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Successional Effects of No-Till Cover Cropping with Black Oat (*Avena strigosa*) vs. Soil Solarization on Soil Health in a Tropical Oxisol

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Abstract: Black oat (*Avena strigosa*) is a cover crop with great potential for weed suppression and erosion control while conserving soil moisture. Little is known about the potential of black oat for enhancing the soil food web structure and the ecosystem services in tropical Oxisols. Two-year field trials were conducted in Hawaii to compare three pre-plant treatments: (1) black oat (BO) as a pre-plant cover crop followed by no-till practice (previously managed by cover crop and cash crop rotation and conservation tillage for 7 years); (2) bare ground (BG) followed by conventional tillage (previously managed by conventional tillage and cash crop planting for 7 years); (3) conventional tilling of bare ground followed by soil solarization (SOL) (previously fallow with weeds for 5 years then summer solarization and cash crop planting for 2 years). Various soil properties and the soil food web structure using nematodes as soil health indicators were monitored throughout the subsequent corn (*Zea mays*) crops. SOL served as a negative control pre-plant treatment known to manage plant-parasitic nematodes but be destructive to the soil food web. No-till cropping with BO resulted in higher levels of volumetric soil moisture, field capacity, and soil organic matter, and supported a fungal-dominated decomposition pathway in trial I and more structured nematode communities than BG and SOL in trial II. This study provides evidence that no-till cover cropping with black oat improves the soil water conservation and soil food web structure following a continuous conservation tillage system in tropical Oxisols if the black oat biomass is high (36 tons/ha). However, no-till cropping with BO in Oxisol decreased the soil macroporosity and increased the soil bulk density, which were not favorable outcomes for water infiltration. On the other hand, SOL following conventional tillage was successful in generating lethal temperatures to suppress plant-parasitic nematodes and increased water infiltration in both years but was destructive to the soil food web and reduced the soil organic matter and soil moisture in both years, even when solarization failed to generate lethal temperatures in the second year.

Keywords: canonical correlation analysis; conservation agriculture; corn; microporosity; nematode communities; water conservation

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1. Introduction

Soil tillage provides the benefits of soil aeration, reductions in initial pest populations, the creation of planting beds [1], and weed control [2], but intensive tillage has led to soil degradation and erosion [3]. No-till cropping, also known as zero-till, direct drilling [4], and chemical till [2] cropping, can be described as planting directly into the previous crop residue in the absence of tillage. One of the most important benefits from no-till cropping is that it mitigates the risk of soil erosion, which can be influenced by the soil organic matter, soil structure, aggregate stability, buffering capacity, water retention, and biological activity [4]. Erosion occurs when the organic C content of the soil falls below 2% [5,6]. Increases in the soil organic matter via no-till cropping progress slowly over time [7], as it relies on the delay in decomposition of organic matter during conservation tillage compared to the faster decomposition of residue in tilled soil [8,9]. Conservation tillage can increase the soil carbon by 8% after 4 years compared to conventional tillage in the U.K. [4], and leguminous cover crop-based no-till cropping increased soil organic matter in an Oxisol in Hawaii by 14% after 7 years of consecutive crop rotation between vegetable crops and sunn hemp (*Crotalaria juncea*) cover cropping [10]. However, despite significant soil organic matter increases, the soil organic matter after 7 years of no-till cover cropping with this tropical legume at the field site in Hawaii remained <1.4% [10], which is still prone to soil erosion.

Cover cropping with high carbon-to-nitrogen (C/N) ratios could improve soil organic matter and lead to soil moisture retention, improved soil porosity, or water infiltration, which are all preferable features of cover crops for no-till farming. Black oat (*Avena strigosa*) is a grass that grows all year-round in Hawaii and produces crop residue with a high C/N ratio, resulting in only 1.5% tissue nitrogen at cereal heading [11]. High C/N ratio residues will persist longer in the field as organic mulch due to their slower decomposition rate. The dense root mass of black oat plants can improve the soil structure more than other cover crops such as clover, phacelia, and tillage radish [12]. Another advantage of growing black oat as a cover crop is its weed suppression properties [13], largely due to its allelopathic effect against annual grasses and small-seeded broadleaf weeds [14].

This project focuses on examining the impacts of no-till cover cropping with black oats on soil health and soil quality in a tropical Oxisol, Haplustox soil, with low soil organic matter. Little is known on how effective no-till cover cropping with black oat is in terms of enhancing the soil health and quality of this tropical Haplustox soil. Besides comparing no-till cropping with black oat to bare ground conventional till cropping, soil solarization was included as a negative control, as it is an effective pre-plant treatment for weed management [15]. However, soil solarization involves covering the soil with a transparent polyethylene film to reach temperatures detrimental to soil organisms [16]. Its effect on soil health is compromised temporarily after termination of the solarization process [17,18], and has been shown to disturb free-living nematodes on the topsoil layer by reaching the lethal temperature of 42 °C [19].

Soil quality is "the capacity of a soil to function within ecosystem and land-use boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health" [20], whereas soil health is "the continued capacity of the soil to function as a vital living ecosystem that sustains plants, animals, and humans" [21]. Nematodes are good soil health indicators because they are ubiquitous and functionally diverse [22], as they are well classified into functional groups and functional guilds (a combination of trophic group and life strategies) [23]. They play important roles in soil nutrient cycling and are the most abundant and diverse multicellular soil microorganisms [24,25]. They influence soil processes and reflect the structure and function of other taxa within the soil food web. Among the nematode trophic groups, predatory, and omnivorous nematodes in the higher hierarchy of the soil food web are sensitive to soil food web structure disturbances, whereas the abundance of bacterivorous and fungivorous nematodes reflects the bacterial- or fungal-dominated decomposition that occurs in the soil food web [26,27]. In 2001, a nematode fauna analysis was developed using nematode guild information and nematode biomass estimations to provide three metrics: an enrichment index to assess food web responses to soil nutrient resources, a structure index to reflect the degree of trophic connections in food webs of increasing complexity as the system matures, and a channel index to represent the decomposition pathway occurring in the soil food web [28].

The specific objectives of this study were to examine whether continuous conservation practice with no-till cover cropping with black oat could (1) improve soil properties associated with water conservation and (2) improve the soil food web structure versus whether continuous practice of soil solarization would decrease the soil health and soil qualities. A third objective was to determine whether the soil food web structure is closely related to improvements in soil water properties.

2. Materials and Methods

2.1. Field Trials

Two field trials were conducted in long-term field management plots at Poamoho Experiment Station, University of Hawaii (2132′9.6756″ N, 158 5′21.8796″ W), Waialua, Oahu. The soil at the site is a well-drained silty clay Oxisol (Wahiawa series, very fine, kaolinitic, isohyperthermic, rhodic haplustox) [29] with a pH of 6.6, 18.6% sand, 37.7% silt, and 43.7% clay in the top 25 cm of the soil.

Prior to the initiation of the current experiment, green onion (*Activum cepa*) was planted in all plots in 2014 and 2015. Subsequently, in 2016, three pre-plant treatments were installed: (1) black oat cover crop in a no-till system (BO); (2) soil solarization (SOL); (3) conventional till with bare ground (BG). Each treatment was replicated in 4 plots and arranged in a randomized complete block design (RCBD). BO was established in field plots with a history of 7 years no-till sunn hemp (*Crotalaria juncea*) cover cropping in rotation with vegetables. 'Soil saver' black oat was sown on 20 April 2016 at 32 kg seeds/ha as a cover crop and terminated on 8 July 2016 using a flail mower. SOL was established in field plots with a history of 5 years fallow with weeds and 2 years of summer solarization (2.5-month long) in rotation with vegetables. The SOL soil was tilled and covered with 1.2-m-wide, 25-μm-thick, ultra-violent-light-stabilized, low-density transparent polyethylene mulch (ISO Poly Firms, Inc., Gary Court, SC, USA). The soil temperature was monitored using temperature probes (WatchDog B-series button data logger, Spectrum® technologies, Aurora, IL, USA) buried at depths of 5 and 15 cm in each treatment plot during the cover cropping period. Solarization plots were left bare with no plant residue incorporated. The soil in the BG plot was bare-fallowed followed by rototilling prior to planting vegetables for the last 7 years. Each treatment plot measured 3.7×11 m^2. After 2.5 months of the pre-plant treatments described above, six rows of corn were directly seeded on 14 July 2016 with 35.5 cm row spacing and 23 cm between plants within each row at a rate of 15,240 seeds/ha (equivalent to 78 Kg seeds/ha).

The experiment was repeated in the same field as in trial I from December 2016 to May 2017. Black oat was grown using no-till practices from 8 December 2016 to 23 February 2017. The solarization plots were tarped with solarization mulch from December 2016 to February 2017. Corn was planted on 2 March 2017 and harvested on 25 May 2017.

In both trials, the black oat biomass was estimated immediately before flail mowing by randomly placing 3 quadrants (0.09 m^2) per plot, clipping the black oat shoots above the ground, and weighing. All corn was fertilized with 130 kg of nitrogen, 56.7 kg of phosphorus, and 108 kg of potassium per ha, and was drip-irrigated and harvested 12 weeks after planting.

2.2. Soil Sample Analysis

Six soil cores measuring 7.6 cm in diameter were systematically collected in a zig-zag pattern from the top 10 cm of soil per plot using a GroundShark shovel (W.W. Manufacturing, Inc., Bridgeton, NJ, USA) prior to the initiation of pre-plant treatments and at 0, 2, and 3 months after corn planting. Soil cores from each plot were composited into a plastic bag and transported to the laboratory for various soil analyses. A subsample of 20 g of soil from each sample was subjected to gravimetric soil moisture measurement. The soil samples at planting and harvest were submitted to Agriculture Diagnostic Services Center (ADSC) at the University of Hawaii at Manoa for analysis of the total carbon using a LECO TruSpec CN (LECO Corporation, Saint Joseph, MI, USA) and for analysis of the soil organic matter.

2.3. Nematode Assays

A 250 cm^3 subsample was taken from each soil sample for nematode extraction via elutriation [30] and centrifugal floatation methods [31]. All nematodes were identified to the genus level under an inverted microscope (Leica DM IL LED, Wetzlar, Germany) and counted. Nematode genera were assigned to their trophic groups (bacterivores, fungivores, herbivores, omnivores, and predators) based on the categorization method of

Yeates et al. [23]. *Filenchus* and *Tylenchus* were designated as fungivores [32]. *Prismatolaimus* was classified as a bacterivore instead of a substrate digester [23]. The abundance and percentage of each trophic group were calculated. Richness was calculated as the total number of taxa per sample. Dominance (λ) was calculated as $\lambda = \sum(p_i)^2$, where p_i is the proportion of each taxon present [33], and diversity was calculated as $1/\lambda$. The fungivore (F)-to-bacterivore (B) ratio was calculated as F/F + B to characterize the dominant decomposition pathways [34].

For nematode fauna analysis, each genus was assigned to a 1–5 c-p scale [22]. Nutrient enrichment in the soil was indicated by the weighted abundance of bacterivores with a c-p value of one (Ba1) and fungivores with a c-p value of two (Fu2), calculated as the enrichment index (EI) using the equation $100 \times [e/(e + b)]$, in which e is the total weighted abundance of Ba1 and Fu2 and b is the weighted abundance of nematodes in the basal food web consisting of Ba2 and Fu2. The characterization of the fungal or bacterial decomposition pathway was also represented by the channel index (CI), calculated as $100 \times [0.8F_2/e]$ [28]. The maturity index (MI) represents free-living nematode fauna weighted by c-p values and is calculated as $\sum(v_i f_i)$, in which v_i is the c-p value and f_i is the frequency of the taxon [35]. The resilience, speciousness, and abundance of trophic links associated with the soil food web structure are represented by the structure index (SI), calculated as $100 \times [(s/s + b)]$, in which s is the weight abundance of free-living nematodes with c-p values higher than 2 [28].

2.4. Soil Water and Other Physical Properties and Temperature Monitoring

Gravimetric soil moisture levels were measured by drying the soil in an oven for 48 h at 70 °C. The soil water tension in the corn rhizosphere was monitored using a WatchDog Watermark Soil Moisture Sensor (Spectrum Technologies, Inc., Aurora, IL, USA) every hour throughout the corn cropping period. A FieldScout TDR 100 Soil Moisture Meter (Spectrum Technologies, Inc., Aurora, IL, USA) was used to measure volumetric soil moisture levels weekly with 12 cm rods in the corn rhizosphere from 3 random spots per plot.

At the end of the corn crop, the soil infiltration rate was measured for each plot using a single-ring infiltration method [36] using a 25.4-cm-diameter metal ring (infiltrator). The water level inside the infiltrator was maintained at 1 cm for 30 min. The steady infiltration rate was derived from the slope of the linear regression line of the volume of water infiltrated between 500 to 1800 s after the infiltration test. The infiltration sites were then covered with a plastic bag to avoid evaporation and precipitation. The bulk density was measured 2 days after infiltration by taking a 10-cm-diameter polyvinyl chloride (PVC) core to a depth of 10 cm using the procedure described by Blake [37]. The soil porosity [38] was calculated as (1-bulk density/particle density), assuming 2.85 g/cm^3 as the standard particle density for Oxisols in Hawaii [39]. The field capacity of the soil was measured from the volumetric soil moisture of the bulk density core [40]. The macroporosity was measured by subtracting the volumetric soil moisture at field capacity from the total porosity.

In trial II, soil temperature probes (WatchDog B-series button data logger, Spectrum® technologies, Aurora, IL, USA) were buried to a depth of 5 cm on the day of corn planting in the center of each plot and the soil temperature was record hourly for 12 weeks.

2.5. Corn Growth and Yield

Corn height and chlorophyll content measurements were taken monthly from 3 plants per plot. The chlorophyll content was measured with a SPAD-502 chlorophyll meter (Konica Minolta, Tokyo, Japan) on the third leaf from the top. Due to the high infestation of corn leafhoppers (*Dalbulus maidis*) and early corn senesces, chlorophyll was not measured on the third month. Corn ears were not harvested in trial I due to feeding damage from feral pigs. Instead, the shoot biomass of one-third of the corn plot was weighed. In trial II, Sevin® (Novasource, Phoenix, AZ, USA) was applied to manage leafhoppers. Corn was harvested at 12 weeks after planting from the center 4 rows per plot.

2.6. Statistical Analysis

The homogeneity of variance of all data was tested using PROC UNIVARIATE in SAS 9.3 (SAS Inc, Cary, NC, USA). When the nematode abundance did not fit a normal distribution, the counts were log-transformed [log10 (x + 1)] while all other parameters in the percentage or ratio were square-root-transformed [$\sqrt{}$(x + 0.1)] before the analysis of variance (ANOVA). Data with one sampling date were subjected to one-way ANOVA using PROC GLM. If the interaction between the sampling date and treatment was not significant, data were subjected to repeated measures over time. Means were separated using the Waller–Duncan *k*-ratio (k = 100) *t*-test wherever appropriate. Only true means are presented here.

All parameters collected from the termination of pre-plant treatments to the corn crop phase in each trial were first subjected to principal component analysis using R package 2.5–7 [41]. Parameters that contributed significantly to PCA were selected and subjected to canonical correspondent analyses (CCA) separately using CANOCO 5.1 for Windows [42] to deduce associations between species (nematode abundance in each trophic group, including algivores (Alg), bacterivores (Bact), fungivores (Fungi), herbivores (Herb), omnivores (Omn), predators (Pred)) and environmental variables (soil quality data, soil health indices, and corn measurements). Average data across dates for each treatment were used. Soil health indices included nematode richness (rich), EI, SI, CI, and MI. Soil quality measurements included the volumetric soil moisture, volumetric field capacity, soil organic matter, total soil porosity, macroporosity, and water infiltration rate. The lowest and highest daily soil temperatures were added to trial II but were not available in trial I. Corn measurements (height, chlorophyll content, and yield) were added in trial II based on high eigenvalues from the PCA. To identify the general relationship between the treatments, PCA scatter plots were created from variables included in the CCA using CANOCO 5.1 for Windows.

3. Results

3.1. Pre-Plant Conditions

The soil organic matter readings prior to initiation of the current study were 1.38, 1.11, and 1.21% in BO, SOL, and BG plots, respectively. The black oat biomass weights that accumulated at cover crop termination in the no-till BO equaled 9 tons/ha and 36 tons/ha in trial I and trial II, respectively. In trial I, the SOL plots reached maximum soil temperatures of 50.5 °C and 43.5 °C at 5 cm and 15 cm soil depths, respectively. In trial II, pre-plant treatments were conducted in the cooler months of the year (December to February); thus, the SOL plot only reached maximum soil temperatures of 36 °C and 33 °C at 5 cm and 15 cm soil depths, respectively. The soils in BO and BG plots did not experience temperatures > 30 °C and 35 °C, respectively, during the pre-plant period in both trials.

3.2. Effects of No-Till Cropping and Black Oat Cover Cropping on Soil Properties

No significant interaction was found between sampling time and treatment effects for soil physical properties in both trials; thus, data from all dates were subjected to a repeated measures analysis. The soil bulk densities were lower in the SOL plot, resulting in higher total porosity than in the BG and BO plots in trial I. Although BO did not reduce the bulk density more than BG in trial I, BO significantly increased the bulk density and reduced the total porosity compared to BG and SOL in trial II ($p \leq 0.05$; Table 1). Consequently, BO resulted in a slower and more steady infiltration rate than SOL in trial I ($p \leq 0.05$; Table 1), but no difference in infiltration was observed in trial II ($p > 0.05$). The reduction in total porosity by BO was mostly due to the reduction in macroporosity, which was consistent in both trials ($p \leq 0.05$). The soil organic matter was significantly increased in BO compared to BG and SOL in both trials ($p \leq 0.05$), with the lowest soil organic matter values recorded in SOL in both trials. Compared to the initial SOM values measured prior to the initiation of this experiment (1.21, 1.38, and 1.11% in BG, BO, and SOL plots, respectively), BO was the only treatment to cause steady increases in SOM in both trials, while both BG and SOL caused decreases from the initial readings. The field capacity and volumetric soil moisture values were higher in BO than BG and SOL plots in both trials ($p \leq 0.05$). Although the field capacity was not reduced by SOL in trial I, it was lower ($p \leq 0.05$) than with BG in trial II. Similarly, SOL reduced the soil moisture in trial I compared to BG ($p \leq 0.05$), although it did not reduce the soil moisture in trial II.

Table 1. Effects of tillage practices on soil physical properties in a corn agroecosystem from field plots managed in no-till black oat (BO), bare ground (BG), and solarization (SOL) plots.

Soil	Trial I			Trial II		
Properties [y]	**BG**	**BO**	**SOL**	**BG**	**BO**	**SOL**
Db (g/cm^3)	1.01 ± 0.02 [z] A	1.06 ± 0.01 A	0.95 ± 0.01 B	1.08 ± 0.01 B	1.16 ± 0.02 A	1.05 ± 0.02 B
I (cm/hour)	44.8 ± 5.43 B	24.6 ± 5.82 B	150.5 ± 21.84 A	33.2 ± 9.3 A	18.8 ± 6.8 A	27.9 ± 7.5 A
TP (%)	64.6 ± 0.9 B	62.9 ± 0.5 B	66.7 ± 0.4 A	62.1 ± 0.4 A	59.4 ± 0.6 B	63.1 ± 0.6 A
MP (%)	32.1 ± 2.0 A	24.3 ± 1.9 B	36.1 ± 1.4 A	27.4 ± 1.0 B	22.0 ± 0.8 C	30.5 ± 1.4 A
SOM (%)	1.08 ± 0.01 B	1.45 ± 0.05 A	0.98 ± 0.02 C	1.11 ± 0.03 B	1.46 ± 0.08 A	0.94 ± 0.02 B
SM (θ_v)	33.0 ± 0.6 B	39.6 ± 0.5 A	28.5 ± 0.5 C	32.4 ± 0.4 B	36.9 ± 0.3 A	32.4 ± 0.2 B
FC (θ_v)	32.5 ± 1.4 B	38.5 ± 1.5 A	30.6 ± 1.1 B	34.8 ± 0.6 B	37.4 ± 0.5 A	32.6 ± 0.9 C

[z] Means (±SE) are averages of 4 replications in repeated measures of planting and harvesting for Db, I, FC, TP, MP, and SOM ($n = 8$), and of weekly samples for SM in trial I ($n = 44$) and trial II ($n = 48$). Means in a row followed by the same letter(s) are not different according to the Waller–Duncan k-ratio ($k = 100$) *t*-test. [y] Db = bulk density; I = infiltration rate; FC = volumetric field capacity; TP = total porosity; MP = macroporosity; SOM = soil organic matter; SM = volumetric soil moisture throughout the corn growing period.

Hourly monitoring of the soil water tension revealed that BO maintained lower soil water tension rates than BG and SOL throughout the corn growing period in both trials, indicating the presence of more plant-available water in BO than in BG or SOL plots (Figure 1). This event was most obvious during periods of water stress, when water tension levels in the BG and SOL plots were increased at 4, 7, and 8 weeks after corn planting in trial I, or in the SOL plot at 2, 3, and 5 weeks after corn planting in trial II (Figure 1).

Additional soil temperature data were monitored during the corn growing period in trial II. The BO plot accumulated fewer hours of extreme temperatures for nematodes (15–20 °C or ≥35 °C) compared to BG and SOL plots ($p \leq 0.05$, Table 2). The maximum temperature reached in the BO plot (32 °C) was also significantly lower than in the BG and SOL plots (36 °C and 37 °C, respectively, $p \leq 0.05$). On the other hand, the SOL plot accumulated 4 h of sublethal temperature for many nematodes (≥37 °C), whereas the BG and BO plots did not reach this threshold (Table 2).

Table 2. Effects of pre-plant treatments on hours of soil temperature ranges during the corn crop phase in no-till black oat (BO), bare ground (BG), and solarization (SOL) plots.

Temperature (°C)	BG	BO	SOL
		-hours-	
15–20	143.8 [z] ±6.8 AB	77.8 ± 8.3 B	183.3 ± 32.6 A
30–35	91.5 ± 12.1 A	16.8 ± 5.1 B	110.5 ± 14.1 A
35–37	2.3 ± 1.3 B	0.0 ± 0.0 B	14.3 ± 2.8 A
≥37	0.0 ± 0.0 B	0.0 ± 0.0 B	3.5 ± 2.2 A
		-°C-	
Max	35.6 ± 0.5 A	32.0 ± 0.5 B	37.3 ± 0.4 A
Min	17.0 ± 0.2 A	17.8 ± 0.3 A	16.6 ± 0.4 A

[z] Mean (±SE) of total hours within a temperature range. Means are averages of 4 replications. Means in a row followed by the same letter(s) are not different according to the Waller–Duncan *k*-ratio ($k = 100$) *t*-test. [z] Max = mean maximum temperature reached throughout the corn growing period; Min = mean minimum temperature reached throughout the corn growing period.

The soil temperature data collected hourly during the corn growing period in trial II were summarized as 7-day hourly mean soil temperatures (Figure 2). After corn planting, in the warmer hours of the day, BO maintained lower temperatures than BG and SOL from 10 am to 5 pm on the first week and from 11 am to 7 pm on weeks 2 and 3 ($p \leq 0.05$). On week 4, BO was cooler than SOL from 11 am to 5 pm ($p \leq 0.05$). No significant difference among the treatments was observed during the warmer hours of the day during week 5 ($p > 0.05$). As the corn canopy filled in from week 7 and beyond, BO was consistently warmer than BG and SOL regardless of the hour of the day ($p \leq 0.05$), but temperatures did not exceed 29.7 °C in BO, with generally cooler soil temperatures than those occurring in weeks 1–6. On the other hand, during the early hours of the day, BO maintained warmer soil temperatures than BG and SOL from 2 am to 8 am in the first week and from 5 am to 8 am on the second week ($p \leq 0.05$). During weeks 3 to 5, BO had higher temperature than SOL at 7 am on the third week, from 6 am to 8 am on the fourth week, and from 7 am to 8 am on the fifth week ($p \leq 0.05$).

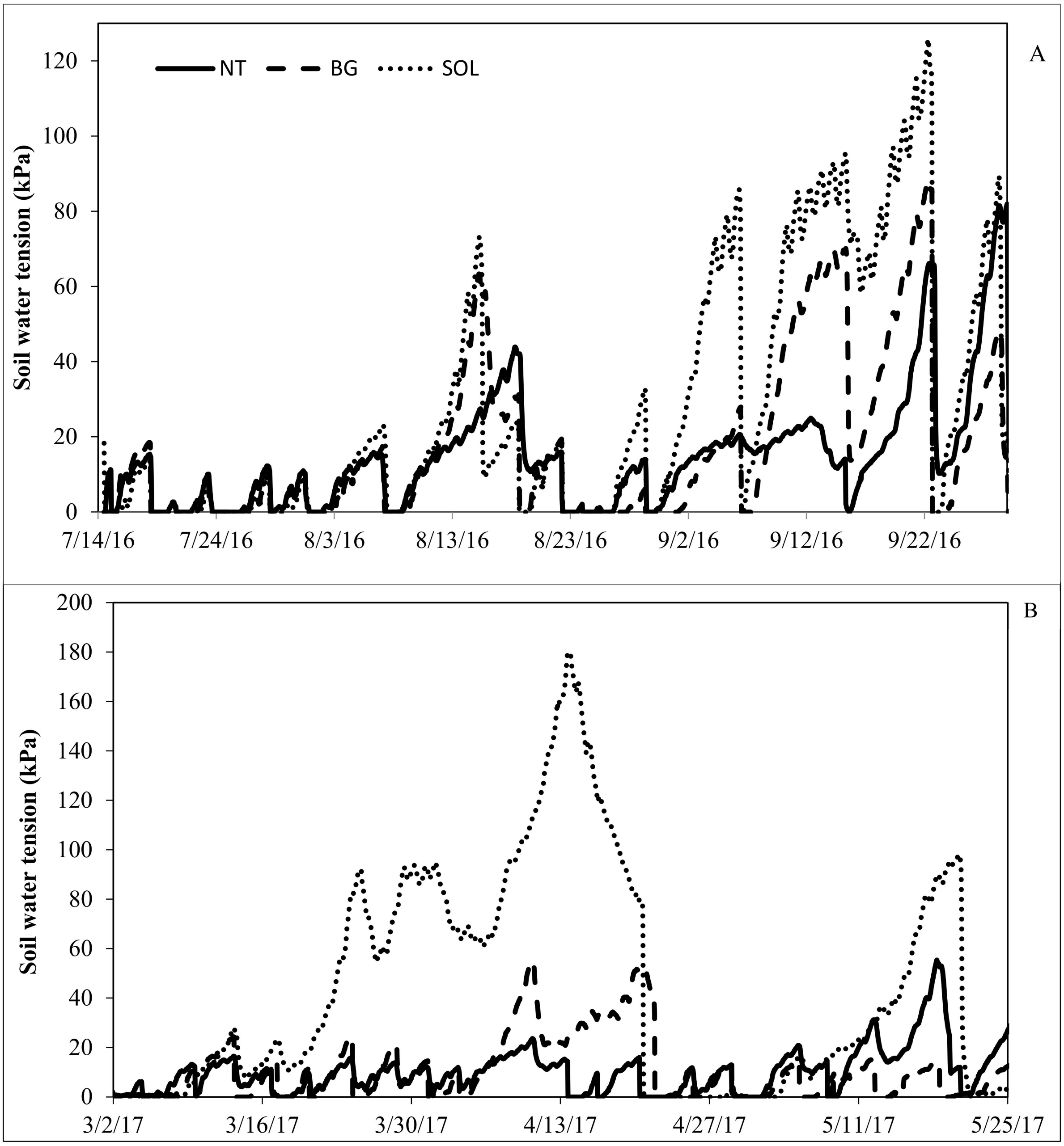

Figure 1. Soil water tension values recorded hourly throughout the 3 month corn growing period in (**A**) trial I and (**B**) trail II. BG = bare ground conventional tillage; BO = no-till with black oat cover crop; SOL = solarization.

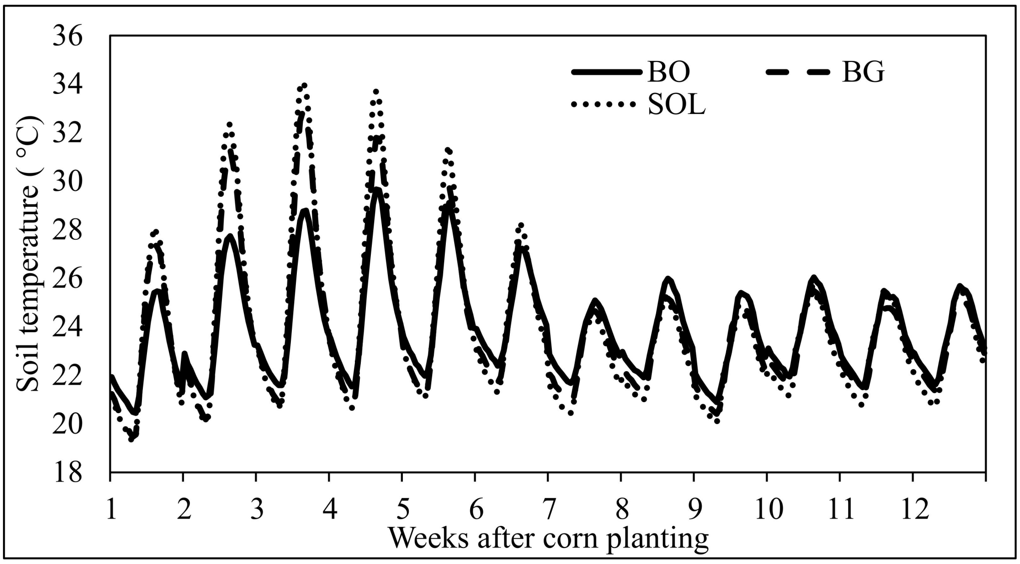

Figure 2. Means of 7-day soil temperatures recorded hourly throughout the 3 months of the corn growing period in trial II. BG = bare ground conventional tillage; BO = no-till with black oat cover crop; SOL = solarization.

3.3. Effects on Nematode Community as Soil Health Indicators

The herbivorous nematodes found at this site included *Helicotylenchus*, *Meloidogyne*, *Paratrichodorus*, *Pratylenchus*, and *Rotylenchulus*, among which *R. reniformis* was the most abundant plant-parasitic nematode. SOL was the most effective in reducing the abundance of *R. reniformis* and total abundance of herbivorous nematodes in trial I as compared to the BG control ($p \leq 0.05$; Table 3). Lesion (*Pratylenchus* spp.) and root-knot (mixed population of *M. incognita* and *M. javanica*) nematodes, which can infect corn, were either not detected or detected at lower than economic threshold levels, respectively, in trial I, but their abundance slowly increased in trial II (Table 3). BO and SOL both were able to significantly suppress the abundance of *Meloidogyne* spp. and *Pratylenchus* spp. compared to BG ($p \leq 0.05$) in trial II. SOL consistently suppressed the abundance of bacterivorous and fungivorous nematodes throughout both trials ($p \leq 0.05$; Table 3). The abundance levels of different trophic groups of free-living nematodes from BO did not differ from BG in both trials, but BO had higher abundance levels of omnivorous nematodes than SOL in trial II ($p \leq 0.05$; Table 3).

In terms of nematode community indices, BO reduced its % bacterivore but increased its % fungivore, fungivore-to-bacterivores ratio (F/F + B), and CI values in trial I ($p \leq 0.05$, Table 3). BO also increased its MI value in trial I ($p \leq 0.05$). Although the % bacterivores and % fungivores were not affected by BO in trial II, BO increased its % omnivores leading to an increase in SI in trial I ($p \leq 0.05$). Conversely, SOL reduced its % bacterivore, % fungivore, EI, and nematode richness values compared to BG consistently in both trials ($p \leq 0.05$). SOL also reduced its nematode diversity and SI values compared to BG in trial I ($p \leq 0.05$), which resulted in the lowest F/F + B and MI values among the pre-plant treatments in trial I ($p \leq 0.05$) (Table 3).

Although corn yields were not different among treatments for both trials ($p > 0.05$, Table 4), the chlorophyll content was greater in BO than BG in both trials ($p \leq 0.05$). The plant height was also higher in SOL than in BO and BG in trial II ($p \leq 0.05$).

3.4. Relationships between Soil Properties and Free-Living Nematode Abundance

Based on the PCA, we selected the variable listed in Figure 3A for the CCA. The first two canonical axes explained 100.0% of the variance between the environmental variables (the nematode community indices and the various soil properties measured) and species variables (abundance of nematode trophic groups of bacterivores, fungivores, and omnivores) from trial I (Figure 3A). The soil moisture, field capacity, and soil organic matter were negatively related to soil water infiltration but positively related to the enrichment index (EI; more abundant of opportunistic bacterial feeding nematodes) and CI (higher ratio of fungal-feeding nematodes to bacterial- and fungal-feeding nematodes), as well as to the abundance of fungivores (Figure 3A). On the other hand, infiltration was positively related to the total soil porosity and macroporosity. The SI was not related to either the soil moisture, soil organic matter, or field capacity complex nor to infiltration, the total porosity, or the macroporosity complex. The first two principal component axes in the scatter plot of sampling points explained 82.91% of the variance. Samples from BG overlapped with both SOL and BO, but BO and SOL were segregated from each other (Figure 3B). Fungivore abundance provided the largest contribution (27.4%) to the first principal component, whereas bacterivore abundance provided the largest contribution (37.4%) to the second principal component.

Table 3. Effect of no-till cover cropping with black oat (BO) on nematode communities compared to bare ground (BG) and soil solarization (SOL) treatments during the corn growing season.

Nematode Parameters	Trial I			Trial II		
	BG	BO	SOL	BG	BO	SOL
Abundance	Number of nematodes/250 cm^3 soil					
Helicotylenchus	3 ± 3 [z] AB	21 ± 10 A	0 ± 0 B	13 ± 8 AB	16 ± 7 A	1 ± 1 B
Meloidogyne	10 ± 8 A	3 ± 2 A	137 ± 455 A	133 ± 33 A	76 ± 45 B	336 ± 263 A
Paratrichodorus	4 ± 2 A	1 ± 1 A	0 ± 0 A	15 ± 6 A	2 ± 1 A	22 ± 18 A
Pratylenchus	0 ± 0 A	0 ± 0 A	0 ± 0 A	166 ± 52 A	13 ± 7 B	10 ± 6 B
Rotylenchulus	152 ± 38 A	288 ± 50 A	48 ± 29 B	611 ± 141 A	464 ± 78 A	627 ± 177 A
Bacterivore	373 ± 105 A	178 ± 29 B	151 ± 51 C	659 ± 167 A	542 ± 108 A	293 ± 33 B
Fungivore	156 ± 35 A	201 ± 26 A	17 ± 12 B	307 ± 46 A	255 ± 51 A	131 ± 30 B
Herbivore	170 ± 45 A	313 ± 51 A	185 ± 136 B	938 ± 144 A	571 ± 86 A	997 ± 297 A
Omnivore	10 ± 5 A	8 ± 4 A	1 ± 1 A	31 ± 7 AB	49 ± 12 A	17 ± 8 B
Predator	2 ± 2 A	1 ± 1 A	0 ± 0 A	3 ± 3 A	4 ± 2 A	1 ± 1 A
Indices [y]						
% Bacterivore	44.3 ± 4.5 A	25.7 ± 3.4 B	39.8 ± 10.1 B	32.6 ± 4.3 A	35.3 ± 4.0 AB	27.4 ± 5.2 B
% Fungivore	22.3 ± 3.3 B	29.1 ± 3.2 A	3.6 ± 1.9 C	15.9 ± 1.6 A	17.0 ± 2.4 A	10.7 ± 2.5 B
% Herbivore	28.0 ± 5.4 AB	42.6 ± 3.8 A	22.8 ± 8.3 B	48.6 ± 4.9 AB	42.4 ± 5.6 B	60.1 ± 6.6 A
% Omnivore	1.3 ± 0.3 A	1.0 ± 0.5 A	0.1 ± 0.1 A	1.7 ± 0.4 B	3.3 ± 0.6 A	1.1 ± 0.5 B
% Predator	0.3 ± 0.3 A	0.1 ± 0.1 A	0.0 ± 0.0 A	0.2 ± 0.1 A	0.3 ± 0.1 A	0.0 ± 0.0 A
Diversity	8.1 ± 1.3 A	5.1 ± 0.6 AB	4.4 ± 1.9 B	7.0 ± 1.3 A	6.8 ± 0.9 A	11.7 ± 6.8 A
Dominance	16.5 ± 3.2 A	23.0 ± 2.8 A	18.4 ± 5.4 A	20.7 ± 3.9 B	19.9 ± 3.8 B	32.9 ± 7.6 A
Richness	13 ± 2 A	12 ± 1 A	4 ± 1 B	17 ± 1 A	17 ± 1 A	10 ± 1 B
CI	31.8 ± 3.8 B	55.8 ± 6.4 A	20.8 ± 11.1 B	36.4 ± 6.8 A	36.9 ± 8.0 A	58.3 ± 10.7 A
EI	57.2 ± 2.8 A	52.9 ± 1.6 A	9.0 ± 5.8 B	56.7 ± 3.5 A	59.6 ± 6.5 A	34.2 ± 5.5 B
F/F + B	33.3 ± 4.1 B	53.4 ± 5.0 A	4.0 ± 2.0 C	34.7 ± 4.1 A	31.8 ± 3.6 A	27.8 ± 4.8 A
MI	1.9 ± 0.0 B	2.0 ± 0.0 A	1.3 ± 0.3 C	1.9 ± 0.0 A	2.0 ± 0.1 A	2.0 ± 0.0 A
SI	11.9 ± 5.2 A	11.6 ± 3.8 A	2.6 ± 1.9 B	20.4 ± 2.7 B	38.8 ± 4.6 A	13.1 ± 4.5 B

[z] Means (±SE) are repeated measures over 3 dates from 4 replications (n = 12). Means in a row followed by the same letter(s) are not different according to the Waller–Duncan k-ratio (k = 100) t-test based on log(x + 1) for nematode abundance or $\sqrt{(x + 0.1)}$ for other parameters wherever necessary prior to ANOVA. [y] CI = channel index; EI = enrichment index; F/F + B = ratio of the abundance of fungivores to bacterivores; MI = maturity index; SI = structure index.

The PCA of all the variables collected in trial II justified the addition of a few more variables to the CCA. The environmental variables added included plant growth parameters (chlorophyll content, plant height, and yield), the lowest daily soil temperature averaged by week, and the highest daily soil temperature averaged by week. The EI and CI were removed from the environmental variables as the PCA analysis indicated that these variables contributed eigenvalues that were too low. The species variables were similar to those used in trial I, except that the weed pressure was also added based on the PCA results. The first two canonical axes explained 94.0% of the variance in this species–environment multivariate analysis (Figure 4). Unlike trial I, the SI was positively related to the soil organic matter and soil moisture in trial II (Figure 4A). Infiltration, total porosity, macroporosity, field capacity, and corn yield were positively related with each other, while being negatively related with corn height, chlorophyll content, and the lowest soil temperatures of the day. Scatter plots of BO, BG, and SOL on the first two principal component axes (explaining 62.8% of total variance) showed more segregation among the three treatments in trial II than in trial I (Figure 4B), whereby SOL no longer overlapped with BG and BO only overlapped with BG minimally. The total porosity (TP) provided the largest contribution (28.8%) to the first principal component axes, whereas corn yield provided the largest contribution (40.6%) to the second principal component axes.

Table 4. Effects of no-till cover cropping with black oat (*Avena strigosa*) on corn growth, yield, and weed pressure.

Growth Parameters [y]	Trial I [†]			Trial II		
	BG	BO	SOL	BG	BO	SOL
Yield (kg/ha)	3733 ± 143 [z] A	3873 ± 712 A	3923 ± 884 A	6663 ± 420 A	5808 ± 180 A	6737 ± 536 A
Chlorophyll (SPAD)	32.7 ± 1.9 B	38.2 ± 1.4 A	37.2 ± 1.4 A	41.6 ± 1.7 B	45.1 ± 1.4 A	43.4 ± 1.5 AB
Height (cm)	100.4 ± 15.9 A	97.2 ± 15.9 A	100.6 ± 15.1 A	143.0 ± 22.1 A	133.0 ± 21.7 B	148.8 ± 23.4 A

[z] Means (±SE) are averages of 4 replications. Means in a row followed by the same letter(s) are not different according to the Waller–Duncan *k*-ratio (k = 100) *t*-test. [y] Height and chlorophyll content values consist of 3 repeated measures of 4 replications (n = 12). [†] Biomass was record in trial I instead of yield due to lack of harvestable cobs.

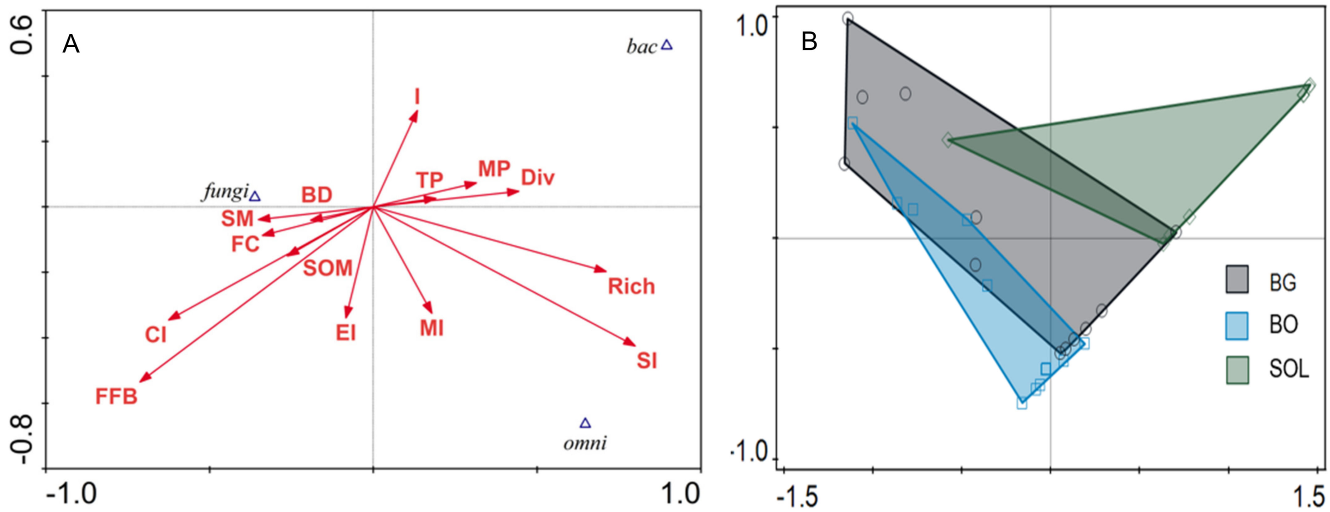

Figure 3. (**A**) Ordinance diagram of trial I depicts the first two canonical axes of a canonical correspondence analysis between the free-living nematode abundance (bac = bacterivores; fungi = fungivores; omni = omnivores) and environmental variables (BD = bulk density; Div = diversity; FC = field capacity; FFB = fungi/fungi + bacteria; I = infiltration rate; TP = total soil porosity; MP = macroporosity; SOM = soil organic matter; SM = soil moisture; CI = channel index; EI = enrichment index; SI = structure index; MI = maturity index; Rich = Richness). The first two axes explained 100% of the variance. (**B**) Scatter plot of samples on the first two principal component axes explaining 82.91% of the variance from no-till black oat (BO), bare ground (BG), and solarization (SOL) regimes.

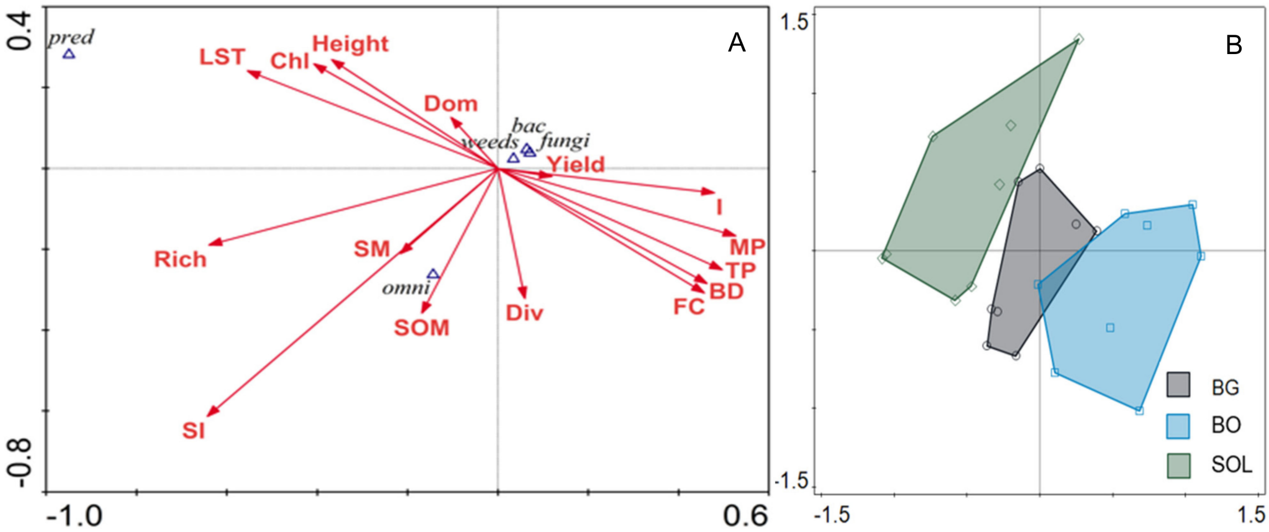

Figure 4. (**A**) Ordinance diagram of trial II depicting the first two canonical axes of a canonical correspondence analysis between free-living nematode abundance (bac = bacterivores; fungi = fungivores; herb = herbivores; omni = omnivores; pred = predatory nematodes) and environmental variables (BD = bulk density; Div = diversity; Dom = dominance; FC = field capacity; I = infiltration rate; TP = total soil porosity; MP = macroporosity; SOM = soil organic matter; SM = soil moisture; LST = lowest daily soil temperature; Yield = corn yield; Chl = chlorophyll content; Height = corn height; Rich = richness; and SI = structure index). The first two axes explained 94.0% of the variance. (**B**) Scatter plot of samples on the first two principal component axes explaining 62.8% of the total variance from no-till black oat (BO), bare ground (BG), and solarization (SOL) regimes.

4. Discussion

4.1. Effects of No-Till Black Oat and Soil Solarization on Different Soil Properties

4.1.1. Water-Holding Capacity

The positive effects from no-till cover cropping with black oat conducted in this study included consistent increases in soil organic matter, soil moisture, and field capacity and reductions in soil water tension in both trials. Like other tropical Oxisols where the soil organic matter is generally below 2% [43], the continuous no-till cover cropping practice for 9 years at this site only increased the soil organic matter from 1.11% in BG to 1.46% in BO (31.53% increase) towards the end of the two-year experiment and increased from 1.38% in BO plots prior to the initiation of this experiment to 1.46% at the end of trial II (15.94% increase). None-the-less, it is worth noting that the continuous practice of conventional tillage resulted in reductions in soil organic matter from 1.21% to 1.11% in BG (8.26% decrease) and from 1.11 to 0.98% in SOL (11.71% decrease). Although the increase in soil organic matter in BO was slow, this result highlights the destruction of soil quality from poor soil treatments such as SOL and BG.

Despite a slow increase in soil organic matter following no-till BO over the two years of this study, this approach generates surface organic mulch [2,44] that can lead to the aggregation of soil organic matter with variable charges from iron and aluminum oxides to form microaggregates (<250 μm) [43,45], especially in no-till Oxisols [9]. Increases in microaggregates or microporosity and capillary pores are responsible for the water-holding capacity [46]. The higher soil moisture and field capacity in BO could be the result of more micropores, as reflected in its higher field capacity. Hill et al. [47] also reported that no-till cropping retained more moisture at higher water potential levels (3.9 to 40 kPa) than conventional tillage, although conventional tillage retained more moisture at lower water potential levels (0–2 kPa) in a Hapludult soil from Maryland. This finding of an improvement in the water-holding capacity with no-till cover cropping is consistent with the results reported in a 14-year no-till Hapludox (one suborder of Oxisol) study in Brazil [7] and a 6 year no-till Argiudoll study [37] and another Argiudoll study of southern pampas in Argentina [48]. In this experiment, BO maintained lower water potential levels than BG and SOL, making the soil water more available for plants to uptake.

The presence of surface organic mulch from black oat may also explain the improved water-holding capacity in the BO. The cover crop mulch can reflect solar radiation [46] and maintain cooler temperatures [48], reducing soil evaporation and maintaining higher soil moisture levels. In this study, no-till cover cropping with black oats maintained lower soil temperatures compared to other pre-plant treatments, not only during the pre-plant period but also during the first few weeks of the corn growing season, thereby reducing soil moisture loss. Conversely, the lack of organic mulch and continuous exposure to warmer temperature in the SOL treatment led to lower soil moisture in trial I and lower field capacity during the corn growing period in trial II. Although the soil solarization in trial II took place in December–January, SOL still resulted in warmer maximum temperatures than those recorded in the BG (<35 °C) and BO (<30 °C) plots during the pre-plant phase in both trials. Soil temperatures continued to be affected by these pre-plant treatments during the first 5 weeks after corn planting.

4.1.2. Infiltration and Macroporosity

Solarization relies on tillage to provide a smooth surface to lay plastic mulch. Tillage preceding solarization in trial I dramatically increased the rate of infiltration to a level expected of a sandy soil. This may be due to irreversible drying of oxides and organic matter leading to the formation of stable sand-sized aggregates [49], resulting in increased macroporosity for water infiltration. Signs of irreversible aggregates from drying were observed in trial II, as SOL plots were not re-tilled and did not reach the solarization heat lethal to most soil fauna, yet SOL still had higher MP values than BG and BO. However, infiltration was no longer greater in SOL. Although an increase in soil macroporosity could improve the soil hydraulic conductivity (the ease with which water can move through pore spaces or fractures) and reduce water erosion [7,37,50,51], it would also reduce the microporosity and capillary pores responsible for the water-holding capacity [46]. In this study, BO had the lowest macroporosity, yet the highest field capacity and microporosity, resulting in the highest soil moisture levels in both trials. Bacq-Labreuil et al. [12] found that black oat produced substantial fine root growth and induced the breakdown of the larger soil aggregates, resulting in an increased proportion of microaggregates (1000–2000 µm). This increase in microaggregates may explain the higher microporosity observed. Our multivariate analysis presented in Figures 3 and 4 provided further evidence that the soil water infiltration was positively related to the total porosity and macroporosity but negatively related to the soil organic matter and soil moisture retention, although the relationships with the soil bulk density and field capacity levels varied between trials. Therefore, even though solarization is an effective organic approach to managing soil-born pests, pathogens, and weeds [15], it can have negative impacts on soil moisture and field capacity beyond the first subsequent crop.

4.1.3. Bulk Density

The Haplustox soil in our experiments revealed that after 9 years of no-till cropping (trial II), the bulk density was significantly higher while the total porosity and macroporosity were significantly lower. This phenomenon has been commonly reported for Oxisols and Ultisols [7,47,52,53]. No-till has commonly been reported to have greater soil compactness with higher bulk density in farmland and grazing pastures compared to conventional till systems [37,47,52,54–58], especially in long-term no-till fields [7,59]. However, there are reports of no-till cropping reducing the bulk density in loamy Ultisols as well [60,61]. A higher bulk density indicates soil compaction, which is unfavorable for plant growth. Soil compaction is a risk in no-till cropping when heavy equipment is employed for cover crop termination, as was the case in this study. Options to operate flail mowers for cover crop termination using lighter equipment are available and should be explored.

4.2. Effects of No-Till Black Oat Cropping and Solarization on Nematode Communities

4.2.1. Soil Food Web Structure

Enhancing the soil food web structure by using no-till black oat cover cropping is contingent on biomass production. In trial I, insufficient black oat biomass (9 tons/ha) production resulted in no enhancement in terms of the bacterial decomposition, soil nutrient enrichment (indicated by EI), and stability of nematode communities (indicated by SI). However, no-till fields are known to have less bacterivores and more omnivorous and predatory nematodes than conventional tillage fields due to there being less soil disturbance [62]. BO stimulated fungal decomposition pathways, as suggested by the higher F/(F + B) and CI values. The higher CI value for BO reflects the high C/N ratio from the black oat biomass with more non-labile carbon sources that favor fungal decomposition [63]. Bacq-Labreuil et al. [12] also reported an increased proportion of fungal biomass from the black oat rhizosphere. Similarly, Zhang et al. [64] reported that no-till resulted in a higher CI than conventional tillage but would increase the EI and SI values if the biomasses of the cover crop residues were high. When there was a four-fold increase in black oat residue in trial II (36 tons/ha) compared to trial I, BO enhanced the soil food web structure, as the SI was higher for BO than BG and the % omnivorous nematodes was higher for BO than SOL. In contrast, SOL was rather destructive to the soil food web, consistently reducing the abundance levels of bacterivores, fungivores, and omnivores, as well as the richness, SI, and EI values throughout the corn cropping cycle compared to BG in both trials.

4.2.2. Plant-Parasitic Nematodes

Solarization was successful in reducing the population densities of the most abundance plant-parasitic nematode, *R. reniformis*, only in the first trial when temperatures were lethal, but was still successful in reducing the abundance levels of other plant-parasitic nematodes such as *Helicotylenchus* and *Pratylenchus* in trial II, despite not reaching the lethal temperature for nematodes due to the overcast weather and more frequent precipitation. However, in trial II, the % herbivores were greater in SOL than in BG and BO. The non-host status of black oats may have reduced the abundance of *Meloidogyne* and *Pratylenchus* in trial II, as had been reported previously [65,66], although different black oat cultivars than 'soil saver' were used. The many weed species present in the fallow period of BG may have served as hosts to plant-parasitic nematodes and may have contributed to their greater abundance.

4.3. Relationship between Soil Food Web Structure and Soil Water Conservation

The PCA and CCA ordination diagrams from trial I and trial II depicted a successional soil health event following two consecutive cycles of BO, BG, and SOL pre-plant treatments. The PCA scatter plots for both trials further confirmed that the continuous no-till cover cropping with black oat and higher biomass generation from BO in trial II progressively improved the soil health conditions (Figures 3 and 4). Less overlapping between BO and BG was observed in trial II than in trial I, which suggested an improvement in the soil food web structure with BO over time. Despite the less intense solarization heat during the winter in trial II, the destruction of the soil health by SOL persisted, further segregating SOL from BG.

Prior to trial I, the BO plots were in a rotation of a leguminous cover crop, sunn hemp (*Crotalaria juncea*), with various vegetable crops for the last 7 years, which did not increase the soil organic matter dramatically, despite following no-till practices. In trial I the BO biomass was minimal (9 tons/ha), yet at the end of trial I positive relationships between the EI and CI with soil organic matter, soil moisture, and field capacity were observed. This suggested that the stimulation of fungal decomposition tended to also enhance the accumulation of soil organic matter, soil moisture, and field capacity. Maintaining higher volumetric soil moisture and field capacity levels is important for soil water conservation. However, these above-mentioned soil parameters (e.g., soil moisture, field capacity, soil organic matter, EI, and CI) were all negatively related to the infiltration, total porosity, and macroporosity. While this is less than an ideal scenario, it has been commonly reported that the macroporosity will become lower in Oxisols and Ultisols with the continuous practice of no-till cropping [7,47,52,53], while the microporosity and capillary pores are responsible for the increased water-holding capacity [46]. The CCA here also suggested that the higher macroporosity was responsible for the faster water infiltration but was negatively related with the soil moisture holding capacity in both trials. However, in trial II, the soil health indicators EI and CI were no longer closely related to the soil organic matter or soil moisture retention; instead, those indices related to a structured food web (e.g., SI, diversity, and richness). This is not a contradictory result but rather a successional event where the soil health conditions in BO plots slowly progressed from fungal dominated decomposition in trial I to a more complex and structured soil food web with a higher SI in trial II.

The soil temperature extremes were buffered in BO plots, probably from the insulation offered by the organic mulch. This contributed to a more stable environment for the microfauna and microflora, resulting in an enhanced soil food web structure. The weekly lowest daily soil temperatures were higher in the BO than BG and SOL plots due to the total porosity and microporosity, but were positively related to the corn height and chlorophyll content. Keeping the soil warm during the low temperatures of the day might improve corn growth. However, the corn yields did not differ among treatments. While the CCA depicted the relationships between the corn growth and soil parameters well, the complications from other pest damages (e.g., *Practilenchus, Helicotylenchus.* or weed densities) in terms of corn yield did not show a clear positive relationship between the corn yield and soil health parameters. Nonetheless, the higher chlorophyll content in BO than BG in trial II suggested a positive benefit from improving the soil food web structure.

Noticeable yield reductions due to the risk of soil erosion or soil health destruction may not be detected unless the soil organic carbon (C) falls below 1% [67]. Unfortunately, all soil treatments examined in this long-term field management site are still close to 1%. After 9 years of continuous practice of cover crop rotation and no-till cropping, soil organic matter in the BO plots slowly but steadily increased. It is quite common to find soil <1% soil C in the tropics [67]. Thus, a continued decline in soil organic matter in BG and SOL would be alarming. This insignificant corn yield response to soil health management seen here is consistent with a metanalysis comparing the benefits of till vs. no-till cropping by Pittelkow et al. [68]. They found that no-till cropping could increase the crop yield only when integrated with cover cropping, and only became more apparent under water stress conditions. Future research should examine the corn yield responses to soil health management with different irrigation regimes.

5. Conclusions

This study provides evidence that no-till cover cropping with black oats can improve soil water conservation and the soil food web structure over time in tropical Oxisols, especially following a continuous conservation tillage system and if the biomass of black oat plants is high (36 tons/ha). However, terminating BO with a tractor-operated flail mower decreased the soil macroporosity and increased the soil bulk density, which reduced the water infiltration rate. Despite lower infiltration rates from no-till black oat cover cropping, other water conservation properties such as the average volumetric soil moisture and field capacity were improved. Tillage preceding solarization was successful in generating lethal temperatures to suppress plant-parasitic nematodes and increased the water infiltration in both years, although it was destructive to the soil food web and consistently reduced soil organic matter and soil moisture levels, even when solarization failed to generate nematode-lethal temperatures in the second year.

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