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Integration of cover crops and vermicompost tea for soil and plant health management in a short-term vegetable cropping system

Koon-Hui Wang[a,*], Theodore Radovich[b], Archana Pant[b], Zhiqiang Cheng[a]

[a] Department of Plant and Environmental Protection Sciences, Honolulu, HI 96822, USA
[b] Department of Tropical Plant and Soil Sciences, University of Hawaii at Manoa, Honolulu, HI 96822, USA

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ABSTRACT

Short-term vegetable crop production often involves frequent tillage and other farm activities that results in disturbed soil food web communities. A less disturbed soil community would have a more structured soil food web which contains soil fauna higher up in the food web hierarchy, thus higher integrity in soil nutrient cycling. The objective of this study is to examine if strip-till cover cropping and drenching soil with vermicompost tea could improve soil food web structure in a short-term agroecosystem. Two field trials were conducted in Waialua, HI, USA to evaluate the effect of strip-till planting of sunn hemp (SH, *Crotalaria juncea*) or crimson clover (*Trifolium incarnatum*) cover crops in a zucchini (*Cucurbita pepo*) cropping system. At zucchini planting, each cover crop plot was split to receive four soil treatments: fertilizer (F, chicken pellet), compost tea (CT), fertilizer plus compost tea (F + CT), and none. Compost tea was prepared from chicken manure based vermicompost aerated overnight in water at 1:10 (v:v). Planting of SH increased bacterivorous nematodes and suppressed plant-parasitic nematodes throughout both zucchini cropping cycles, but did not enhance the numbers of omnivorous or predatory nematodes. Crimson clover did not enhance beneficial nematodes nor suppress plant-parasitic nematodes. Adding CT to F suppressed the key plant-parasitic nematodes only at the initial stage of the zucchini growth, increased percentage of predatory or omnivorous nematodes only toward the end of zucchini crops, and increased the structure index at harvest in the first trial. Zucchini yield was increased by planting of SH but not by drenching of CT. Despite the benefits of CT in improving the soil food web structure, a correlation analysis revealed that zucchini yields were correlated to the reduction in the percentage of fungivorous nematodes at planting, an increase in the percentage of bacterivorous nematodes at harvest, and to reduction in the percentage of plant-parasitic nematodes at harvest.

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1. Introduction

Short-term vegetable cropping systems usually involve more usage of pesticides, fertilizers and intensive cultivation of land that likely leads to a greater disturbance of soil and a negative impact on aquatic ecosystems than perennial cropping systems (Allan, 2004). This disturbance to agroecosystems is especially intensive in warm tropical climates. While farmlands are limited due to ever expanding urbanization, the tropical climate in Hawaii allows for multiple short-term crops in the same field per year. This type of frequent cultivation in the same field site creates intensive disturbance to the soil food web (Bongers and Korthals, 1994; McSorley and Wang, 2009). To conserve soil productivities, soil food web complexity must be restored periodically despite the continuous crop production. A healthy soil food web should continuously compose of high complexity of soil organisms with diverse functional guilds so as to maintain soil nutrient cycling and other chemical and physical soil processes, to ensure soil communities are resilient to transient disturbance, and to keep pest species in check (Doran and Zeiss, 2000). Unfortunately, short-term vegetable crop production often involves frequent tillage and other farm activities that may lead to the disturbance of soil communities. A less disturbed soil community would compose of a more structured soil food web and thus have higher integrity in soil nutrient cycling. Conducting no-till farming would offer an option, but many short-term vegetable growers prefer to cultivate their soil due to the high turnover rate of cropping cycles and challenges of weed pressure.

Nematodes are good soil health bioindicators because they have a wide range of functional guilds and have universal distribution (Ferris et al., 2001; Ferris, 2010; Neher, 2001) and thus they can be used to examine how various land management practices impact

* Corresponding author. Tel.: +1 808 956 2455; fax: +1 808 956 2428.
E-mail addresses: koonhui@hawaii.edu (K.-H. Wang), theodore@hawaii.edu (T. Radovich), apant@hawaii.edu (A. Pant), Cheng241@hawaii.edu (Z. Cheng).

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on soil health (Ferris et al., 2012a,b; Sánchez-Moreno et al., 2009; Ugarte et al., 2013). A healthy soil food web should sustain nematodes with different life strategies and feeding behaviors ranging from fast growing and reproducing bacteria-feeding nematodes (colonizers) at the bottom of the soil food web to slow reproducing but longer living predaceous nematodes (persisters) at the top (Bongers, 1990). Most importantly, nematodes have numerous interactions with other soil organisms and play important roles in soil nutrient cycling (Ingham et al., 1985).

Some have suggested that the restoring of a complex soil community characterized by several trophic links and functional guilds is not possible in disturbed agroecosystems (DuPont et al., 2009; Ferris and Matute, 2003; McSorley et al., 2007; Neher, 2001) whereas others argue that a more complex food web could be re-established by implementing practices that increase organic matter and reduce tillage frequency and depth (Okada and Harada, 2007; Wardle et al., 1999). The key index used by nematode ecologists to evaluate reduction in soil disturbance here is the structure index, SI, which is mainly a weighed abundance of the omnivorous and predatory nematodes. Using Canonical Correspondent Analysis, Ugarte et al. (2013) reported a positive relationship between the quantity of particulate organic matter (POM) and SI in a pasture agroecosystem but not in row crop or vegetable production system on the 3rd year of an organic certification process in Illinois. This again suggested the challenge of enhancing SI (or reducing soil disturbance) in a vegetable cropping system. While multiple soil ecology papers admit the difficulties in improving SI in short-term vegetable cropping system that rely on conventional tillage, little research is addressing how to increase SI in this agroecosystem.

Growing sunn hemp (*Crotalaria juncea*) as a leguminous cover crop in a strip-till cover cropping system (STCC) followed by periodic clipping of living mulch intercropped between vegetable cropping rows and added as organic surface mulch (SM) provided an alternative approach to reduce soil disturbance, while fueling organic materials to the soil food web over a longer period of time than a conventional cover cropping system (Wang et al., 2011). This STCC + SM practice periodically supplied organic matter through surface mulching, continuously enhanced bacterivorous and fungivorous nematodes, and subsequently enhanced SI within two cropping cycles as compared to the bare ground treatment (Wang et al., 2011). Similar phenomenon was reported on fueling organic matter to soil with residues of sugarcane in the sugarcane plantations in Australia, resulting in increased abundance of free-living nematodes and nematophagous fungi in the top soil layer compared to the deeper soil layer (Stirling et al., 2011).

Another approach to improve the soil food web structure in short-term agroecosystems is to enrich the soil with vermicompost tea extract. Compost tea, a water-based extract, can be prepared using a wide range of composts. Vermicompost is the product of accelerated bio-degradation of organic matter by earthworms through mesophilic decomposition. It generally has higher concentrations of plant available nutrients (NO_3^-, exchangeable Ca, P and soluble K) and significantly larger and more diverse microbial populations (Tognetti et al., 2005). Compost teas may supply microbial biomass, fine POM, organic acids, plant growth regulator like substances and soluble mineral nutrients to plant surfaces and soils (Edwards et al., 2006; Scheuerell and Mahaffee, 2002, 2004). This advantage of compost tea may serve as a mean to enhance the soil food web structure.

In addition, compost tea has been shown to suppress plant pathogens including nematodes (Edwards et al., 2006; Gamaley et al., 2001). Sunn hemp has also been documented to be suppressive to several genera of plant-parasitic nematodes including reniform (*Rotylenchulus reniformis*) and root-knot (*Meloidogyne* spp.) nematodes (Wang et al., 2002b). In this study, we compared STCC + SM of sunn hemp to that of crimson clover. Crimson clover was studied because it is a legume and it is known to be a good insectary plant to attract pollinators, which is important for cucurbit crop production. However, crimson clover is also a good host for root-knot nematodes (Wang et al., 2002a,b). It is hypothesized that integration of sunn hemp STCC + SM and chicken manure based vermicompost tea drenching could have a synergistic effect in improving soil health in vegetable agroecosystems. On the other hand, planting of crimson clover in STCC + SM would improve nematode community structure, attract pollinators, but may increase plant-parasitic nematode pressure. The third hypothesis of the study was that mix planting of sunn hemp and crimson clover followed by strip-tilled of sunn hemp and maintaining crimson clover as living mulch would complement the strength of both of these leguminous cover crops planted individually.

Specific objectives of this experiment were to examine if: (1) drenching chicken manure based vermicompost tea could suppress plant-parasitic nematodes as a post-plant nematode management approach; (2) integrating cover cropping with drenching of vermicompost tea could further improve the soil food web structure than growing a cover crop alone; and (3) nematode community indices are good indicators of zucchini plant health.

2. Materials and methods

Two field trials were conducted at Twin Bridges Farm in Waialua, Oahu, HI from 2010 to 2011 to evaluate the effects of strip-till cover cropping and vermicompost tea application on plant-parasitic nematodes and soil food web structure in a zucchini agroecosystem.

2.1. Trial I

The first trial (Trial I) was initiated by planting cover crops on December 2, 2010. A 4 × 4 factorial (cover crops × vermicompost tea) strip-till experiment was conducted. Cover crop treatments included sunn hemp (SH), crimson clover (CC), combination of SH and CC (SHCC), and weed-free bare ground (BG). SH and CC were planted at 33 and 22 kg/ha, respectively. Cover crops were planted in rows at 0.9 m row spacing. Each experimental plot was 15 m × 2.1 m in size. Each treatment was replicated three times. All cover crop plots were arranged in randomized complete block design, with a 7.5 m bare ground spacing between plots, whereas the BG plots were separated 15 m away from the cover crop area to avoid living mulch effects from the nearby cover crop plots. It is important to avoid cross contamination from living mulch effects as this project was part of a bigger project that involve evaluating the use of SH and CC as living mulch to attract pollinators. Initial soil sampling prior to the initiation of cover cropping showed no significant difference in nematode communities between the designated cover crop area and the BG area. Cover crops were irrigated whenever needed by drip irrigation. Due to slow establishment of crimson clover, cover crops were maintained for the entire winter to early spring. Alternate rows of cover crops were mowed using flail mower and tilled 15-cm deep with hand-held tiller (0.6 m wide) on March 17, 2011. Thus, alternate rows of cover crop remained as living mulch, while the tilled strips were prepared for zucchini planting. Weeds between the cover crop strips were further managed by glyphosate prior to crop planting. On April 7, 2-week old zucchini 'Elite F1 (Harris Seeds, NY) seedlings were transplanted at 1.2-m apart into strip-tilled cover crop strips, thus they were interplanted between cover crop strips. Zucchini seedlings were transplanted at the same planting densities in the BG, with 1.8 m between rows.

At transplanting, each cover crop plot was split into four subplots: organic fertilizer (F), vermicompost tea (CT), F + CT, and unfertilized control (C). Each subplot contained 12 zucchini plants planted in three rows. Plants that received F or F + CT treatments were fertilized with 15 g chicken pellets (4-2-2) per plant at planting, equivalent to 66 kg N/ha. Plants in CT or C plots received no fertilizer. Plants receiving CT treatment were drenched with 120 ml/plant of chicken manure-based vermicompost tea (equivalent to 16.7 mg/plant) at weekly intervals until the beginning of fruit harvest on May 5. The CT was prepared by suspending chicken manure based vermicompost in water at 1:10 (v:v) rate and continuously aerated with an air pump for 12 h (Pant et al., 2009). The chicken manure vermicompost was cured by removing the compost from vermicompost bin and kept in a cool and ventilated condition over a 3-month period before used for CT extraction. The purpose of curing vermicompost is to allow more decomposition take place so as to convert more organic matter into nutrients readily available for plant uptake.

Soil samples were collected from each main plot at termination of cover crop (March 8), from F and F + CT subplot treatments at 1 week after zucchini planting (April 14), and at the end of fruit harvest (May 19). Subplot CT and C treatments were mainly to serve as a control for yield comparison, thus no soil samples were taken. Six shovels (GroundShark shovel, Forestry Suppliers, Jackson, MS, USA) of soil of 20 cm-deep × 5 cm-diameter in a half cylinder shape core were collected systematically in a diagonal pattern throughout a main plot (March 8) or subplot (April 14 and May 19) and pooled together as one sample per plot. Soil was taken from the rhizosphere of the cover crop or from the bareground in the BG plot prior to zucchini planting, but was taken from the zucchini root zone after zucchini planting. Soil samples collected were transported to the laboratory and nematodes were extracted as described below.

Zucchini plants were harvested weekly from each of the 4 × 4 factorial (cover crop × vermicompost tea) subplots beginning May 5 and ending on May 16, 2011. Fruits damaged by pickleworms (*Diaphania nitidalis*) and/or fruitflies (*Bactrocera cucurbitae*) were categorized as unmarketable. Marketable and unmarketable fruits were counted, graded according to US Standards for grades of summer squash (USDA, 1997), weighed, and accumulated over time.

2.2. Trial II

The experiment was repeated in the same field site at the end of Trial I. All zucchini plants in Trial I were removed and discarded, but the cover crop planting rows remained intact. Weeds were managed by spraying glyphosate between the living mulch. Crimson clover failed to grow during the summer time in Hawaii despite reseeding at termination of Trial I. Thus, only SH and BG plots were included as main plot treatments in Trial II. Sunn hemp growth from Trial I remained vigorous, thus, was trimed back to approximately 1.2-m tall using sickles on July 14, 2011. The trimmed sunn hemp biomass was left on the zucchini planting rows as a surface mulch. Another challenge from Trial I was the heavy infestation of papaya ring spot virus on the zucchini 'Elite H1″ (Harris Seeds, NY). Thus, we changed the zucchini variety in Trial II to 'Felix F1″ (Harris Seeds, NY) which was reported to be resistant to papaya ring spot virus. Two-week old 'Felix F1″ zucchini seedlings were transplanted on September 1, 2011. The subplot treatment remained the same as Trial I. Soils were sampled from F and F + CT subplots at 1 week after transplanting of zucchini (September 8) and toward the end of the zucchini harvest (October 8, 2011).

2.3. Nematode assays

Nematodes were extracted from a 250-cm^3 subsample of soil collected from each field plot by elutriation followed by centrifugal flotation (Jenkins, 1964). All extracted soil nematodes were identified to the genus level wherever possible except for those in the family, Rhabditidae. All nematodes were counted and assigned to one of six trophic groups: algivores, bacterivores, fungivores, plant-parasitic nematodes, omnivores, or predators (Yeates et al., 1993). The feeding habit of Tylenchidae (mainly *Filenchus* and *Tylenchus*) was classified as fungivore (McSorley and Frederick, 1999; Okada and Kadota, 2003; Okada et al., 2005). *Prismatolaimus* was grouped as a bacterivore rather than a substrate ingestor reported by Yeates et al. (1993). The total numbers of every trophic group in the community were calculated. Nematode richness was the total number of taxa recorded per sample. Simpson's reciprocal index of diversity was calculated as $1/\lambda$, where $\lambda = \sum (p_i)^2$, and p_i is the proportion of each of the i genera present (specimens identified only to the order level were excluded) (Simpson, 1949). The fungivore to bacterivore (F:B) ratio was calculated to characterize decomposition and mineralization pathways (Freckman and Ettema, 1993). All free-living nematodes were assigned a colonizer–persister (c–p) rating at the family level according to the 1 to 5 c–p scale of Bongers and Bongers (1998). A weighting system based on c–p value and feeding group of each nematode (known as nematode functional guilds) was used to calculate enrichment, structure and channel indices of the soil food web as described by Ferris et al. (2001). The enrichment index (EI) assesses food web responses to available resources, and the structure index (SI) reflects the degree of trophic connection in food webs of increasing complexity as the system matures. The channel index (CI) represents the decomposition pathway in the soil food web. In general, higher EI and lower CI suggest greater bacterial activity, more nutrient enriched soil food web, whereas higher SI indicate a less disturbed soil food web. Since the objective of the study was to evaluate soil health conditions affected by different cover cropping practices with and without CT drenching, nematode community was analyzed only on F and F + CT treatments from each cover crop plots excluding CT and no fertilizer treatments.

2.4. Statistical analysis

All nematode parameters were first subjected to sampling date × cover crop × vermicompost tea three-way analysis of variance (ANOVA) to examine for homogeneity of variance over time (Proc GLM in SAS, SAS Institute Inc., Cary, NC, USA). Nematode abundance data was $\log(x + 1)$ transformed to normalize the data prior to ANOVA. Whenever significant intereaction between sampling date and the treatement effects (cover crop or vermicompost tea) occurred, data were then analyzed by 4 × 4 factorial (cover crop × vermicompost tea) ANOVA in Trial I, and by 2 × 4 factorial (cover crop × vermicompost tea) ANOVA in Trial II for each sampling date. Similar ANOVA was conducted for total zucchini fruit weight and fruit numbers harvested for each trial. Mean separation for cover crop effect was conducted using Waller–Duncan k-ratio ($k = 100$) t-test. Whenever interaction between treatment effects and sampling date were not significant, repeated measure analysis over time (Proc MIXED in SAS) was conducted, and treatment means were separated based on Tukey–Kramer t-test. To further determine which nematode community indices or parameters were good indicators of zucchini yield, nematode parameters (% of each trophic group, F/(F + B), richness, diversity, EI, SI, and CI collected from initial planting (Pi) and final harvest (Pf) of each trial were subjected to principle component analysis (PCA) using MINITAB v.15 (Minitab, Inc., State College, PA, USA). The PCA results were used to identify key nematode parameters that contribute most to variation in each dataset. Then Pearson's correlation analysis between the identified key nematode parameters and zucchini yield (zuchinni fruit weight and fruit number) was conducted.

Table 1
Chemical properties and nutrient concentrations of chicken manure based vermicompost tea prepared for field trials at Waialua, HI in 2011.

	Concentration ($mg L^{-1}$)		Concentration ($mg L^{-1}$)		
N (Total)	139.1	Na	72.10	EC ($mS cm^{-1}$)	1.0
NO_3-N	137.9	Fe	0.08	pH	7.5
NH_4-N	0.6	Mn	0.01		
P	11.0	Zn	0.01		
K	45.1	Cu	0.02		
Ca	59.6	B	0.27		
Mg	61.6	Humic acid	464.80		

3. Results

3.1. Nutrient analysis from cover crops and CT

Prior to the initiation of zucchini planting in Trial I, sunn hemp generated 8360 kg/ha of dry biomass, 3423 kg/ha of C and 140 kg/ha of N. All of which were higher ($P < 0.10$) than that from CC (3337 kg/ha dry biomass, 1346 kg/ha of C, and 85 kg/ha of N). No C and N were contributed from the bare fallow treatment in BG prior to the zucchini planting. Majority (96%) of the N from the cover crop biomass was in organic form which was less readily available for plant uptake, whereas that from the CT contained higher percentage of NO_3-N (98.5%), making N more readily available for plant to uptake. Other nutrient contents of CT are presented in Table 1.

3.2. Effects of cover crop and CT treatments on plant-parasitic nematodes

The key plant-parasitic nematodes present in this field site were reniform nematode (*Rotylenchulus reniformis*) and root-knot nematodes (*Meloidogyne javanica*). In terms of the abundance of plant-parasitic nematodes either reniform, root-knot or total plant-parasitic nematodes, no significant interaction ($P > 0.05$) between cover crop and vermicompost tea treatments occurred (Table 2). Thus, main plot treatment means are presented. Results from both field trials confirmed that strip-tilled of sunn hemp in SH or SHCC plots suppressed these two genera of plant-parasitic nematodes efficiently (Fig. 1). Planting of crimson clover supported high numbers of *R. reniformis* and *M. javanica* toward the end of the zucchini crop (Fig. 1A and B). Unfortunately, crimson clover was slow growing and did not flower well in Hawaii. Although it grew during the winter time in Trial I, it senesced and could not be regrown in Trial II during the summer. Thus, this treatment was eliminated from Trial II.

In Trial I, compost tea (CT) suppressed reniform nematode significantly ($P < 0.001$, Table 2) only at the early stage of zucchini crop (April 14, 2011) but not toward the end of the crop (May 19, 2011) (Fig. 2A). A similar trend was observed in Trial II, but results were not significant ($P > 0.05$, Fig. 2D). Synergistic effect between SH and CT treatments on plant-parasitic nematodes was not observed as no significant interaction occurred between the main plot and subplot treatments (Table 2).

3.3. Effects of cover crop and CT treatments on nematode community structure

Nematode faunal analysis was presented in an enrichment index (EI), structure index (SI), channel index (CI) as well as percentage of trophic groups (bacterivorous, fungivorous, herbivorous, omnivorous and predatory nematodes). Planting of sunn hemp either in the SH or SHCC plots enhanced % bacterivorous nematodes ($P < 0.05$) throughout the zucchini cropping cycle in Trial I as compared to the bare ground (BG) and crimson clover (CC) (Fig. 3A and F). A similar trend was observed in Trial II where % bacterivorous nematodes were higher in SH than BG. In Trial I, where the sunn hemp cover crop was between 4 and 5 months-old, % fungivorous nematodes was lower in the SH and SHCC plots at initial and mid-term sampling dates as compared to the BG control

Table 2
Analysis of variance of the effects of sampling date, cover crop (CC) and vermicompost tea (CT) on nematode abundance, percent trophic groups, indices, and zucchini yield in Trials I and II in 2011.

	Trial I							Trial II						
	Date	CC	CT	Date × CC	Date × CT	CC × CT	Date × CC × CT	Date	CC	CT	Date × CC	Date × CT	CC × CT	Date × CC × CT
Reni	<0.0001[a]	<0.0001	0.0008	ns	0.030	ns	ns	ns	ns	ns	ns	ns	ns	ns
RK	0.02	0.0005	ns	ns	ns	ns	ns	ns	0.042	ns	ns	ns	ns	ns
Ba	ns	0.02	ns	0.056	ns	ns	ns	ns	0.003	ns	ns	ns	ns	ns
Fu	ns	0.032	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
PPN	0.0001	<0.0001	ns	ns	ns	ns	ns	ns	0.004	ns	ns	ns	ns	ns
Om	0.001	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	0.031	ns	ns
Pr	0.06	0.053	ns	ns	0.047	ns	ns	–	–	–	–	–	–	–
% Ba	ns	<0.0001	ns	0.020	ns	ns	ns	ns	0.002	ns	0.024	ns	ns	ns
% Fu	ns	0.0004	ns	0.018	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
% PPN	<0.0001	<0.0001	ns	<0.0001	ns	0.048	ns	ns	0.0004	ns	ns	ns	ns	ns
% Om	0.029	0.062	ns	ns	ns	ns	ns	ns	ns	ns	0.047	ns	ns	ns
% Pr	ns	ns	ns	ns	0.041	ns	ns	–	–	–	–	–	–	–
EI	0.034	ns	ns	ns	ns	ns	ns	ns	ns	ns	0.019	ns	ns	ns
SI	<0.0001	0.018	0.025	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
CI	ns	0.041	ns	ns	ns	ns	ns	0.043	ns	ns	0.033	ns	ns	ns
Zucchini yield														
FW	–	0.008	0.040	–	–	ns	–	–	0.005	ns	–	–	ns	–
FN	–	<0.001	0.008	–	–	ns	–	–	<0.001	ns	–	–	ns	–

ns, not significant. Reni, reniform nematodes; RK, root-knot nematodes; Ba, bacterivorous nematodes; Fu, fungivorous nematodes; PPN, plant-parasitic nematodes; Om, omnivorous nematodes; Pr, predatory nematodes; EI, enrichment index; CI, channel index; SI, structure indexFW, fruit weight; FN, number of fruits. Nematode abundance data was log transformed, $\log(x+1)$ prior to ANOVA.

[a] Probability of significance based on analysis of variance (ANOVA).

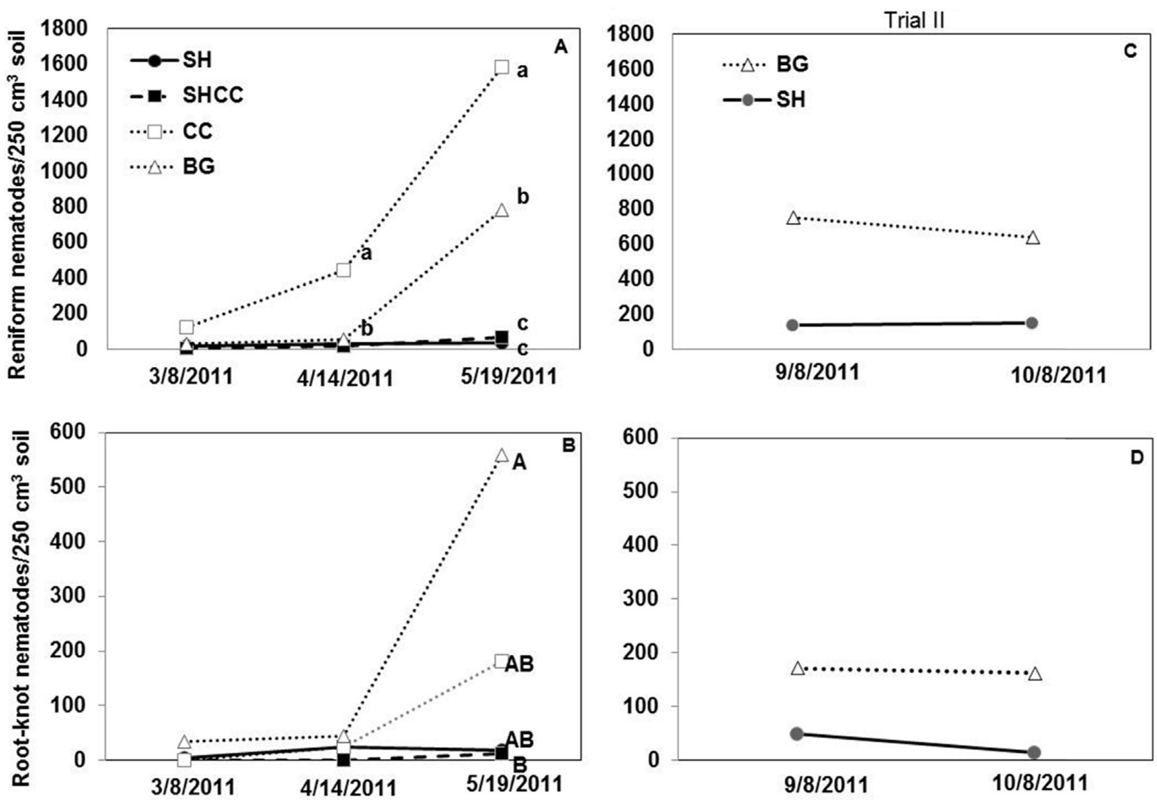

Fig. 1. Effects of cover crop treatments on plant-parasitic nematodes (reniform and root-knot nematodes) in Trial I (A, B) and Trial II (C, D) of a zucchini agroecosystem, Waialua, HI. SH = sunn hemp; CC = crimson clover; SHCC = sunn hemp + crimson clover; and BG = bare ground. Means (n = 3 on 3/8/11; n = 6 on all other dates) in a sampling date followed by the same lower case letter(s) are not different based on Waller–Duncan k-ratio (k = 100) t-test. Cover crop treatment lines followed by the same upper case letter(s) are not different based on repeated measure analysis and Tukey–Kramer t-test.

(Fig. 3B). However, % fungivorous nematodes in SH was not different (P > 0.05) from the BG in Trial II where sunn hemp had reached 10–11 months-old (Fig. 3G). Planting of sunn hemp continuously suppressed plant-parasitic nematodes in both trials (Fig. 3C, H). Percentage of omnivorous nematodes was greater in plots planted with crimson clover than BG at final sampling in Trial I, but was not affected by planting of sunn hemp (Fig. 3D and I). Abundance of predatory nematodes was relatively low as compared to other nematode trophic groups, and tended to be higher in the SH and CC plots, but no significant difference was detected in Trial I (Fig. 3E) and the predatory nematodes became undetectable in Trial II.

Calculation of nematode community indices showed that planting of sunn hemp (SH and SHCC) only increased EI at early planting of zucchini in Trial I but not in subsequent sampling dates (Fig. 4A and D). Planting of cover crops (either SH or CC) reduced CI in the first two sampling dates but not toward the end of the zucchini crop (Fig. 4B). Similar trend was observed in Trial II (Fig. 4E). Both cover crops did not increase SI as compared to the BG control in Trial I or II (Fig. 4C and F).

Interestingly, CT drenching increased predatory nematodes (P < 0.10) in Trial I and omnivorous nematodes (P < 0.05) in Trial II (Fig. 3 B and E) at the end of each zucchini crop. Similarly, CT increased SI toward the end of the zucchini crop in both trials (Fig. 2C and F), though not significantly in Trial II.

3.4. Effects of cover crop and CT treatments on zucchini yield

No significant interaction was observed based on the 4 × 4 (4 cover crops × 4 CT) ANOVA (Table 2). Thus, only means of main and subplot effects were presented (Fig. 5). Zucchini fruit yield, in term of fruit weights in Trial I, was higher (P < 0.05) in sunn hemp planted plots (SH and SHCC) as compared to BG (Fig. 5A and B). Planting of crimson clover increased number of fruits but not fruit weights as compared to BG (Fig. 5B). Due to a change in planting a zucchini cultivar 'Felix F1' that is more resistant to viruses in Trial II, yield in Trial II was much higher than that in Trial I. Performance of SH was consistent in Trial II where zucchini fruit weights and fruit numbers were higher in SH than BG (P < 0.05; Fig. 5E and F). However, drenching of CT alone did not improve zucchini yield better than that of an unfertilized control and did not significantly improve zucchini yield on chicken pellets fertilized plants in both trials (Fig. 5C, D, G and H).

3.5. Correlation between nematode parameters and zucchini yield

Four PCA between nematode parameters and zucchini yield measurements were conducted at initial nematode data set (Pi) and at the final nematode data set (Pf) of Trial I and Trial II to determine (1) which soil health parameters measured were most correlated with crop yields; and (2) whether soil health parameters measured at Pi or Pf were most correlated with crop yields. First two principal components generated from nematode parameters from Pi accounted for higher percentage of variance (74.1% and 77.0% for Trial I and Trial II, respectively) than those generated from Pf (65.6% and 69.5% of the total variance for Trial I and Trial II, respectively) (Table 3), suggesting soil health parameters measured at Pi were a better indicator of zucchini yield. Number of nematode parameters selected for correlation analysis with zucchini yield were based on eigenvalues of the first two principal components of each data set. For example, eigenvalues of 4.67 means 4 to 5 of the parameters in the PC1 were selected for the subsequent correlation analysis. Thus, % bacterivores, % fungivores, F/(F + B), EI and CI from principal

Table 3
Principal component analysis of nematode community indices contributing to variation in the dataset from Trial I and Trial II of a zucchini agroecosystem, Waialua, HI, USA.

	Trial I (Pi[b] = March 8, 2011)		Trial II (Pi = September 8, 2011)	
	Component 1[a]	Component 2	Component 1	Component 2
Eigenvalue	4.67	2.03	4.89	2.04
Variation explained	0.52	0.23	0.54	0.23
Cumulative variation	0.52	0.74	0.54	0.77
	Trial I (Pf[b] = May 19, 2011)		Trial II (Pf = October 8, 2011)	
	Component 1[a]	Component 2	Component 1	Component 2
Eigenvalue	3.62	2.94	3.51	1.74
Variation explained	0.36	0.29	0.39	0.30
Cumulative variation	0.36	0.66	0.39	0.70
	Trial I		Trial II	
	PC1	PC2	PC1	PC2
Attribute loading for eigenvectors (Pi)				
% Ba	−0.44	−0.06	−0.43	0.07
% Fu	0.38	−0.39	0.31	0.34
% PPN	0.20	0.53	0.33	−0.29
% Om	−0.17	−0.37	−0.14	0.52
F/(F + B)	0.23	0.42	0.44	−0.003
Richness	0.40	−0.34	0.10	0.58
EI	−0.41	−0.15	−0.39	−0.25
SI	−0.19	−0.20	−0.22	0.53
CI	0.42	−0.27	0.43	0.04
Attribute loading for eigenvectors (Pf)				
% Ba	−0.09	0.54	0.49	0.15
% Fu	−0.41	−0.29	−0.18	0.51
% PPN	0.28	−0.42	−0.39	−0.32
% Om	0.29	−0.24	0.12	0.36
% Pr	0.23	−0.07	–	–
F/(F + B)	−0.35	−0.41	−0.49	0.12
Richness	0.26	−0.32	0.28	0.36
EI	0.29	0.02	0.24	−0.34
SI	0.41	−0.15	0.09	0.33
CI	−0.40	−0.32	−0.43	0.33

Ba, bacterivorous nematodes; Fu, fungivorous nematodes; PPN, plant-parasitic nematodes; Om, omnivorous nematodes; Pr, predatory nematodes; F/(F + B), Fu/(Fu + Ba); EI, enrichment index; CI, channel index; and SI, structure index.
[a] Only eigenvector loading for components 1 and 2 are shown.
[b] Pi, initial nematode samples for each trial; Pf, final nematode samples for each trial.

component 1 (PC1) and % plant-parasitic nematodes and diversity from PC2 were selected for the subsequent correlation analysis for data set from Pi of Trial I. For Pf of Trial I, % fungivores, F/(F + B), SI, CI, % bacterivores, and % plant-parasitic nematodes (Table 3) were selected. Only significant correlations are presented in Table 4. Pearson's correlation analysis indicated that zucchini fruit number was negatively correlated with % fungivore, F/(F + B) and CI at Pi, and was positively correlated with % bacterivores at Pf of Trial I (Table 4). In Trial II, % bacterivores, % plant-parasitic nematodes, F/(F + B), EI, CI, SI and richness were selected from Pi, whereas % bacterivores, % plant-parasitic nematodes, F/(F + B), CI, % fungivores, and % omnivores were selected from Pf. Among the correlation analysis conducted in Trial II, only positive correlation ($P < 0.05$) between % fungivores and zucchini fruit numbers was observed at Pf (Table 4).

4. Discussion

These two zucchini trials supported earlier findings that planting cover crop alone often do not increase omnivorous or predatory nematodes even after two cropping cycles. It is encouraging to see that the drenching of chicken manure based vermicompost tea (CT) increased abundance of predatory nematodes and SI in Trial I and

Table 4
Correlation analysis between zucchini yields and nematode community indices in Trial I and Trial II of a zucchini agroecosystem, Waialua, HI.

	Zucchini fruit weight		Zucchini fruit number	
	r[a]	*P*	*r*	*P*
Trial I (Pi[b] = March 8, 2011)				
% Fu	–	NS	−0.62	0.03
F/(F + B)	–	NS	−0.62	0.03
CI	–	NS	−0.61	0.04
Trial I (Pf = May 19, 2011)				
% Ba	–	NS	0.44	0.03
F/(F + B)	−0.41	0.05	–	NS
Trial II (Pf = October 8, 2011)				
% Fu	–	NS	0.63	0.03

Ba, bacterivorous nematodes, Fu, fungivorous nematodes, F/(F + B), Fu/(Fu + Ba); CI, channel index.
[a] *r*, Person's correlation coefficient; *P*, probablility. Only significant correlations ($P < 0.05$) were shown. No significant correlation between zucchini yield and nematode parameters were observed in Pi of Trial II.
[b] Pi, initial nematode parameters for each trial; Pf, final nematode parameters for each trial.

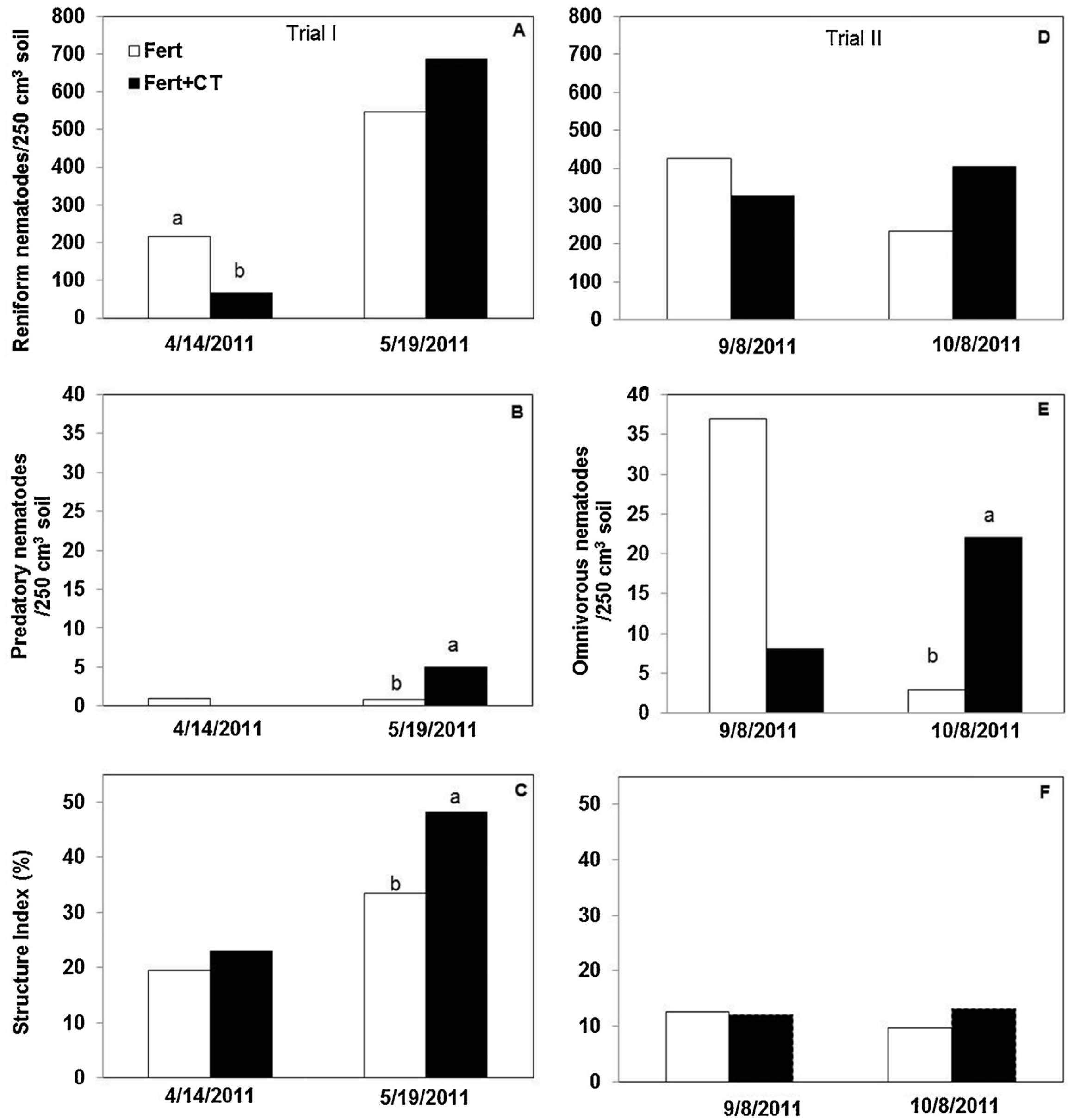

Fig. 2. Effect of chicken manure based vermicompost tea (CT) treatment on abundance of reniform nematodes (*Rotylenchulus reniformis*), predatory nematodes and structure index as compared to chicken pellet fertilizer (F) alone treatment in Trial I (A–C) and Trial II (D–F) of zucchini agroecosystem, Waialua, Hawaii, USA. Columns ($n = 12$ in Trial I, $n = 6$ in Trial II) at each sampling date followed by the same letter(s) are not different based on analysis of variance.

omnivorous nematodes in Trail II at termination of both cropping cycles. Drenching zucchini plants with CT also consistently suppressed the abundance of the key plant-parasitic nematodes (*R. reniformis* and *Meloidogyne* spp.) at the initial stage of the zucchini growth but not toward the end of zucchini harvest. In contrast, planting SH in STCC system followed by continued clipping of living mulch as a surface mulch provided a continuous input of organic matter, and thus resulted in enhancement of % bacterivorous nematodes throughout the two zucchini cropping cycles. Sunn hemp treatment also suppressed plant-parasitic nematodes throughout the entire growing season for both zucchini trials. Despite the benefits contributed by SH cover cropping and CT drenching individually, no synergistic effect was observed when integrating both approaches together in terms of enhancing beneficial soil nematodes or suppressing plant-parasitic nematodes. However, it is worth the efforts to integrate these two soil health management approaches together due to the different services they provide to improve soil food web structure.

4.1. Drenching of CT improve soil food web structure within one crop cycle

The main goal of this study is to improve the soil food web structure within one zucchini cropping cycle. Higher abundance of omnivorous and predatory nematodes are indicators of improvement of the soil food web structure as these are nematode trophic groups higher in the soil food web hierarchy (Ferris et al., 2012a,b). The current study showed that the drenching of CT increased SI within one cropping cycle of zucchini, which suggested a faster approach to improve the soil food web in this short-term agroecosystem. Higher concentrations of plant available nutrients and organic acids, larger and more diverse microbial populations, and its constituent of plant growth regulator-like substances (Tognetti et al., 2005; Edwards et al., 2006; Scheuerell and Mahaffee, 2002) could be the main reason of enhancement of the soil food web structure in CT treated plots. Pant et al. (2011) measured dehydrogenase activity and soil respiration and found that increased CT

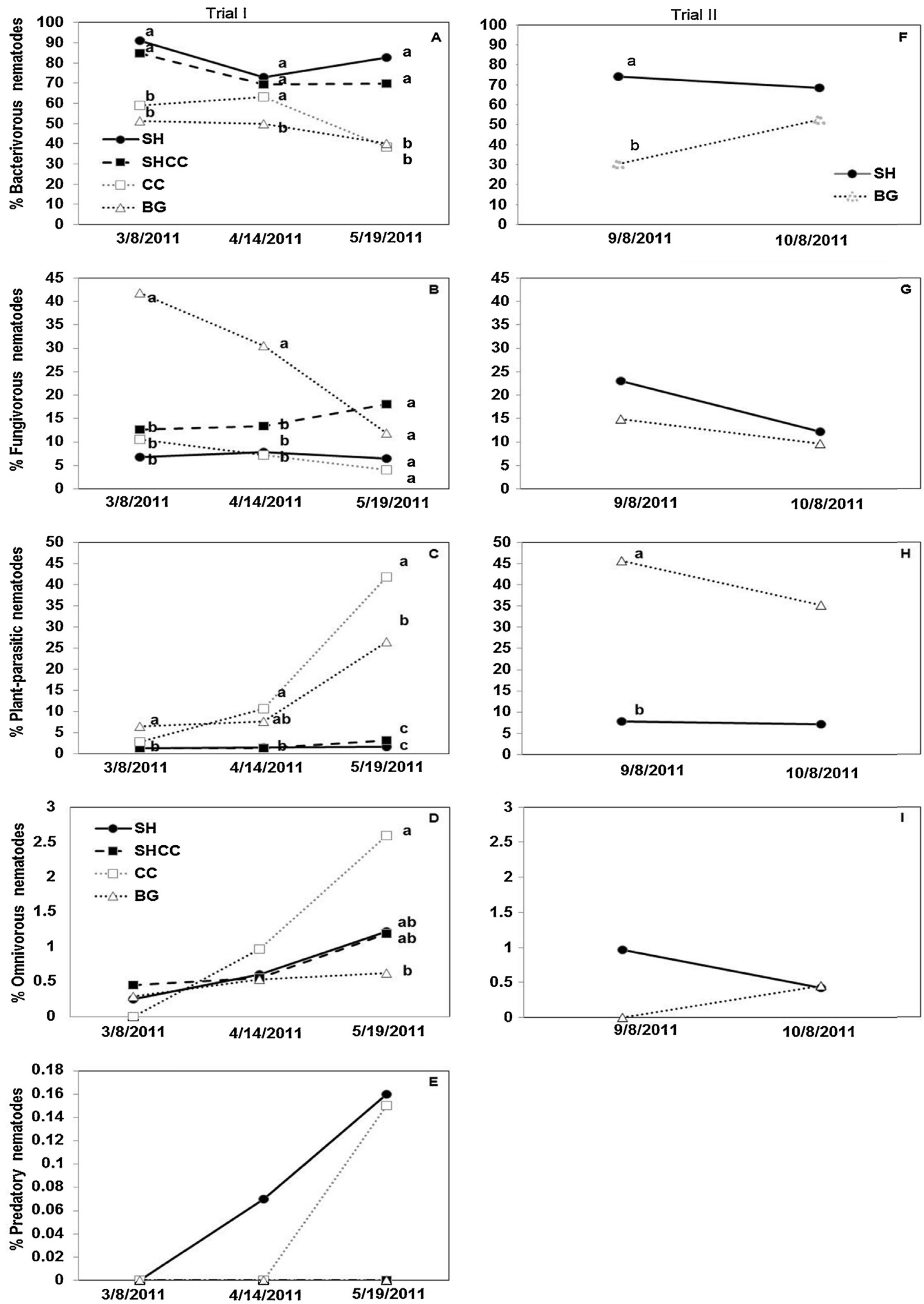

Fig. 3. Effects of cover crop treatments on percentage distribution of different trophic groups of nematodes in the soil communities of a zucchini agroecosystem, Waialua, Hawaii, USA. SH = sunn hemp; CC = crimson clover; SHCC = sunn hemp + crimson clover; and BG = bare ground. Means (n = 3 on 3/8/11; n = 6 on all other dates) followed by the same letter(s) on a sampling date indicates there are no difference based on Waller-Duncan k-ratio (k = 100) t-test.

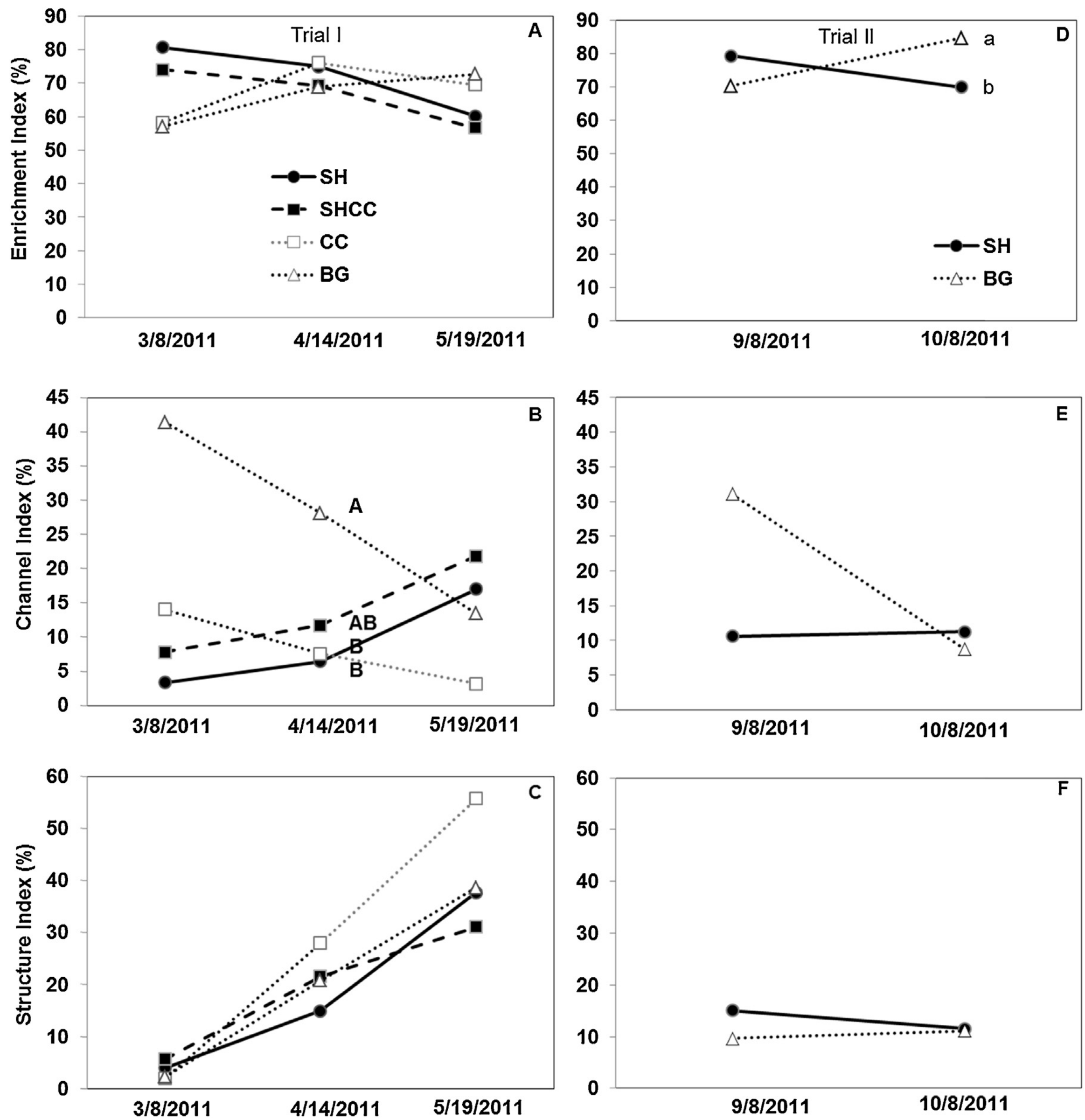

Fig. 4. Effects of cover crop treatments on nematode community indices (enrichment index, channel index, and structure index) in Trial I (A–C) and Trial II (D–F) of a zucchini agroecosystem, Waialua, Hawaii, USA. SH = sunn hemp; CC = crimson clover; SHCC = sunn hemp + crimson clover; and BG = bare ground. Means (n = 3 on 3/8/11; n = 6 for all other dates) followed by the same lower case letter(s) on a sampling date indicates no significant difference based on Waller-Duncan k-ratio (k = 100) t-test. Cover crop treatment lines followed by the same upper case letter(s) are not different based on repeated measure analysis and Tukey-Kramer t-test.

concentration increased total soil microbial activities. These properties of vermicompost tea might serve as a mean to enhance the soil food web structure that eventually leads to a tolerance of plant to stress (Arancon et al., 2004). Unfortunately, CT alone did not increase % bacterivores and EI, indicating that unlike STCC + SM, CT did not improve soil enrichment which is also essential for maintaning soil health.

4.2. CT provides early suppression, SH provides whole season suppression of plant-parasitic nematodes

Drenching of CT consistently reduced abundance of plant-parasitic nematodes early in the zucchini crop in both trials but not toward the end. In contrary, SH suppressed plant-parasitic nematodes throughout the zucchini crop in the STCC system. Suppression of plant-parasitic nematodes by CT has been documented (Edwards et al., 2006; Gamaley et al., 2001). Amending soil with chicken manure has also been known to suppress plant-parasitic nematodes such as root-knot nematodes (Kaplan and Noe, 1993; Riegel et al., 1996). The mode of action of chicken manure is thought to be based on the release of toxic levels of ammonium, although alterations in soil structure, the stimulation of antagonistic organisms, and improved plant tolerance also may play some roles (Lazarovits et al., 2001). The plant-parasitic nematode suppressive effect of CT that is constrained to the early zucchini cropping cycle could be due to the termination of CT drenching soon after the zucchini fruits began to develop. The purpose of this early termination is to avoid food safety concerns. Future study could look into continued application of CT toward beginning of harvesting through drip irrigation system that could avoid the exposure of zucchini fruits to CT.

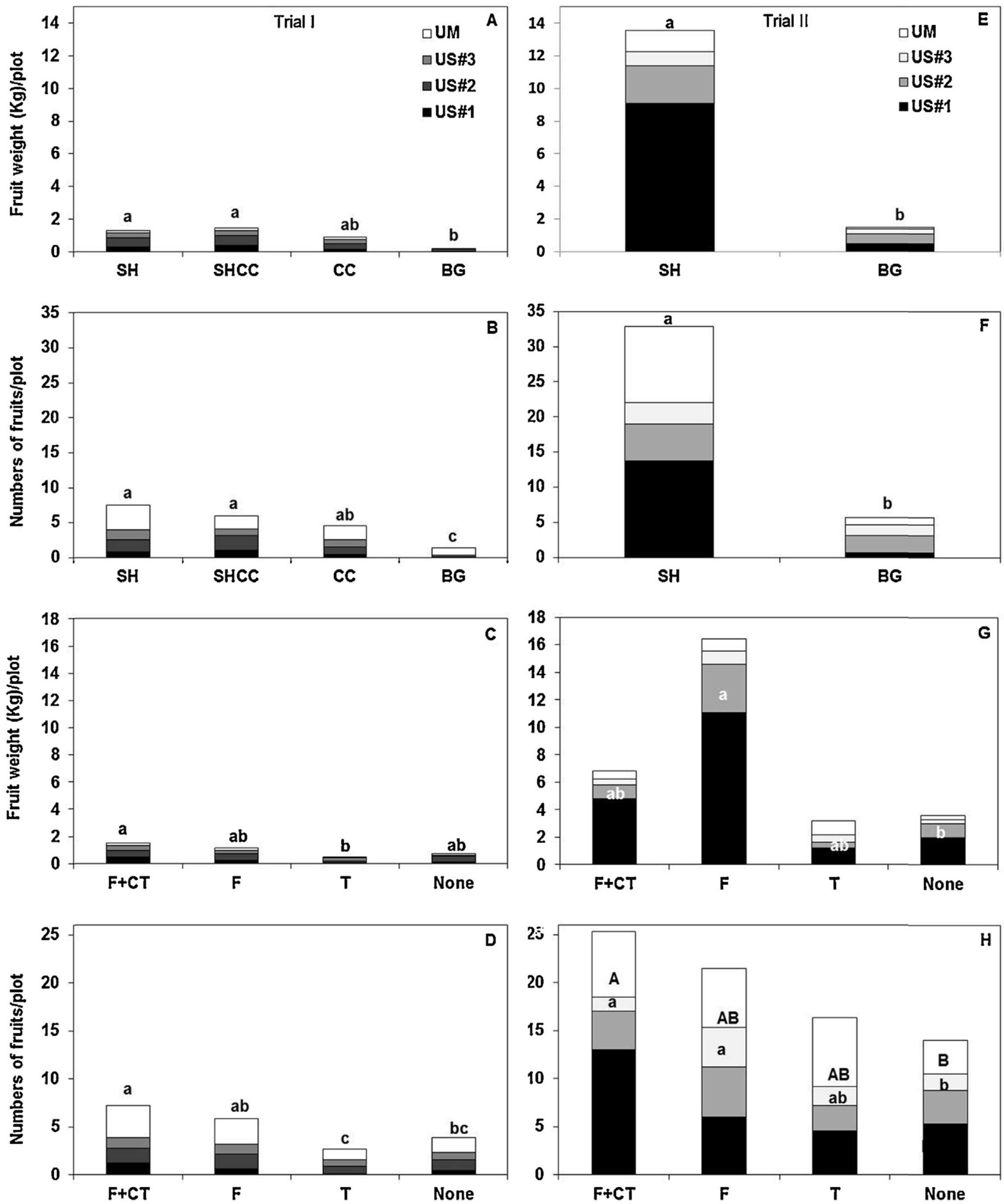

Fig. 5. Accumulated zucchini fruit weight and fruit numbers in Trial I (A–D) and Trial II (E–H). Means are an average of 12 except for G and H where $n = 6$. US#1 = firm, tender, no damage; US#2 = firm, tender, no major damage; US#3 = off shape, multiple damages; and UM = unmarketable, serious damage mainly due to fruit flies, some pickleworms, and viruses. Grading in each columns followed by same letters were not different among treatments based on Waller-Duncan k-ratio ($k = 100$) t-test.

4.3. STCC + SM alone enriched the soil but did not improve soil food web structure for long

Planting of SH in STCC + SM system maintained higher % bacterivores throughout the two cropping cycles, indicating a rather enriched soil food web condition. However, EI was only increased in SH plots at termination of cover crop in Trial I, and SI was not different between SH and BG throughout the two trials. This result was similar to that reported previously (Wang et al., 2011) and continued to show that using sunn hemp in a STCC + SM could not improve the soil food web structure in short period. This result supported our theories that SH cover cropping alone even with the practice of organic mulching is not sufficient to enhance soil food web structure.

Crimson clover is not a suitable cover crop for the tropical climate in Hawaii. It grew during the winter time, but only flower sparsely at the end of the spring. It failed to grow in the summer time. In addition, it did not suppress *R. reniformis* and *M. javanica*. This is consistent with the previous report by Wang et al. (2002a,b) that crimson clover is a good host of *Meloidogyne* spp. Unlike planting SH, planting of CC did not increase bacterivorous nematode population densities. Thus, CC is not an ideal cover crop for soil health management in this tropical climate in Hawaii.

4.4. Sunn hemp STCC + SM improve plant health more efficient than CT drenching

The main yield improvement came from planting sunn hemp in the STCC + SM system as shown in the higher yield of this treatment than the BG in both trials. Similar crop yield was observed between SH and SHCC as we only strip-tilled the SH rows in the SHCC plots. Another benefit of planting zucchini in sunn hemp STCC + SM system was the weed suppressive effect from the periodic clipping of SH as a surface mulch. Although weeds in all plots were consistently spot treated by glyphosate until prior to harvest, weed coverage data collected at the end of harvesting in Trial II showed a trend of lower weed coverage in SH (5.33% weed coverage) than that in BG (21.7% weed coverage), but the data was not significant ($P > 0.05$).

It was anticipated that CT could further improve plant health than STCC and thus increase zucchini fruit yield. However only minor or no improvement of zucchini yield by CT drenching was observed in both trials. This result is different from that reported by Pant et al. (2012a) where CT was prepared in the same manner as in this study (3-month old chicken manure based vermicompost brewed in water at 1:10 ratio). Pant et al. (2012a) reported that CT increased shoot and root weight of greenhouse grown pak choi (*Brassica rapa* Chinensis group). This positive effect of CT on plant growth and yield were also reported by Hargreaves et al. (2008), Reeve et al. (2010), Pant et al. (2011) and Keeling et al. (2003). Contradictory results of the current study to the literature cited could be due to the diluted CT concentration when soil drenched in field grown zucchini. Total amount of N drenched from CT per plant each week was 16.7 mg/plant, over a 5-week drenching period, only a total of 83.4 mg N/plant were drenched. Conversely, sunn hemp was incorporated once prior to planting with 140 kg of total N/ha. At zucchini planting densities of 0.84 m^2, there was 11.8 g total N/plant contributed from the sunn hemp biomass. This means that the total N contributed from the sunn hemp cover crop is 713 folds higher than that from CT drenching. Although mineralization rate of sunn hemp organic mulch would be very slow (Reeves et al., 1996), the SH plot would have still contributed more total N than CT drenching. Lack of synergistic effect between SH and CT on crop yield is not surprising when soil was already enriched by SH cover cropping. Pant et al. (2012b) also found that chicken manure based CT improved plant fresh weight of pak choi only in plants fertilized by chicken manure but not on plants fertilized by tankage (meat and blood meal) which has a higher N mineralization rate. Future work should examine CT applied in a drip chemigation system to increase the amount of CT application.

The yield of zucchini in Trial II was better than Trial I due to better management of melon flies through establishment of sorghum-sudangrass as a field border for GF-120 (a.i. spinosad) insecticide spray (Vargas et al., 2008). It could also be due to selecting a virus resistant variety ‘Felix’ in Trial II vs a susceptible variety ‘Elite’ in Trial I. However, similar SH or CT treatment effects were observed in both trials regardless of the melon fly management program and varieties used.

4.5. Nematode soil health bioindicators at initial planting is better indicator of zucchini yield

In general, zucchini fruit numbers were more responsive to nematode parameters than fruit weight. More nematode parameters were correlated with zucchini yield in Trial I than Trial II possibily due to much older stage of growth of sunn hemp in Trial II. Mansoer et al. (1997) reported that when SH residues was used as surface mulch in no-till system, the % N mineralization were 30–40% if residues were younger than 3-month old, but reduced to 11% if it is older than 4-month old. Sunn hemp living mulch was 4–6 month old in Trial I, but was 9–11 month old in Trial II. As sunn hemp aged, its C:N ratio increased (Mansoer et al., 1997), which stimulated more fungal decomposition, hence more fungivorous nematodes (Wang et al., 2004). This correlation analysis also implicated that it might be worthwhile to perform more frequent clipping of sunn hemp living mulch so as to maintain younger age of sunn hemp residues in STCC + SM system for better zucchini yield.

Within Trial I, zucchini yields were more responsive (based on *r* values) at initial planting (Pi) than at final harvest (Pf). This suggests that managing soil health at initial planting is more important than managing it at final stage of cropping. Correlation analysis results obtained from Trial I indicated that it is important to avoid higher % of fungivores, F/(F + B) and CI at Pi to obtain a better yield of zucchini. However, it is important to maintain higher % bacterivores and lower F/(F + B) at Pf to obtain a better yield of zucchini. These results are consistent with that suggested previously as higher % bacterivores would indicate a more nutrient enriched soil ecosystem whereas higher % fungivores, F/(F + B) or CI resembled fungal dominated soil conditions. Fungal dominated decomposition has slower decomposition rate than bacteria dominated decomposition, thus may lead to less nutrient supply for the crop (Ferris et al., 2001). The percent of herbivorous nematodes was anticipated to be negatively correlated with zucchini yield, but only a slight negative correlation occurred between the zucchini fruit numbers and the % plant-parasitic nematodes ($P = 0.07$) at Pf in Trial II. This is most likely due to a low plant-parasitic nematode pressure in both trials (<250 and <500 *R. reniformis*/250 cm^3 at planting in Trial I and Trial II, respectively). More significant negative correlation between herbivorous nematodes with zucchini yield might occur if population densities of *R. reniformis* increased.

5. Summary and conclusions

Drenching zucchini plants with chicken-manure based vermicompost tea consistently suppressed the abundance of the key plant-parasitic nematodes (*R. reniformis* and *Meloidogyne* spp.) but only at the initial stage of the zucchini growth in this experiment. This suggests that vermicompost tea drenching may serve as an approach for initial post-plant nematode management. This effect could potentially be extended if CT was continued to be drenched toward the end of the cropping cycle. Results of this study supported the hypothesis that drenching CT increased the soil food web structure as indicated by increased abundance of predatory or omnivorous nematodes as well as SI within one zucchini cropping cycle which was not achievable by SH cover cropping alone. Unfortunately, CT drenching did not result in an increase in zucchini yield. In contrary, planting sunn hemp in the STCC + SM system provided much higher amount of N inputs than CT, suppressed plant-parasitic nematodes and enhanced bacterivorous nematodes throughout the zucchini cropping cycle, and resulted in increased of zucchini yield. Although no synergistic effect occurred between cover cropping and CT drenching, it is recommended that farmers should still grow sunn hemp in a STCC + SM system followed by CT drenching at post-plant to achieve soil enrichment and improve the soil food web structure for a short-term crop like zucchini. Based on the fact that zucchini yields were more responsive to lower % fungivorous, or higher % bacterivorous nematodes during early stage of zucchini growth, it is important to manage soil health early in the cropping cycle.

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