resistance presented negative correlation in sugarcane area. This

Table 6 Descriptive statistics for soil nematodes and soil physical properties under conventional sugarcane and remaining Atlantic Forest in Pernambuco

	Endo	Ecto	PF	FL	PR	WC	Po	BD
Sugarcane								
Max	196.00	279.00	462.00	176.00	0.73	0.24	53.67	1.69
Min	0.00	0.00	0.00	0.00	0.10	0.13	31.61	1.16
Mean	70.00	110.11	198.95	54.69	0.38	0.19	42.60	1.44
Median	61.00	98.00	189.50	44.00	0.37	0.20	41.51	1.45
Kurtosis	-0.26	-0.19	0.16	0.19	-1.06	-0.65	-0.61	0.22
CV (%)	71.27	64.16	53.10	88.94	46.72	14.23	12.71	7.69
St. D.	49.89	70.64	105.63	48.65	0.18	0.03	5.41	0.11
KS	*	*	*	*	*	*	*	*
Forest Remaining								
Max	84.00	159.00	272.00	259.00	0.34	0.23	59.34	1.51
Min	0.00	0.00	0.00	0.00	0.06	0.10	33.91	1.05
Mean	26.72	46.21	72.84	82.81	0.21	0.14	49.11	1.26
Median	31.00	38.00	74.00	66.00	0.21	0.14	49.02	1.24
Kurtosis	-0.97	0.25	0.68	-0.86	-0.25	0.50	0.39	-0.84
CV (%)	100.61	94.17	89.35	87.84	30.20	20.11	11.51	9.41
St. D.	26.89	43.52	65.08	72.74	0.06	0.03	5.65	0.12
KS	— ^a	— ^a	— ^a	— ^a	— ^a	— ^a	— ^a	— ^a

Endo plant endoparasites, Ecto plant ectoparasites, PF plant-feeders, FL free-living, PR penetration resistance, WC water content, Po total porosity, BD bulk density, KS Kolmogorov–Smirnov Test
^aNormal distribution with level of 1% and 5% of significance

Table 7 Semivariogram parameters, degree of spatial structure, and cross-validation of the nematodes communities and physical properties of soil from the sugarcane cultivation and remaining of Atlantic Forest in Pernambuco

Variable	Model	C ₀	C ₁	C ₀ +C ₁	Range (m)	R ²	C ₀ /C ₀ +C ₁	Spatial structure	Jack-Knifing parameters		
									Mean	St. Deviation	
Sugarcane											
Endo	Pure nugget effect										
Ecto	Pure nugget effect										
PF	Pure nugget effect										
FL	Pure nugget effect										
PR	Spherical	0.0205	0.0155	0.0361	52.52	0.53	0.57	Moderated	-0.04	0.833	
WC	Spherical	0.0001	0.0006	0.0007	27.30	0.36	0.14	Strong	-0.01	1.08	
Po	Spherical	8.9500	23.12	32.07	84.50	0.73	0.28	Moderated	-0.017	0.934	
BD	Exponential	0.0042	0.0083	0.0125	94.80	0.76	0.34	Moderated	0.002	0.961	
Forest Remaining											
Endo	Pure nugget effect										
Ecto	Spherical	1554.97	554.971	2109.94	29.98	0.23	0.73	Moderated	0.04	1.035	
PF	Pure nugget effect										
FL	Spherical	3443.3	1943.3	5383.6	23.37	0.21	0.63	Moderated	-0.01	1.03	
PR	Spherical	0.0006	0.0033	0.0039	15.66	0.12	0.15	Strong	0.065	1.019	
WC	Spherical	0.0004	0.0006	0.0010	89.5	0.84	0.40	Moderated	0.027	0.925	
Po	Spherical	16.145	15.145	31.29	62.35	0.57	0.36	Moderated	0.001	1.038	
BD	Exponential	0.0075	0.0076	0.0151	33.70	0.46	0.49	Moderated	0.051	0.911	

Endo plant endoparasites, Ecto plant ectoparasites, PF plant-feeders, FL free-living, PR penetration resistance, WC water content, Po total porosity, BD bulk density

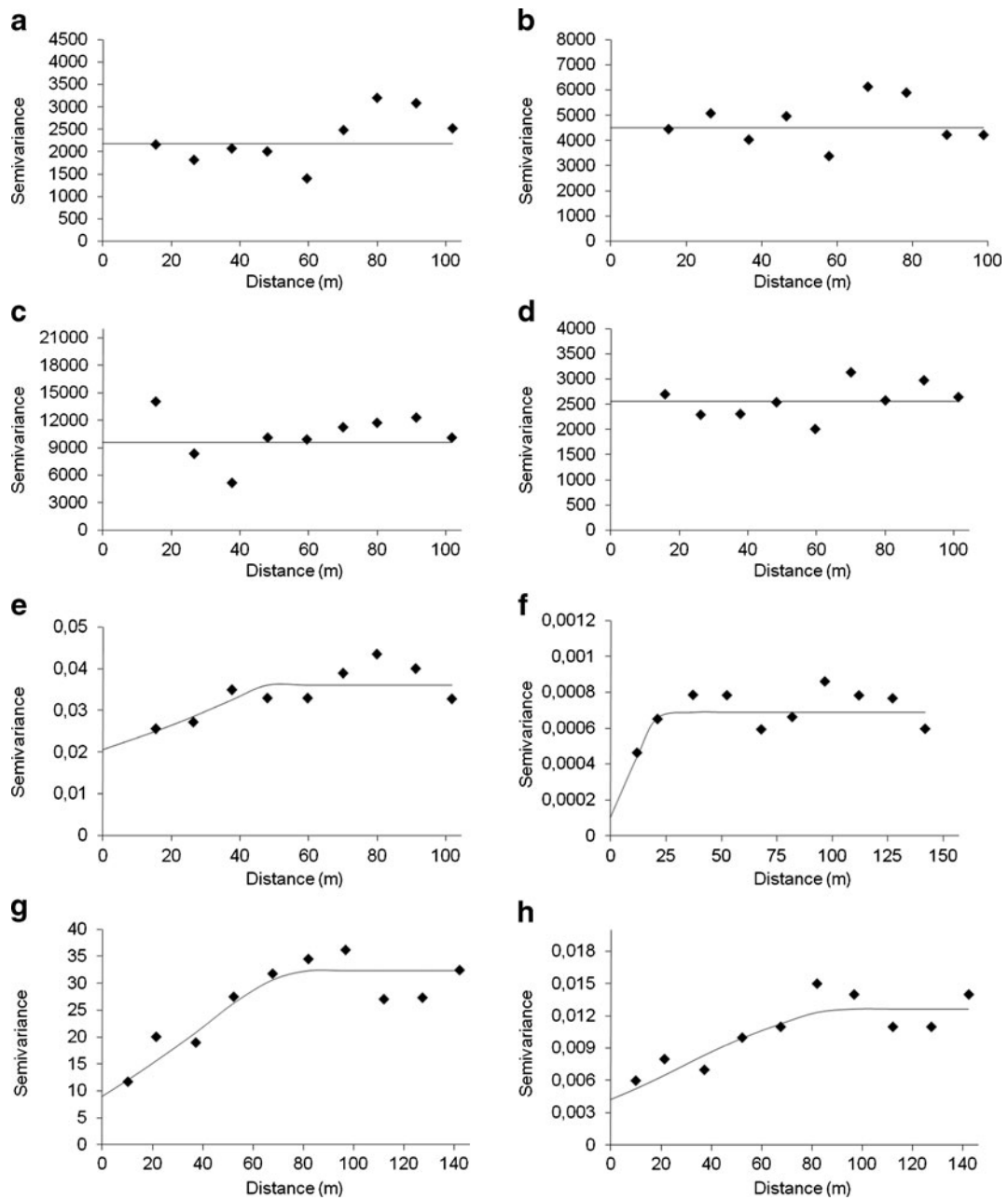


Fig. 2 Semivariograms fitted of conventional sugarcane **a** plant endoparasites **b** plant ectoparasites **c** plant-feeders **d** free-living **e** penetration resistance **f** water content **g** total porosity **h** bulk density

result means the bulk density and the penetration resistance are directly influenced by total porosity. Confirming data found by Araújo et al. (2004) that also compare forest and cultivated soil observed that bulk density and total porosity affected the penetration resistance.

Soil texture

Regarding the size fractions, the clay was positively correlated with the bulk density, similar to the result of Kılıç et al. (2004). The clay was also positively correlated with water content and silt. The sand was

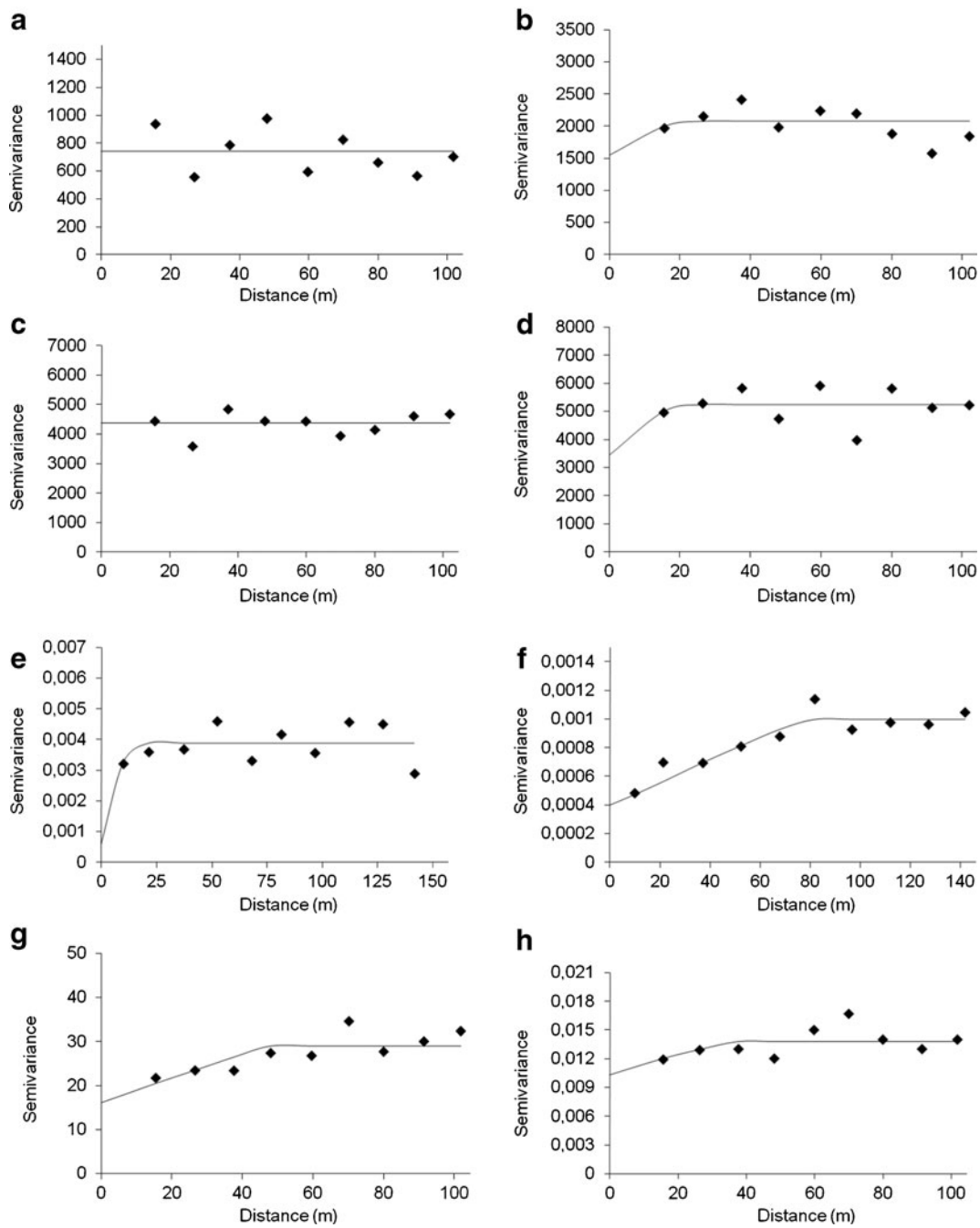


Fig. 3 Semivariograms fitted of forest area **a** plant endoparasites **b** plant ectoparasites **c** plant-feeders **d** free-living **e** penetration resistance **f** water content **g** total porosity **h** bulk density

negatively correlated with water content and positively with total porosity and bulk density. The silt was positively correlated with the water content and total porosity and negatively with sand and soil bulk density.

Spatial variability analyses of soil physical properties and soil nematodes

The Kolmogorov–Smirnov Test for forest and sugarcane areas indicated normality for soil physical

properties and soil nematodes (Table 6). According to classification proposed by Warrick and Nielsen (1980) the coefficients of variation (CV) for soil nematodes were extremely elevated in both studies sites, presenting higher differences between maximum and minimum population (Table 6), except plant-feeders nematode in sugarcane area. This result corroborate with Shi et al. (2008) when comparing degraded with meliorated area, obtaining CV in degraded area similar to this study in sugarcane area.

Soil physical properties variation was lower than the nematodes, except for total porosity in sugarcane area and bulk density in both areas. The bulk density CV was relatively low as compared to the other measured properties, this value agrees with those values reported for Utset and Cid (2001) and Amaro Filho et al. (2007).

Based in the obtained experimental semivariations in the studied sites (Table 7), the semivariogram models fitted of soil water content, soil total porosity and penetration resistance exhibited spherical model but exponential model for the soil bulk density. Spherical model was the best fitted for ectoparasites and free-living nematodes under forest. The estimated parameters for the models (C_0 , C_1 , a) were validated by criteria of Jack-Knifing, since the standard errors showed mean near to zero and standard deviation near to one (Table 7).

Range values obtained for soil physical properties (penetration resistance, water content, total porosity, and bulk density) in both forest and sugarcane areas ranged of 27 to 95 and 15 to 90 m, respectively (Table 7). Nematodes (plant ectoparasites and free-living) in forest presented ranges of 23 and 30 m. These results mean that the classic statistic can be applied from collected samples above of these distances, since collected points with distance higher than the range are independents.

The semivariograms corresponding to the soil nematodes in sugarcane area exhibited pure nugget effect (Fig. 2a–d). This result is in agreement with those reported by Dinardo-Miranda and Fracasso (2010) that characterized the spatial and temporal variability of plant-feeders nematodes in sugarcane and observed this behavior in 22 of 52 calculated semivariograms. In forest, the plant endoparasites and plant-feeders nematodes also could not be fitted to any model (pure nugget effect, Fig. 3a, c), indicating that the spatial distribution occurred at random. Thus,

the spatial variability of the soil physical properties was similar in both forest and sugarcane areas. However, the plant endoparasites nematodes no presented spatial dependence in forest, as well as, the soil nematodes in sugarcane, presenting at random. The plant ectoparasites and free-living nematodes in forest show up in aggregate, but in sugarcane, they did not have dependence, showing up uniform. This fact can be reflex of the applied management in the conventional sugarcane system, causing the spread nematodes stay more regularly.

Conclusion

The total amount of nematodes did not differ between the environments, but in forest the free-living nematodes: omnivorous followed by bacterivores were the most prevalent. While in area under sugarcane, plant-feeders were the most prevalent.

- Dorylaimidae demonstrated greater sensitivity to changes in soil physical properties.
- Nematode diversity of soil nematodes was higher in the remaining of Atlantic Forest.
- The soil penetration resistance was higher in area cultivated with sugarcane.
- Spatial variability of the soil physical properties was similar in both forest and sugarcane areas.
- The plant endoparasites nematodes do not present spatial dependence in forest, as well as, in sugarcane, presenting at random.
- The plant ectoparasites and free-living nematodes in forest showed up in aggregate but in sugarcane showed up in uniform.

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