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ORIGINAL ARTICLE

Nematode abundance and diversity in sugarcane fields in Brazil

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Abstract

Edaphic climatic conditions directly affect the population dynamics of nematode assemblages and management strategies. The objective of this study was to characterize spatiotemporal changes in nematode abundance and diversity in sugarcane fields of northeastern Brazil under different edaphic climatic conditions. Soil samples from seven geoenvironmental sites under continuous cultivation were taken at planting and 4, 9, and 14 months after planting. Nematode abundance and diversity varied with the soil's physical and chemical characteristics. Sites in the rainfed and irrigated coastal tables as well the floodplain had higher number of nematodes in contrast to the flat-land and hillside. The abundance of plant-parasitic nematodes increased concurrently with crop development, but the number of taxa decreased. *Meloidogyne* and *Pratylenchus* were the dominant plant-parasitic genera across locations, but bacterivores were dominant in southern sites at field replanting. Heat map delineated two distinct groups of nematode distribution within the geoenvironmental zones, rather than the sampling times. *Pratylenchus* density was high in both groups, but in contrast with *Meloidogyne* and *Criconemella*, the abundance of *Pratylenchus* and *Helicotylenchus* was higher in sites with lower soil bulk density and higher porosity, clay, organic matter, and water contents as those in the southern sites, reflecting edaphic climatic conditions.

Keywords Biomonitoring · Edaphic climatic effect · *Meloidogyne* · Microbivores · *Pratylenchus* · *Saccharum*

Introduction

Sugarcane (*Saccharum* spp. L.) is one of the most important crops in northeastern Brazil. This crop has been extensively cultivated for over five hundred years in the coastal area once covered by an extension of the Atlantic Forest in eastern Brazil (Rêgo and Hoeflich 2001; Dinardo-Miranda et al. 2008). The life cycle of sugarcane is long (12 to 14 months), requiring warm weather and heavy rainfall or irrigation throughout the growing season. Fields are burned before harvest, during the dry period between September and December. When the cane is harvested, a portion of the stalk is left underground to give rise to a succeeding growth of cane, the ratoon or stubble crop. The ratooning process is usually repeated four to six times, although the yield of ratoon crops decreases after each cycle. At the end of the last cycle, all stumps are plowed out and the field is replanted. Constant use of a few varieties and increasing the planted area on a yearly basis are factors that contribute to high incidence and diversification of pathogens, especially nematodes. Damage is exacerbated by irregular rainfall and sandy soil with poor fertility and low organic matter (dos Santos et al. 2009; de Oliveira et al. 2011).

Meloidogyne incognita (Kofoid & White) Chitwood, *M. javanica* (Treub) Chitwood and *Pratylenchus zeae*, Graham are the most adundant, causing significant damage to the crop (Chaves et al. 2002; Rodrigues et al. 2011; Mbega and Nzogela 2012; Silva et al. 2016). Nematodes from the genera *Criconemella* De Grisse and Loof, *Helicotylenchus* Steiner, *Paratrichodorus* Siddiqi, and *Trichodorus* Cobb, comprise a

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second nematode group in northeastern sugarcane fields, but not recognized as important pathogens (Chaves et al. 2003).

Conventional crop management practices, such as applying pesticides and fertilizers to crops and cultivating and irrigating fields, have been continuously applied to increase sugarcane yields. However, these practices lead to changes in the soil's physical, chemical, and biological properties (Stirling et al. 2010; Godefroid et al. 2013), which affect the free-living nematodes assemblages (Yeates 2003; Figueira et al. 2011), as well as the function and stability of soil food webs (Ferris 2010; Sánchez-Moreno et al. 2011; Briar et al. 2012).

The management practices and environmental conditions affect the nematode community composition and damage levels that arise from the number and density of species involved. Due to the abundance, specificity, short reproductive cycle, morphology, and response to changes in the environment, nematodes have been used to evaluate soil quality (Yeates 2003; Godefroid et al. 2013). Indicators based on nematode assemblage composition are among the best-developed metrics of soil health (Ugarte et al. 2013).

In sugarcane fields of northeastern Brazil, nematode assemblage has been correlated to the soil's physical (Cardoso et al. 2011; Rodrigues et al. 2011) and chemical properties (Matos et al. 2011). Knowledge of the relationships between plant-parasitic nematodes and trophic communities' composition during replanting and harvest periods are essential to understand shifts in population dynamics and minimize yield losses (Abd-Elgawad and Askary 2015). Studies of nematode assemblages in monoculture systems can contribute to understanding of the occurrence, relevance, and ecology of plant-parasitic and other soil nematodes. Therefore, the aim of this study was to characterize plant-parasitic nematodes from planting to harvest under different edaphic climatic conditions in sugarcane fields of Northeast Brazil.

Material and methods

Study site

The study was conducted from September 2014 to November 2015 in seven sites from three different sugarcane mills in the state of Pernambuco, Brazil: a) Santa Teresa Mill, located in Goiana (07°33′38"S 35°00′09"W) near the coast; b) Cruangi II Mill, located in Timbaúba (07°30′19"S 35°19′06"W), which is also near the coast, and c) Salgado Mill, located in Barreiros (08°49′06"S 35°11′11"W) in the south coastal area of Pernambuco. The sites from the three mills were once covered by the extension of the Atlantic Forest, but they have been cultivated with sugarcane for more than 100 years.

According to the Köppen's Climate Classification (Alvares et al. 2013), the climate at all study sites are categorized as 'As', or hot and humid with rains from autumn to winter, and an annual average temperature of 24 °C and irregular rainfall distribution (Souza et al. 2004). Rainfall patterns and monthly temperatures during sampling are in Fig. 1; maximum and minimum temperature and relative air humidity (RH) are in Fig. 2.

Soil sampling

Include paragraph to historical records of high nematode infestation from the mills' database, soil samples were taken from seven areas of continuous sugarcane cultivation. The

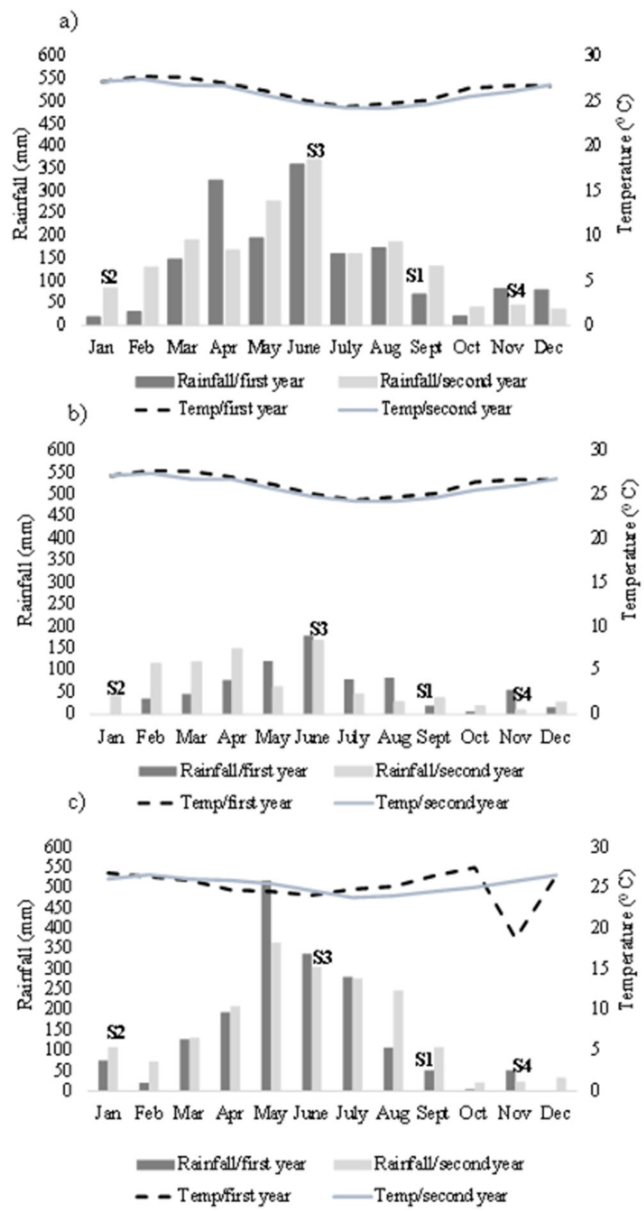

Fig. 1 Monthly distribution of rainfall in 2014 and 2015 in municipalities of Goiana (**a**) and Timbaúba (**b**) in northern Pernambuco, and Barreiros (**c**) in southern Pernambuco, Brazil

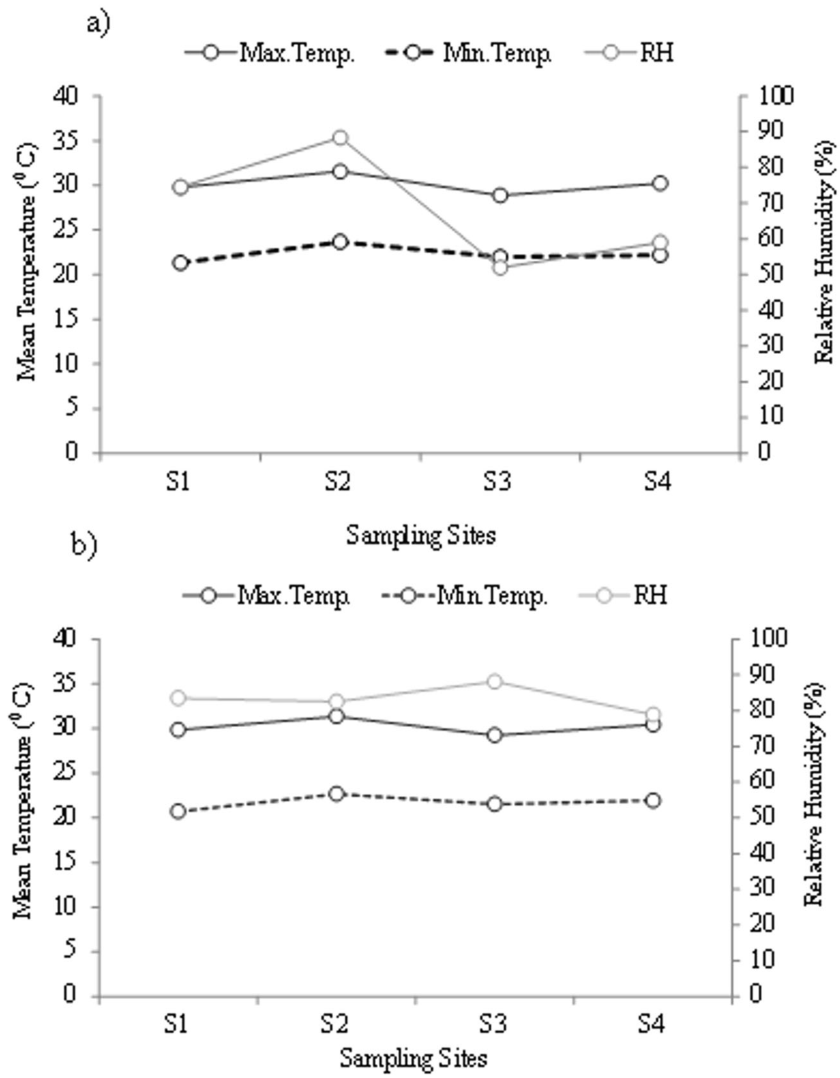

Fig. 2 Maximum and minimum temperature and relative humidity in 2014 and 2015 in municipalities of Goiana (**a**) and Timbaúba (**b**) in northern Pernambuco, Brazil

mill, geoenvironmental zone, and sugarcane variety of each area are presented as following: Site 1 - Santa Teresa, Floodplain (STFP), RB872552; Site 2 - Santa Teresa, Rainfed Coastal Table (STCT), SP71–6949; Site 3 - Santa Teresa, Hillside (STH), RB863129; Site 4 - Cruangi II, Irrigated Coastal Table (CICT), RB863129; Site 5 - Cruangi II, Rainfed Coastal Table (CRCT), RB863129; Site 6 - Salgado, Hillside (SH), SP81–3250; Site 7 - Salgado, Flatland (SF), RB92579. Soil samples were collected a month before field replanting in September of the first year - S1 (sampling time 1); four months after planting in January during the second year - S2; nine months after planting in June during the second year - S3; and 14 months after planting at harvest time in November of the second year - S4.

In each site, 1 kg of soil cores were collected from 0 to 0.25 m depth from a regular square sampling grid, comprising of 36 georeferenced points spaced 5 m from one another, 1008 soil samples throughout the experiment. Samples were packed in plastic bags, containing standardized labels, and taken to the laboratory.

Physical and chemical soil analyses were conducted once at the first sampling period for characterization of the sites (Tables 1 and 2).

Soil physical analysis

Soil physical analyses were performed using methods detailed in Donagema et al. (2011):

i. Soil texture was determined by the hydrometer method using sodium hydroxide as a dispersant.
ii. Soil bulk density (BD) was determined for intact soil cores 5 cm in diameter, 2.5 cm in length, and 50 cm^3 in volume. To determine the water content (WC), soil samples were dried at 105–110 °C for 24 h and weighed before and after to determine their weight loss. BD was

Table 1 Chemical of soils from sugarcane fields in northeastern Brazil in 2014

[1]Site	[2]pH (water −1:2,5)	[3]P (mg/dm^3)	[4]Na^+ (cmol$_0$/dm^3)	[5]K^+	[6]Ca^{+2} + Mg^{+2}	[7]Ca^{+2}	[8]Al^{+3}	[9]H + Al (cmol$_0$/dm^3)	[10]OC g/kg	[11]OM
1 - STFP	5.0	0.8	0.05	0.11	1.50	0.85	0.50	3.73	5.15	8.88
2 - STCT	6.1	52	0.02	0.07	4.00	2.50	0.10	2.58	5.39	9.28
3 - STH	5.6	14	0.03	0.06	2.20	1.15	0.20	2.93	4.04	6.96
4 - CICT	6.9	41	0.05	0.14	4.50	2.40	0.00	2.43	8.60	14.83
5 - CRCT	6.4	22	0.04	0.12	3.40	2.20	0.10	2.93	7.02	12.11
6 - SH	5.9	10	0.05	0.06	3.00	1.60	0.10	3.31	8.72	15.04
7 - SF	6.5	16	0.07	0.39	4.25	2.90	0.50	2.58	9.07	15.64

[1] Study sites: STFP – Santa Teresa floodplain, STCT – Santa Teresa coastal table, STH – Santa Teresa hillside, CICT – Cruangi II irrigated coastal table, CRCT – Cruangi II rainfed coastal table, SH – Salgado hillside, SF – Salgado flatland, [2] Hydrogenionic potential; [3] P – Phosphorus; [4] Na^+ – Sodium; [5] K^+ – Potassium; [6] Ca^{+2} + Mg^{+2} – Calcium + Magnesium; [7] Ca^{+2} – Calcium; [8] Al^{+3} – Aluminum; [9] H + AL – Hydroxide + Aluminum; [10] OC – Organic carbon; [11] OM – Organic matter

estimated by the division between dry weight (DW) and core volume (BD = DW/50 cm^3).

iii. Soil particle density (PD) was determined in a 50 mL volumetric flask using 20 g of air-dried soil and alcohol as fluid to determine the volume occupied by the particles (PD = 20 g/ (50 mL – alcohol volume)).

iv. Total porosity (Po) was calculated from the values of PD and BD (Po = (1- (BD/PD)) × 100).

v. Hydraulic conductivity was calculated based on grain-size distribution through the material.

Soil chemical analysis

Soil samples were air-dried, crushed, and sieved through a 2 mm mesh. Soil pH, P (mg/dm^3), Na^+ (cmol$_0$/dm^3), K^+ (cmol$_0$/dm^3), Ca^{+2} (cmol$_0$/dm^3), Al^{+3} (cmol$_0$/dm^3), Ca^{+2} + Mg^{+2} (cmol$_0$/dm^3), H + Al (cmol$_0$/dm^3), organic carbon content (COT) (g/kg), and organic matter (MO) (g.kg) were investigated. The soil pH in water (1:2.5) was determined electrochemically with the help of the glass electrode pH meter. The macronutrients P, K^+, Na^+ were extracted through Mehlich solution (Pansu and Gautheyrou 2006). Exchangeable bases (Ca^{+2} + Mg^{+2} + K^+) were determined after extraction with KCL 1 mol L^{-1} and an atomic absorption spectrometer (AAS), whereas extractable acidity (H^+ + Al^{+3}) was determined after Al extraction with KCl. Organic carbon content was determined following Yeomans and Bremmer (1988) and organic matter was calculated by multiplying the percent value of organic carbon with the conventional Van-Bemmelene's factor of 1.724 (Donagema et al. 2011).

Soil nematode analysis

Each sample was homogenized and immediately processed for nematode extraction using 60 and 400 mesh sieves from 300 cm^3 of soil subsample through the centrifugal flotation method for 4 min (Jenkins 1964). Suspensions containing plant-parasitic

Table 2 Soils from sugarcane fields in northeastern Brazil in 2014

[1]Site	Particle size composition (%)						[2]FD (%)	[3]BD (g/cm^3)	[4]Po (%)	[5]WC (%)	[6]K(0) (cm/h)
	Sand	Clay	Silt	Silt/Clay	Dispersed clay	Texture					
1 - STFP	74.90	12.60	12.50	0.99	7.60	Sandy loam	39.68	1.39	47.15	2.73	28.63
2 - STCT	93.90	4.10	2.00	0.49	1.60	Sand	60.97	1.56	41.57	1.77	217.85
3 - STH	83.40	10.10	6.50	0.64	5.60	Loamy sand	44.55	1.45	44.87	2.67	21.72
4 - CICT	87.40	7.10	5.50	0.77	3.60	Loamy sand	49.29	1.42	44.53	3.53	24.11
5 - CRCT	89.40	6.60	4.00	0.61	2.60	Sand	60.61	1.48	43.08	2.30	30.24
6 - SH	69.90	24.60	5.50	0.22	17.60	Sandy clay loam	28.45	1.25	52.47	4.10	37.39
7 - SF	74.40	20.60	5.00	0.24	16.10	Sandy clay loam	21.84	1.28	50.77	2.97	27.62

[1] Study sites: STFP – Santa Teresa floodplain, STCT – Santa Teresa coastal table, STH – Santa Teresa hillside, CICT – Cruangi II irrigated coastal table, CRCT – Cruangi II rainfed coastal table, SH – Salgado hillside, SF – Salgado flatland, [2] Flocculation degree; [3] BD – Bulk density; [4] Po – Porosity; [5] Water content; [6] K(0) – Hydraulic conductivity

nematodes were kept under refrigeration (4–6 °C) for genus-level identification. Specimens were counted in Peters slides under microscope (Motic - BA310) at 40× and 100× magnification; the average of the three readings was used.

According to Yeates et al. (1993), nematodes were classified into five trophic groups (plant-parasitic, bacterivores, fungivores, predators, and omnivores) in terms of their feeding habits, which were based on stoma and esophagus morphology. Identification of plant-parasitic nematodes was performed at the genus-level (Mai et al. 1996; Mekete et al. 2012). The nematofauna structure was described through the trophic groups, the ratio of fungivores and bacterivores (F/B), and the ratio of omnivores + predators and bacterivores + fungivores + plant-parasitic (O + P) / (B + F + PP) (Cardoso et al. 2011). The ratio (F/B) is considered an important indicator of the organic matter decomposition process in the food chain (Sohlenius and Sandor 1987), and reflects the structure of soil microbial communities (Ruess 2003). The ratio (O + P) / (B + F + PP) may be a reflection of native or cultivated systems. The low values of this ratio (< 0.2) may indicate annual crops (Neher 1994).

Statistical analysis

Comparisons between the total of each taxon, in each sampling grid separately, were performed searching for relationships among nematode taxa populations, measured by Pearson correlation coefficient using the SAS Statistical Analytical System (SAS, 2015). The hierarchical clustering analysis based on Bray-Curtis' dissimilarity matrix and Ward's algorithm was used to study the structure of nematodes in sugarcane fields; the nematode data were log (x + 1) transformed before analysis to reduce the heterogeneity of variances. Based on the scale generated by the dendogram (Fig. 3), a color convention estimated a variation of light yellow to dark green. The software R version 3.4.0 (R Development Core Team 2017) was used to perform the analysis with the packages cluster (Maechler et al. 2017), gplots (Warnes et al. 2016), RColorBrewer (Neuwirth 2014), and vegan (Oksanen et al. 2017).

Results

Climatic variations of the geoenvironmental sites

During the four sampling times the rainfall average was 569 mm in STFP, STCT, and STH; 238 mm for CICT and CRCT; and 488 mm for SH and SF (Table 1). Maximum and minimum temperature ranged from 20 to 31 °C but RH decreased almost 30% from S1 to S2 in STFP, STCT, STH, CICT, and CRCT (Fig. 2) with higher rainfall in S3, in contrast to S1 and S4 (Table 1). In S1 and S4, STF had a higher number of nematode (Fig. 3), suggesting negative correlation between rainfall and nematode diversity.

Dynamics of the nematode community

The total number of nematodes found in 300 cm^3 of soil during sugarcane renovation ranged from 10,328 to 45,667; plant-parasitic nematodes dominance (proportion ratio of specimens of plant-parasitic nematodes by the total number of specimens) was greater (72, 67, 58, 52, and 52%) in CRCT, STH, STFP, STCP, and CICT, respectively. Sites SH and SF, which were located in southern Pernambuco, were characterized by a greater dominance of bacterivores with 58 and 63%, respectively, while plant-parasitic nematodes dominance was 40 and 33%, respectively (Tables 3 and 4).

Two distinct groups were defined within the geoenvironmental zones, rather than the sampling times, first group the flatland (SF) and hillside (STH, SH), and the second one irrigated coastal table (CICT), rainfed coastal table, (STCT, CRCT) and floodplain (STFP) (Fig. 3).

The sites in the rainfed and irrigated coastal tables as well the floodplain had a higher population of nematodes in contrast to the sites in the flat-land and hillside. Although *Pratylenchus* and *Meloidogyne* were dominant in most samples, the distribution of *Pratylenchus* was more uniform in all sites with a higher density in the hillside and coastal tables (rainfed or irrigated) in the initial sampling times (S1 and S2) and in the floodplain at S1 and S4. The population of *Meloidogyne* was higher in rainfed and irrigated coastal tables despite sampling times (Fig. 3).

Number of *Criconemella* was higher in rainfed and irrigated coastal Tables (S1 and S2) and floodplain (S1 and S4), similarly to *Pratylenchus* and *Meloidogyne* in the floodplain (S1 and S4). On the other hand, *Helicotylenchus* was higher in flat-land (S1) and hillside (S1, S2 and S3).

Pratylenchus showed a 0.63 correlation with Meloidogyne in CICT, as well positive correlation to *Criconemella* sp. in STFP and CICT, Trichodorids (*Paratrichodorus* and *Trichodorus*) in STH and CICT, *Helicotylenchus* in CICT, and *Xiphinema* in STH and SF; negative correlation with *Radopholus* in STFP. Positive correlations between *Pratylenchus* and non-plant-parasitic trophic groups were observed with bacterivores in STFP, STH, and CICT with omnivores in STH and SF and with predators in CICT and SF. There was no correlation between these plant-parasitic nematode genera and the other nematodes found in STCT, CRCT, and SH SF (Table 5).

The coastal tables (STCT, CICT, CRCT) showed the lowest number of *Pratylenchus*, as well total abundance of nematodes, when compared to the other sites. However, there was a high abundance of bacterivores (44.29%), in contrast with an extremely low abundance of fungivores, omnivores, and predators.

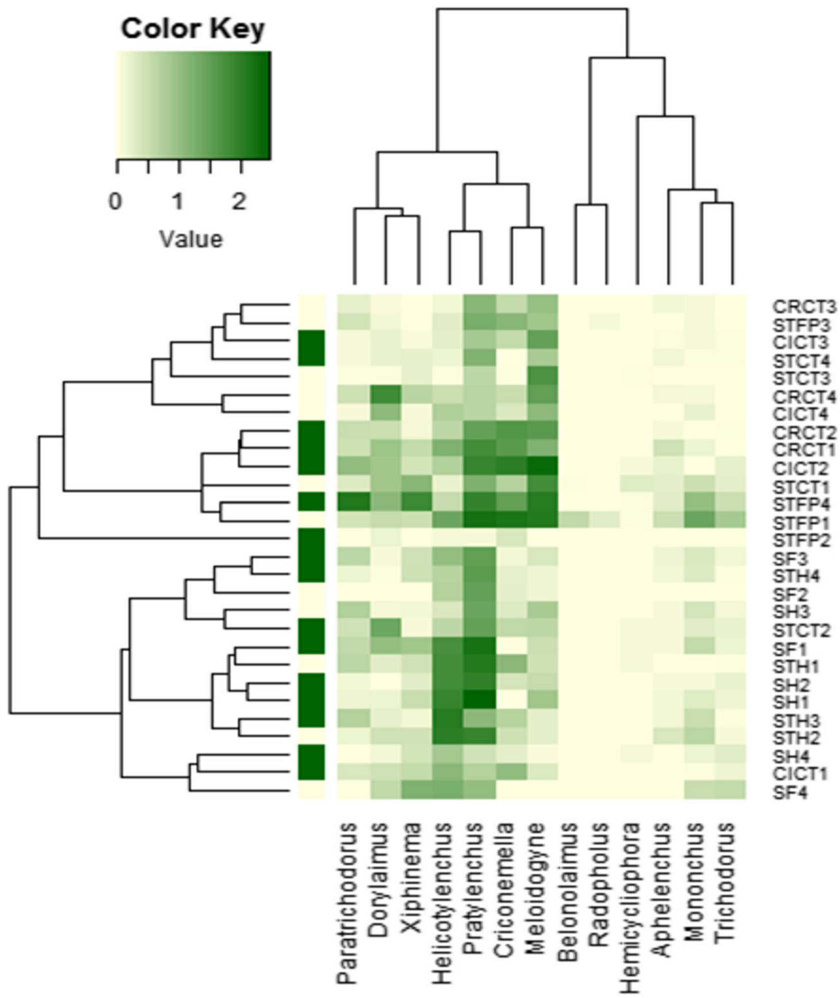

Fig. 3 Heat map of nematode population density in seven sugarcane sites and four sampling time in Brazil. Dendogram in the Y-axes represented the sugarcane fields: Santa Teresa floodplain (STFP); Santa Teresa coastal table (STCT); Santa Teresa hillside (STH); Cruangi II irrigated coastal table (CICT); Cruangi II rainfed coastal table (CRCT); Salgado hillside (SH); Salgado flatland (SF). The color key scale represents log (x + 1) normalized nematode population densities in soil. Light yellow (0–1) represented the spatial and horizontal distribution of the nematodes, which was not uniform (erratic and unequal). Light green (1–2) represented low nematode dominance (low-density population) and dark green (2–3) represented high nematode dominance (high-density population)

Regarding the genus *Meloidogyne*, there were positive correlations with *Criconemella*, *Trichodorus,* and *Pratylenchus* in CICT, and with *Paratrichodorus* in STH and CRCT. A positive correlation between *Meloidogyne* and non-parasitic groups occurred with bacterivores in STCT and STH, omnivores in STFP and STH, and predators in SH. Despite these positive correlations, *Meloidogyne* abundances were low in each site, except STCT (177 specimens per 300 cm^3), corresponding to 30.83% of the total number of nematodes (Table 3).

Pratylenchus was the plant-parasitic nematode dominant in all sites, except STCT and CICT, with the population above damage level. *Meloidogyne* was dominant in STCT, while *Helicotylenchus* was dominant in CICT.

At harvest, there was a change in dominance (proportion ratio of specimens in taxon by the total number of specimens) of important taxa, in contrast to field replanting: *Meloidogyne* was the dominant taxon in STFP, CICT, and CRCT; *Pratylenchus* in STCT and STH; *Helicotylenchus* in SH; and *Xiphinema* in SF (Tables 3 and 4). There was a positive correlation between *Pratylenchus* and the nematodes, *Meloidogyne* in STFP and SH, *Paratrichodorus* in CRCT, *Helicotylenchus* in STH, and *Hemicycliophora* in SH (Table 6). *Meloidogyne* was positively correlated to *Xiphinema* in SH; bacterivores positively correlated with *Pratylenchus* and *Meloidogyne* in STFP, while fungivores negatively correlated to *Meloidogyne* (Table 6).

The total number of nematodes at harvest ranged from 4800 to 46,863, with a higher ratio (ranging from 54 to 67%) of plant-parasitic nematodes by the total abundance of nematodes in all sites, except STCT and STH (Table 4). Apart from STFP, the total number of nematodes per site, including plant-parasitic nematodes, was lower at harvest than at field planting. Concurrently, plant-parasitic nematodes ratio has almost doubled in SH and SF at harvest, presenting smaller fluctuations in the other sites (Tables 5 and 6).

In general, *Criconemella*, *Helicotylenchus*, *Trichodorus*, and *Paratrichodorus* were the most frequent nematodes, but with low abundances (Tables 3 and 4). The number of bacterivores was high in SF at field planting, with a ratio of 63%, similar to STCT (55%) at harvest. Regarding omnivores, it can be highlighted the ratio of 6 and 33% in CRCT at field planting and harvest, respectively. In contrast to predators, the ratio of omnivores and fungivores was not pronounced in STFP at field planting and harvest, though the

Table 3 Mean and dominance of nematode assemblages in sugarcane fields at replanting in northeastern Brazil in 2014

	STFP		STCT		STH		CICT		CRCT		SH		SF	
	Mean ± SD	D^c (%)	Mean ± SD	D^c (%)	Mean ± SD	D^c (%)	Mean ± SD	D^c (%)	Mean ± SD	D^c (%)	Mean ± SD	D^c (%)	Mean ± SD	D^c (%)
B	388 ± 177	34	238 ± 123	41	249 ± 378	32	127 ± 151	44	87 ± 75	19	860 ± 974	58	800 ± 717	63
F	9 ± 13	1	6 ± 14	1	–	–	–	–	9 ± 16	2	5 ± 22	0	2 ± 7	0
O	11 ± 18	1	22 ± 20	4	7 ± 16	1	17 ± 18	4	27 ± 29	6	12 ± 45	1	45 ± 58	3
P	74 ± 73	6	11 ± 16	2	–	–	1 ± 3	0	6 ± 19	1	8 ± 18	1	15 ± 23	1
PP	667 ± 277	58	297 ± 211	52	518 ± 410	67	149 ± 151	52	340 ± 175	72	588 ± 271	40	407 ± 243	33
Belo	13 ± 18	1	1 ± 0	0	–	–	–	–	–	–	–	–	–	–
Crico	164 ± 82	14	21 ± 33	4	61 ± 93	8	32 ± 36	11	102 ± 133	22	–	–	1 ± 7	0
Heli	65 ± 81	6	5 ± 12	1	106 ± 98	14	42 ± 55	14	57 ± 68	12	142 ± 132	9	99 ± 87	8
Hemi	1 ± 3	0	9 ± 22	1	2 ± 9	0	–	–	–	–	–	–	1 ± 6	0
Hoplo	–	–	–	–	–	–	2 ± 7	1	–	–	–	–	–	–
Melo	164 ± 129	14	177 ± 213	31	15 ± 27	2	11 ± 39	4	45 ± 46	10	38 ± 53	3	11 ± 20	1
Para	8 ± 16	1	7 ± 15	1	19 ± 25	2	9± 19	3	16 ± 42	3	4 ± 12	0	20 ± 36	2
Praty	220 ± 128	19	35 ± 32	6	303 ± 337	39	35 ± 63	12	104 ± 74	22	384 ± 240	26	236 ± 182	19
Rado	4 ± 8	0	–	–	–	–	–	–	–	–	–	–	–	–
Tric	18 ± 19	2	5 ± 12	1	–	1	2 ± 7	1	–	–	3 ± 10	1	5 ± 14	0
Xiphi	9 ± 14	1	38 ± 37	7	11 ± 19	1	16 ± 25	6	16 ± 24	3	17 ± 38	1	33 ± 41	3
TN	1.149 ± 426		573 ± 302		774 ± 746		287 ± 250		469 ± 199		1.473 ± 1.096		1.268 ± 835	
F/B	0.03 ± 0.05		0.03 ± 0.06		–		–		–		0.01 ± 0.01		0.01 ± 0.03	
O + P/B + F + PP	0.09 ± 0.08		0.07 ± 0.08		0.01 ± 0.03		0.08 ± 0.16		0.10 ± 0.14		0.01 ± 0.03		0.05 ± 0.07	

STFP – Santa Teresa floodplain, STCT – Santa Teresa coastal table, STH – Santa Teresa hillside, CICT – Cruangi II irrigated coastal table, CRCT – Cruangi II rainfed coastal table, SH – Salgado hillside, SF – Salgado flatland, Mean ± SD = Mean number and standard deviation of nematodes per 300 cm^3 of soil in each area, D (%) = Dominance of each trophic group and taxa expressed in percentage, B = Bacterivores, F = Fungivores, O = Omnivores, P = Predators, PP = Plant-parasitic, Belo = *Belonolaimus* sp., Crico = *Criconemella*, Heli = *Helicotylenchus*, Hemi = *Hemicycliophora*, Hoplo = *Hoplolaimus*, Melo = *Meloidogyne*, Para = *Paratrichodorus*, Praty = *Pratylenchus*, Rado = *Radopholus*, Tric = *Trichodorus*, Xiphi = *Xiphinema*, TN = Total nematodes, F/B = Ratio of fungivores and bacterivores, (O + P)/(B + F + PP) = Ratio of omnivores + predators and bacterivores + fungivores + plant-parasitic, and 0 = Ununiform occurrence

Table 4 Mean and dominance of nematode assemblages in sugarcane fields at harvest in northeastern Brazil in 2015

	STFP		STCT		STH		CICT		CRCT		SH		SF	
	Mean ± SD	D^c (%)	Mean ± SD	D^c (%)	Mean ± SD	D^c (%)	Mean ± SD	D^c (%)	Mean ± SD	D^c (%)	Mean ± SD	D^c (%)	Mean ± SD	D^c (%)
B	395 ± 202	30	133 ± 101	55	125 ± 72	47	34 ± 37	14	32 ± 33	11	44 ± 104	33	62 ± 73	18
F	6 ± 16	1	4 ± 14	2	3 ± 12	1	–	–	2 ± 7	1	–	–	–	–
O	83 ± 101	6	9 ± 28	4	1 ± 6	1	31 ± 29	18	95 ± 64	33	3 ± 12	3	34 ± 68	10
P	64 ± 91	5	1 ± 8	1	10 ± 22	4	4 ± 11	2	1 ± 6	0	4 ± 13	3	16 ± 26	5
PP	753 ± 367	58	93 ± 67	38	124 ± 92	47	101 ± 87	66	156 ± 98	55	82 ± 83	61	233 ± 172	67
Crico	79 ± 93	6	–	–	6 ± 15	2	11 ± 48	9	16 ± 33	6	9 ± 26	7	–	–
Heli	16 ± 28	1	–	–	32 ± 58	12	26 ± 37	16	16 ± 35	6	27 ± 37	20	49 ± 42	15
Hemi	1 ± 5	0	–	–	–	–	–	–	–	–	3 ± 16	2	–	–
Melo	207 ± 185	16	35 ± 45	15	3 ± 9	1	39 ± 48	25	78 ± 71	27	2 ± 15	2	–	–
Para	169 ± 128	13	3 ± 12	2	4 ± 12	2	1± 6	1	12 ± 21	4	–	–	–	–
Praty	167 ± 112	13	41 ± 35	17	62 ± 45	24	19 ± 27	13	18 ± 25	6	13 ± 24	10	55 ± 86	16
Tric	16 ± 27	1	1 ± 7	1	1 ± 3	0	–	–	–	–	8± 21	6	29 ± 58	9
Xiphi	98 ± 73	8	6 ± 15	3	15 ± 30	6	1 ± 6	2	16 ± 21	6	18 ± 37	14	90 ± 93	27
TN	1302 ± 506		240 ± 120		263 ± 104		169 ± 107		286 ± 135		133 ± 169		336 ± 203	
F/B	0.04 ± 0.12		–		–		–		–		–		–	
O + P/B + F + PP	0.15 ± 0.19		0.06 ± 0.16		0.06 ± 0.16		0.43 ± 0.58		0.65± 0.60		0.10 ± 0.24		0.30 ± 0.72	

STFP – Santa Teresa floodplain, STCT – Santa Teresa coastal table, STH – Santa Teresa hillside, CICT – Cruangi II irrigated coastal table, CRCT – Cruangi II rainfed coastal table, SH – Salgado hillside, SF – Salgado flatland, Mean ± SD = Mean number and standard deviation of nematodes per 300 cm^3 of soil in each area, D (%) = Dominance of each trophic group and taxa expressed in percentage, B = Bacterivores, F = Fungivores, O = Omnivores, P = Predators, PP = Plant-parasitic, Crico = *Criconemella*, Heli = *Helicotylenchus*, Hemi = *Hemicycliophora*, Melo = *Meloidogyne*, Para = *Paratrichodorus*, Praty = *Pratylenchus*, Tric = *Trichodorus*, Xiphi = *Xiphinema*, TN = Total nematodes, F/B = Ratio of fungivores and bacterivores, (O + P)/(B + F + PP) = Ratio of omnivores + predators and bacterivores + fungivores + plant-parasitic, and 0 = Ununiform occurrence

Table 5 Nematode taxa associated to sugarcane fields at replanting in northeastern Brazil in 2014

	Belo	O	Heli	Melo	Pred	Prat	Para	Tric	Xiph	Rado	Bac
Site 1 - Santa Teresa (floodplain)											
F		0.34**			0.52**						
Belo		0.43*			0.47*		0.57*		0.40*		
Cric						0.36***				−0.44*	0.34**
O				0.39**	0.55*					0.49*	
P							0.47**				
Para											0.31*
Prat										−0.55*	0.57*
Tric											0.37**
Site 2 - Santa Teresa (Coastal Table)											
F	0.48*										
Cric								0.33**			
O					0.38**						0.57*
Melo											0.56*
Para									0.34**		
Tric									0.32**		
Site 3 - Santa Teresa (hillside)											
Cric							0.47*				
O			0.35**	0.41**		0.34**	0.36**				0.33**
Melo							0.32**				0.37**
P								0.48*			
Para											0.32**
Prat							0.46*	0.36**	0.50*		0.84*
Tric											0.42*
Xiph											0.40**
Site 4 - Cruangi II (irrigated coastal table)											
Cric				0.49*		0.59*	0.45*	0.35**			
Heli					0.68*	0.40**					
Melo						0.63*		0.42**			
P						0.40**					
Para								0.69*			0.44*
Prat							0.55*	0.72*			0.51*
Tric											0.61*
Site 5 - Cruangi II (rainfed coastal table)											
F											0.35**
Cric					0.41**						
O											−0.34**
Melo							0.42**				
Para											0.56*
Área 6 – Salgado (Hillside)											
F											0.33**
O					0.41**		0.55*				
Melo					0.45*						
P					0.45*		0.45*				
Xiph											0.50*
Site 6 - Salgado (flatland)											
F							0.37**	0.67***			
O					0.70*	0.58*	0.39**		0.46*		
P						0.50*			0.50*		
Para								0.39**			
Prat									0.34**		

F = Fungivores. Belo = *Belonolaimus* Crico = *Criconemella*. O = Omnivores. Hemi = *Hemicycliophora*. Heli = *Helicotylenchus*. Melo = *Meloidogyne*. P = Predators. Praty = *Pratylenchus*. Para = *Paratrichodorus*. Tric = *Trichodorus*. Xiphi = *Xiphinema*. Rado = *Radopholus*. and B = Bacterivores. **Significant at 5%. *Significant at 1% of probability by Pearson correlation analysis

dominance of omnivores was greater than that of predators and fungivores. The low values for the ratio (O + P)/ (B + F + PP) corroborate the annual crop cultivation.

Although there were significant correlations among trophic groups; generally, the correlation changed in relation to the sites and periods of evaluation (Tables 5 and 6). Significant positive correlations with the highest values during renovation were between *Pratylenchus* and bacterivores ($r = 0.84$) in STH; predators and *Helicotylenchus* ($r = 0.68$), bacterivores and

Table 6 Nematode taxa associated in sugarcane fields at harvest in northeastern Brazil in 2015

	O	Melo	P	Prat	Para	Tric	Xiph	Bac
Site 1 - Santa Teresa (floodplain)								
F		−0.35**				0.42**		−0.42**
Cric	0.46*		0.47*		0.35**		0.35**	
O			0.74*		0.62*		0.38**	−0.43*
Heli			0.35**					
Hemi							0.59*	
Melo				0.32**				0.40**
P					0.53*		0.35**	
Prat								0.51*
Tric							0.38**	
Site 2 - Santa Teresa (coastal table)								
F					0.85*	0.49*	0.49*	
Heli						0.67*		
Tric							0.43*	
Xiphi								−0.44*
Site 3 - Santa Teresa (hillside)								
F	0.48*						0.53*	
Heli				0.34**				
P							0.56*	
Para							0.42**	
Site 4 – Cruangi II (irrigated coastal table)								
Cric			0.33**		0.69*			
Melo								0.40**
Site 5 - Cruangi II (rainfed coastal table)								
Cric							0.43*	
O							0.46*	
Heli								0.41**
Prat					0.36**			
Site 6 - Salgado (hillside)								
Heli							0.43*	0.67*
Hemi				0.42**				
Melo				0.33**			0.33**	
P							0.59*	
Xiphi								0.53*
Area 7 – Salgado (flatland)								
O							−0.32**	0.51*

F = Fungivores. Belo = *Belonolaimus* sp. Crico = *Criconemella* sp. O = Omnivores. Hemi = *Hemicycliophora* sp. Heli = *Helicotylenchus* sp. Melo = *Meloidogyne* sp. P = Predators. Praty = *Pratylenchus*. Para = *Paratrichodorus*. Tric = *Trichodorus*. Xiphi = *Xiphinema*. Rado = *Radopholus*. Bac = Bacterivores. **Significant at 5%. *Significant at 1% of probability by Pearson correlation analysis

Trichodorus ($r = 0.61$), *Meloidogyne* and *Pratylenchus* ($r = 0.63$), *Paratrichodorus* and *Trichodorus* ($r = 0.69$), *Pratylenchus* and *Trichodorus* ($r = 0.72$) in CICT; omnivores and predators ($r = 0.70$), and fungivores and *Trichodorus* ($r = 0.67$) in SF (Table 5).

At harvest, significant positive correlations were observed between omnivores and predators (r=0.74) and *Paratrichodorus* (r=0.62) in STFP; fungivores and *Paratrichodorus* (r=0.85), and *Helicotylenchus* and *Trichodorus* (r=0.67) in STCT; *Paratrichodorus* and

Criconemella (r=0.69) in CICT; and bacterivores and *Helicotylenchus* (r=0.67) in SH (Table 6).

Discussion

Nematode diversity and distribution in coastal tables, hillsides, flatlands, and floodplains are only slightly explored (Miranda et al. 2012). In Brazilian northeastern, these environments have been cultivated with sugarcane for several decades, modifying the ecosystem and increasing the number and ratio of plant-parasitic nematodes, especially the endoparasitic *Meloidogyne* and *Pratylenchus*, which is probably due to a more suitable condition inside roots. Genera *Criconemella*, *Helicotylenchus, Trichodorus,* and *Paratrichodorus* are common in the region (Chaves et al. 2003; Moura 2005; Rodrigues et al. 2011; Cardoso et al. 2015), though in low numbers (Spaull and Cadet 2005).

The plant-parasitic nematodes are prevalent in sugarcane growing fields around the world (Berry et al. 2007; Stirling et al. 2010; Berry et al. 2011; Steven et al. 2014; Cardoso et al. 2016; Zhang et al. 2017) as well as in northeastern Brazil (Chaves et al. 2002, 2003; Barros et al. 2005; Vicente et al. 2016). Economic damage levels are related to nematode species, sugarcane variety, and environmental conditions, especially soil humidity (Dinardo-Miranda 2005; Barros et al. 2005).

In southeastern Brazil, where soil and temperatures are favorable to nematodes, the economic threshold has been estimated around 2500 *P. zeae* or 400 *Meloidogyne* spp. juveniles per 50 g of roots of susceptible sugarcane varieties (Dinardo-Miranda et al. 1996; Novaretti 1997). However, sand soils under environmental stress from water deficits are more affected by plant-parasitic nematodes (Li et al. 2014; Lu et al. 2016; Vicente et al. 2016), disrupting the soil's natural balance and food web (Sohlenius et al. 2011; Cardoso et al. 2016).

The sandy soils, with high temperatures and low levels of organic matter increases the effect of water deficit on plant stress and therefore intensify the damage of the plant-parasitic nematodes (Omarjee et al. 2008; Kimenju et al. 2009). The use of a sugarcane genotypes susceptible to nematodes (Chaves et al. 2007; Silva et al. 2012; Silva et al. 2016) also contributes to the dominance of *Meloidogyne* and *Pratylenchus*, although the ectoparasites *Helicotylenchus* and *Criconemella* are found in the fields, but in low levels (Cardoso et al. 2015).

The polyphagous feeding habit, low rainfall (especially in S1 and S4), and high temperatures support the low nematode numbers in non-irrigated soils, but the floodplain, which has more moisture and nutrients carried from neighbor areas. On the other hand, the higher dominance of *Meloidogyne* in STCT and *Helicotylenchus* in CICT shows that the irrigated coastal table provided a more suitable environment for the ectoparasitic nematodes.

The relatively low number of omnivores corroborates other studies in sugarcane fields (Rodrigues et al. 2011; Cardoso et al. 2015), reflecting the human intervention (Freckman and Ettema 1993; Gomes et al. 2003). The low numbers of *Mononchus* (predator) are characteristic of this agricultural system as well (Cardoso et al. 2015).

Results related to bacterivores and plant-parasitic nematodes' in SH and SF supports bacterivores as the dominant trophic group in sugarcane fields of northeastern Brazil (Vicente et al. 2016). The dynamics of bacterivores' population effects soil bacteria activity and, consequently, organic matter decomposition (Goulart et al. 2009). Bacterivores defecate 50–80% of the ingested material, contributing directly to organic matter decomposition (Wright and Newall 1976). Furthermore, microbivorous nematodes play direct and indirect roles on organic matter decomposition, leading to higher mineralization rates of carbon and other nutrients (Chen and Ferris 1999), which contributes to a greater organic carbon content found in this study.

Lower abundances of plant-parasitic nematodes in south of Pernambuco, when compared to north, is probably related to greater organic carbon and matter content in the soils in southern (Table 2). Additionally, this behavior may be the result of clay content and porosity, as well as lower bulk densities, degrees of clay flocculation, and silt/clay ratios (Table 1),contrasting to the light sandy soil and low water retention capacity of the coastal table site (Table 1). The increment in water availability from irrigation coupled with chemical fertilizer and organic matter incorporation (Table 2) may have provided better conditions for root system development increasing plant-parasitic nematode population in relation to further taxa (Tables 3 and 4).

Population dynamics of soil nematode assemblages, particularly plant-parasitic ones, are highly influenced by physical and chemical soil attributes, such as temperature, water content, and soil texture, and structure (Huang and Pereira 1994; Cardoso et al. 2015, 2016). Some studies revealed that plant-parasitic nematodes prefer sandy soils, as a function of the greater proportion of macropores, allowing nematode movement toward host plants, causing significant damages to different crops (Kanga et al. 2012).

Meloidogyne and *Pratylenchus* had significant correlation, mainly at field replanting. Even though there are records of the *Pratylenchus* species penetrating the roots of host plants more rapidly than *Meloidogyne* (Gay and Bird 1973), or that *M. incognita* inhibits penetration of *P. penetrans* (Turner and Chapman 1972), the effects of these interactions have varied with time and host resistance (Freckman and Chapman 1972). Sedentary endoparasitic nematodes present a more advanced parasitism than migratory ones and, generally, establish a more complex relationship with their host by markedly altering plant's physiology. In some cases, these changes favor migratory endoparasites (Eisenback 1985).

Pratylenchus was dominant in some areas above damage level cited by Robinson et al. (1997). Ranking changes of recorded taxa at harvest, in contrast to renovation period, agree with Vicente et al. (2016), who has also recorded an increase of population density of *Pratylenchus*, *Trichodorus,* and *Xiphinema* nine months after planting and at harvest, though these genera have been dominating the area during all sampling periods along with the family Criconematidae. The dominance of plant-parasitic nematodes is commonly observed in monoculture (Lu et al. 2016).

The ratio of plant-parasitic and microbivores nematodes observed in this study emphasizes the importance of agricultural practices that reduce before and after sugarcane planting. Bacterivores are the second most dominant trophic group in vinasse-fertigated sugarcane fields of northeastern region of Brazil (Matos et al. 2011; Miranda et al. 2012; Vicente et al. 2016). Nematodes from this trophic group, as restricted colonizers, are mainly influenced by the rapid increase in food sources (Porazinska et al. 1999). The dorylaimids population is sensitive to agricultural practices; therefore, it has been used as an environmental disturbance indicator (Gomes et al. 2003). Studies have shown omnivores as the dominant group before vinasse application (Miranda et al. 2012) and in areas without its application (Matos et al. 2011).

Data from the present study indicate that plant-parasitic nematode population dynamics are dependent on physical and chemical soil attributes. In the hillside and flatland area in southern Pernambuco and in irrigated coastal table in northern, plant-parasitic nematodes tend to increase with crop development, but decline in taxa abundance. In floodplain areas, plant-parasitic nematodes and other taxa are more stable. *Meloidogyne* and *Pratylenchus* were the dominant plant-parasitic genera in all areas and periods; except at harvest in hillside and flat-land areas in south, whose dominant taxa were *Helicotylenchus* and *Xiphinema*. Low taxa richness reflects low equilibrium of nematode assemblages, typical of the continuous and intensive system.

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References

Abd-Elgawad MMM, Askary TH (2015) Impact of phytonematodes on agriculture economy. In: Askary TH, Martinelli PRP (eds) Biocontrol agents of phytonematodes. Wallingford, UK. CAB International, pp 3–49

Alvares CA, Stape JL, Sentelhas PC, Gonçalves JLM, Sparovek G (2013) Köppen's climate classification map for Brazil. Meteorologische Zeitschrift 22:711–728

Barros ACB, Moura RM, Pedrosa EMR (2005) Estudo de interação variedade-nematicida em cana-de-açúcar, em solo naturalmente infestado por *Meloidogyne incognita*, *M. javanica* e *Pratylenchus zeae*. Nematologia Brasileira 29:39–46

Berry S, Spaull VW, Cadet P (2007) Impact of harvesting practices on nematode communities and yield of sugarcane. Crop Protection 26: 1239–1250

Berry SD, Rhodes R, Foster J, Risede JM, van Antwerpen R (2011) The effect of cover crops on plant parasitic-nematodes of sugarcane. International Journal of Pest Management 57:363–375

Briar SS, Culman SW, Young-Mathews A, Jackson LE, Ferris H (2012) Nematode community responses to a moisture gradient and grazing along a restored riparian corridor. European Journal of Soil Biology 50:32–28

Cardoso MSO, Pedrosa EMR, Rolim MM, Silva EFF, Barros PA (2011) Effects of soil mechanical resistance on nematode community structure under conventional sugarcane and remaining of Atlantic Forest. Environmental Monitoring and Assessment 184:3529–3544

Cardoso MSO, Pedrosa EMR, Ferris H, Rolim MM, Vicente TF, Da S, David MF (2015) Comparing sugarcane fields and forest fragments: the effect of disturbance on soil physical properties and nematode assemblages. Soil Use and Management 31:1–11

Cardoso MSO, Pedrosa EMR, Rolim MM, Oliveira LSC, Santos NA (2016) Relationship between nematode assemblages and physical properties across land use types. Tropical Plant Pathology 42:1–8

Chaves A, Pedrosa EMR, Moura RM (2002) Efeitos da aplicação de terbufós sobre a densidade populacional de nematoides endoparasitos em 5 variedades de cana-de-açúcar no Nordeste. Nematologia Brasileira 26:167–176

Chaves A, Pedrosa EMR, Moura RM (2003) Efeito de terbufos em soqueira sobre fitonematóides ectoparasitos de cana-de-açúcar. Fitopatologia Brasileira 28:195–198

Chaves A, Melo LJOT, Simões Neto DE, Costa IG, Pedrosa EMR (2007) Declínio Severo do desenvolvimento da cana-de-açúcar em Tabuleiros Costeiros do Estado de Pernambuco. Nematologia Brasileira 131:10–12

Chen J, Ferris H (1999) The effects of nematode grazing on nitrogen mineralization during fungal decomposition or organic matter. Soil Biology and Biochemistry 31:1265–1279

Dinardo-Miranda LL (2005) Nematoides e pragas de solo em cana-de-açúcar. Potafós 1:25-32 (Encarte do Informações Agronômicas, n. 110)

Dinardo-Miranda LL, Morelli JL, Landell MGA, Silva MA (1996) Comportamento de genótipos de cana-de-açúcar em relação a *Pratylenchus zeae*. Nematologia Brasileira 20:52–58

Dinardo-Miranda LL, Vasconcelos ACM, Landell MGA (2008) Cana-de-çúcar. Campinas, Brasil. Instituto Agronômico

Donagema GK, Campos DVB, Calderano SB, Teixeira WG, JHM V (2011) Manual de métodos de análise de solos. Embrapa Solos, Rio de Janeiro

dos Santos VR, Moura Filho G, de Albuquerque AW, da Costa JPV, dos Santos CG, dos Santos ACI (2009) Crescimento e produtividade agrícola de cana-de-açúcar em diferentes fontes de fósforo. Revista Brasileira de Engenharia Agrícola 13:389–396

Eisenback JD (1985) Interactions among concomitant populations of nematodes. In: Sasser JN, Carter CC (orgs). An advanced treatise on *Meloidogyne*; biology and control. Raleigh: North Carolina State University Graphics 1:193–213

Ferris H (2010) Form and function, metabolic footprints of nematodes in the soil food web. European Journal of Soil Biology 46:97–104

Figueira AF, Berbara RLL, Pimentel JP (2011) Estrutura da população de nematóides do solo em uma unidade de produção agroecológica no Estado do Rio de Janeiro, Brasil. Acta Scientiarum Agronomy 33: 223–229

Freckman DW, Chapman RA (1972) Infection of red clover seedlings by *Heterodera trifolii* Goffart and *Pratylenchus penetrans* (cobb.). Journal of Nematology 4:23–28

Freckman DW, Ettema CH (1993) Assessing nematode communities in agroecosystems of varying human intervention. Agriculture, Ecosystems and Environment 45:239–261

Gay CM, Bird GW (1973) Influence of concomitant of *Pratylenchus brachyurus* e *Meloidogyne* spp. on root penetration and population dynamics. Journal of Nematology 5:212–217

Godefroid M, Delaville L, Marie-Luce S, Quénéhervé P (2013) Spatial stability of a plant-feeding nematode community in relation to macro-scale soil properties. Soil Biology and Biochemistry 57: 173–181

Gomes GS, Huang SP, Cares JE (2003) Nematode community, trophic structure and population fluctuation in soybean fields. Fitopatologia Brasileira 28:258–266

Goulart AMC, Cares JE, Ferraz LCCB (2009) Ecologia e biodiversidade de nematóides – parte I. Revisão Anual de Patologia de Plantas 17: 149–188

Huang SP, Pereira AC (1994) Influence of inoculum density, host, and low-temperature period on delayed hatch of *Meloiodgyne javanica* eggs. Journal of Nematology 26:72–75

Jenkins WR (1964) A rapid centrifugal flotation technique for separating nematodes from soil. Plant Disease Report 48:692–695

Kanga FN, Waeyenberge L, Hauser S, Moens M (2012) Distribution of entomopathogenic nematodes in southern Cameroon. Journal of Invertebrate Pathlogy 109:41–51

Kimenju JW, Karanja NK, Mutua GK, Rimberia BM, Wachira PM (2009) Nematode community structure as influenced by land use and intensity of cultivation. Tropical and Subtropical Agroecossystems 11:353–360

Li Y, Cao Z, Hu C, Li J, Yang H (2014) Response of nematodes to agricultural input levels in various reclaimed and unreclaimed habitats. European Journal of Soil Biology 60:120–129

Lu Z-b, Dong D-f, Yang B, Li-li L, L-l YY, Ouyang F, Ge F, V-c V, X-y M (2016) Effects of crop species richness on the community of soil nematodes in an experimental agro-ecosystem. European Journal of Soil Biology 73:26–33

Maechler M, Rousseeuw P, Struyf A, Hubert M, Hornik K. (2017). Cluster: cluster analysis basics and extensions. R package version 2.0.6, available at URL https://cran.r-project.org/web/packages/cluster/index.html

Mai WF, Mullin PG, Lyon HH, Loeffle K (1996) Plant-parasitic nematodes: a pictorial key to genera. Ithaca, NY. Cornell University Press.

Matos DSS, Pedrosa EMR, Guimarães LMP, Rodrigues CVMA, Barbosa NMR (2011) Relações entre a nematofauna e atributos químicos de solo com vinhaça. Nematropica 41:23–38

Mbega ER, Nzogela YB (2012) Strategies used by plant parasitic nematodes to conquer the host. Journal of Animal & Plant Sciences 14: 1848–1854

Mekete T, Dababat A, Sekora N, Akyazi F, Abebe E (2012) Identification key for agriculturally important plant-parasitic nematodes prepared for the international nematode diagnosis and identification course 2012 - a manual for nematology. CIMMYT, Mexico, D.F

Miranda TL, Pedrosa EMR, de Silva EF, Rolim MM (2012) Alterações físicas e biológicas em solo cultivado com cana-de-açúcar após colheita e aplicação de vinhaça. Agrária- Revista Brasileira de Ciências Agrárias, Recife, Pernambuco 7:150–158

Moura RM (2005) Nematoides de interesse agrícola assinalados pela UFRPE no Nordeste do Brasil (1967-2005). Nematologia Brasileira 29:289–292

Neher AD, Campbell (1994) Nematode communities and microbial biomass in soils with anual and perennial crops. Applied Soil Ecology 1:17–28

Neuwirth E. (2014) RColorBrewer: ColorBrewer palettes. R package version 1.1-2, available at URL https://CRAN.R-project.org/package=RColorBrewer

Novaretti WRT (1997) Controle de *Meloidogyne incognita e Pratylenchus* zeae (Nematoda: Heteroderidae) em cana-de-açúcar associados ou não à matéria orgânica. Doctoral dissertation, Universidade de São Paulo. ESALQ, Piracicaba, SP, Brasil

Oksanen J, Blanchet FG, Friendly M, Kindt R, Legendre P, McGlinn D, Minchin PR, O'Hara RB, Simpson GL, Solymos P, Stevens MHH, Szoecs E, Wagner H (2017). Vegan: community ecology package. R package version 2.4-4, available at URL https://cran.r-project.org/web/packages/vegan/index.html

Oliveira ECA de, Freire FJ, Oliveira RI de, Oliveira AC de, Freire MBG dos S (2011) Acúmulo e alocação de nutrientes em cana-de-açúcar. Revista Ciência Agronômica 42:579–588

Omarjee J, Balandreau J, Spaull VW (2008) Cadet P (2008) relationships between Burkholderia populations and plant parasitic nematodes in sugarcane. Applied Soil Ecology 39:1–14

Pansu M, Gautheyrou J (2006) Handbook of soil analysis. Mineralogical, Organic and Inorganic Methods. New York. Springer

Porazinska DL, Duncan LW, McSorley R, Graham JH (1999) Nematode communities as indicators of status and processes of a soil ecosystem influenced by agricultural management practices. Applied Soil Ecology 13:69–86

R Development Core Team (2017) R: A Language and Environment for Statistical Computing. Vienna, Austria: the R Foundation for Statistical Computing, version 3.4.0, Available at URL https://www.r-project.org/

Rêgo GM, Hoeflich VA (2001) Contribuição da pesquisa florestal para um ecossistema em extinção: Floresta Atlântica do nordeste do Brasil. Embrapa Tabuleiros Costeiros, Aracaju, 80p

Robinson AF, Inserra RN, Caswell-Chen EP, Vovlas N, Troccoli A (1997) *Rotylenchulus* species: identification, distribution, host range, and crop plant resistance. Nematropica 27:127–180

Rodrigues CVMA, Pedrosa EMR, Oliveira AKS, Leitão DAHS, Barbosa NMR, Oliveira NJV (2011) Distribuição vertical da nematofauna associada à cana-de-açúcar. Nematropica 41:10–16

Ruess L (2003) Nematode soil faunal analysis of decomposition pathways in diferente ecosystems. Nematology 5:179–181

Sánchez-Moreno S, Ferris H, Young-Mathews A, Culman SW, Jackson LE (2011) Abundance, diversity and connectance of soil food web channels along environmental gradients in an agricultural landscape. Soil Biology & Biochemistry 43:2374–2383

Silva AP, Pedrosa EMR, Chaves A, Maranhão SRVL, Guimarães LMP, Rolim MM (2012) Reação de variedades de cana-de-açúcar ao parasitismo de *Meloidogyne incognita* e *M. enterolobii*. Revista Brasileira de Ciências Agrárias 7:814–819

Silva MS, Bandeira MA, Maranhão SRVL, Carvalho RM, Pedrosa EMR (2016) Comportamento de genótipos RB de cana-de-açúcar ao parasitismo dos nematoides das galhas. Revista Brasileira de Ciências Agrárias 11:73–79

Sohlenius B, Sandor A (1987) Vertical distribution of nematodes in arable soil under grass (*Festuca pratensis*) and barley (*Hordeum distichum*). Biology and Fertility of Soils 3:19–25

Sohlenius B, Boström S, Viketoft M (2011) Effects of plant species and plant diversity on soil nematodes – a field experiment on grassland run for seven years. Nematology 13:115–131

Souza JL, Moura Filho G, Lyra RFF, Teodoro I, Santos EA, Silva JL, Silva PRT, Cardim AH, Amorim EC (2004) Análise da precipitação pluvial e temperatura do ar na região do Tabuleiro Costeiro de Maceió, AL, período 1972-2001. Revista Brasileira de Agrometeorologia 12:131–141

Spaull VW, Cadet P (2005) Nematode parasites of sugarcane. In: Luc M, Sikora RA, Bridge J (eds) Plant parasitic nematodes in subtropical and tropical agriculture. Wallingford, UK. CAB International, pp 645–674

Statistical Analysis Systems Institute (2015) SAS INSTITUTE. SAS/STAT® 14.1 User's guide. SAS Institute Inc., Cary

Steven A, Sunday S, Fisayo D (2014) Biodiversity of plant-parasitic nematodes of sugarcane in Bacita, Nigeria. Journal of Entomology and Nematology 6:71–79

Stirling GR, Moody PW, Stirling AM (2010) The impact of an improved sugarcane farming system on chemical, biochemical and biological properties associated with soil health. Applied Soil Ecology 46:470–477

Turner DR, Chapman RA (1972) Infection of seedlings of alfalfa and red clover by concomitant populations of *Meloidogyne incognita* and *Pratylenchus penetrans*. Journal of Nematology 4:280–286

Ugarte CM, Zaborski ER, Wander MM (2013) Nematode indicators as integrative measures of soil condition in organic cropping systems. Soil Biology & Biochemistry 64:103–113

Vicente TFS, Pedrosa EMR, da Silva LMA, Rolim MM, Castro DB, Leitão AHS (2016) Variabilidade temporal da comunidade de nematoides em cana-de-açúcar em condição de baixa umidade do solo. Nematropica 46:235–243

Warnes GR, Bolker B, Bonebakker L, Gentleman R, Liaw WHA, Lumley T, Maechler M, Magnusson A, Moeller S, Schwartz M, Venables B (2016). Gplots: various R programming tools for plotting data. R package version 3.0.1, available at URL https://CRAN.R-project.org/package=gplots

Wright DJ, Newall DR (1976) Nitrogen excretion, osmotic and ionic regulation in nematodes. In: Croll NA (ed) The organization of nematodes. Academic Press, London, pp 163–210

Yeates GW (2003) Nematodes as soil indicators: functional and biodiversity aspects. Biology and Fertility of Soils 37:199–210

Yeates GW, Bongers T, Goede RGM, de Freckman DW, Georgieva SS (1993) Feeding habits in soil nematode families and genera – an outline for soil ecologists. Journal of Nematology 25:315–331

Yeomans JO, Bremmer JM (1988) A rapid and precise method for routine determination of organic carbon in soil. Communications in Soil Science and Plant Analysis 19:1467–1476

Zhang F, Gao C, Wang J, Lu Y, Shen Z, Liu T, Chen D, Ran W, Shen S (2017) Coupling sugarcane yield to soil nematodes: implications from different fertilization regimes and growth stages. Agriculture, Ecosystems and Environment 247:157–165