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Effects of the Integration of Sunn Hemp and Soil Solarization on Plant-Parasitic and Free-Living Nematodes

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Abstract: Sunn hemp (SH), *Crotolaria juncea*, is known to suppress *Rotylenchulus reniformis* and weeds while enhancing free-living nematodes involved in nutrient cycling. Field trials were conducted in 2009 (Trial I) and 2010 (Trial II) to examine if SH cover cropping could suppress *R. reniformis* and weeds while enhancing free-living nematodes if integrated with soil solarization (SOL). Cover cropping of SH, soil solarization, and SH followed by SOL (SHSOL) were compared to weedy fallow control (C). *Rotylenchulus reniformis* population was suppressed by SHSOL at the end of cover cropping or solarization period (Pi) in Trial I, but not in Trial II. However, SOL and SHSOL did not suppress *R. reniformis* compared to SH in either trial. SH enhanced abundance of bacterivores and suppressed the % herbivores only at Pi in Trial II. At termination of the experiment, SH resulted in a higher enrichment index indicating greater soil nutrient availability, and a higher structure index indicating a less disturbed nematode community compared to C. SOL suppressed bacterivores and fungivores only in Trial II but not in Trial I. On the other hand, SHSOL enhanced bacterivores and fungivores only at Pi in Trial I. Weeds were suppressed by SH, SOL and SHSOL throughout the experiment. SHSOL suppressed *R. reniformis* and enhanced free-living nematodes better than SOL, and suppressed weeds better than SH.

Key words: Crotalaria juncea, enrichment index, nematode community analysis, *Rotylenchulus reniformis*, structure index, *Vigna unguiculata,* weeds.

The reniform nematode, *Rotylenchulus reniformis* [Linford & Oliveira, 1940], is a common plant-parasitic nematode in Hawaiian pineapple, *Ananas comosus*, fields (Rohrbach and Apt, 1986; Ko and Schmit, 1996). This nematode is an economically important pathogen because it can reduce pineapple marketable yield by up to 26.8% (Sipes, 1994) at first crop and by 50% in ratoon crops (Sipes, 1996). *Rotylenchulus reniformis* is difficult to manage because it adopts an anhydrobiotic state under dry conditions (Tsai, 1978) and can survive for 1.5 years in this state (Apt, 1976).

Soil solarization is a non-chemical control tactic for soilborne diseases and pests (Katan et al., 1976). Soil solarization is a method of heating the soil beneath transparent polyethylene mulch for 4 to 6 wk so that soil reaches temperatures detrimental to soilborne pests (Katan et al., 1976). Soil solarization relies on solar energy that is conveyed into the soil after covering the soil with transparent, uv-stabilized, low-density polyethene mulch. Soil solarization has been used to suppress plant-parasitic nematodes (Katan et al., 1976; Katan, 1981; Wang et al., 2006; Zasada et al., 2010) and weeds (McSorley and Parrado, 1986; Chase et al., 1998; McSorley et al., 2008). Thus, soil solarization offers one alternative to nematicide and herbicide for pineapple production in Hawaii. However, in conventional pineapple production, fields are fallowed for 3 to 12 mo after crop termination (Rohrbach and Schmitt, 2003). This fallow period helps *R. reniformis* to enter into an anhydrobiotic state (Tsai, 1978) which is more difficult to manage (Deliopoulos et al., 2010) compared to their active state (Womersley and Ching, 1989). Therefore, conducting soil solarization in a field that has been fallowed for a long period of time may not suppress *R. reniformis* efficiently.

Various cover crops have been used to reduce the abundance of plant-parasitic nematodes in the field (Rodriguez-Kabana et al., 1992; Wang et al., 2001; Marahatta et al., 2010). Sunn hemp, *Crotalaria juncea* L., is a non-host or poor host for many plant-parasitic nematodes including *Meloidogyne* spp. (Good et al., 1965; Rotar and Joy, 1983; Wang et al., 2002) and *R. reniformis* (Wang et al., 2001; 2002). When incorporated into soil, sunn hemp residues produce monocrotaline (Crout, 1968) which is toxic to many plant-parasitic nematodes (Rodriguez-Kabana et al., 1992; Rich and Rahi, 1995; Wang et al., 2001; 2004a). Although sunn hemp roots are penetrated by *R. reniformis*, the development of these nematodes is delayed (Wang et al., 2001) and *R. reniformis* remains in an active stage. Thus, planting sunn hemp prevents *R. reniformis* from entering an anhydrobiotic state. Integration of sunn hemp cover cropping with soil solarization should allow the solarization heat to target the active vermiform stage of the nematode, thus should be a more efficient nematode management strategy as compared to either method used alone. This hypothesis was similar to that examined by Wang et al. (2006), who reported that soil solarization following a cowpea (*Vigna unguiculata* L. (Walp.)) cover crop suppressed *Meloidogyne* spp. equivalent to that treated with methyl bromide fumigation.

Plant-parasitic and free-living nematodes are the dominant nematode fauna in most soil communities. Free-living nematodes are involved in soil nutrient cycling and help to create a healthier soil environment (Wang et al., 2004b; Wang and McSorley, 2005; Oka, 2010). Wang et al. (2006) demonstrated that integration of a cowpea cover crop resistant to *Meloidogyne incognita* along with soil solarization reduced the negative impact of soil solarization

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on free-living nematodes. The purpose of the current research is to further evaluate the effect of integrating sunn hemp and soil solarization on *R. reniformis* and free-living nematodes.

Weed control is an important approach in a crop management program. Weeds not only reduce yield but are hosts to many plant-parasitic nematodes. Therefore, a good nematode management program should include a strategy for suppressing weeds that may serve as nematode hosts.

Specific objectives of the current research were to compare the impacts of integrating sunn hemp cover cropping with soil solarization on: 1) plant-parasitic nematodes, 2) free-living nematodes, and 3) weed densities.

Materials and Methods

A field experiment to integrate sunn hemp cover cropping with soil solarization was conducted at the University of Hawaii Experiment Station, Whitmore, Oahu, HI (21° 30' 50" N, 158° 01' 23" W) in 2009 (Trial I) and repeated in 2010 (Trial II). The soil at the study site is a volcanic Wahiawa silty clay (Wahiawa series; clayey, kaolinitic, isohyperthermic, Tropeptic, Eutrustox; Oxisol) with a pH of 5.0. The experimental site had been fallowed for approximately 5 years since the last pineapple crop. Before the initiation of the experiment, seeds of cowpea variety 'SCL 825' (Peaceful Valley Farm and Garden Supply, Grass Valley, CA) were planted at 56 kg/ha throughout the experimental plots and grown for 10 wk up to 18 September 2009. The purpose of planting cowpea prior to the experiment was to increase *R. reniformis* populations. Cowpea biomass was mowed, and the shoots removed from the field. Plots were cultivated using a rototiller to a depth of 20-cm. The experiment contained four pre-plant treatments: 1) cover cropping of 'Tropic Sun' sunn hemp (SH) (seeded at 34 kg/ha) for 12 wk, 2) soil solarization by low density polythene mulch (SOL) for 12 wk, 3) SH grown for 6 wk followed by SOL for the remaining 6 wk (SHSOL), and 4) fallow with weeds as a control (C) for 12 wk. Solarization was performed by covering the soil with a 25-µm thick, UV-stabilized, transparent, low-density polythene mulch (solarization mulch) (Shields Plastics, Moraga, CA). Treatments were arranged in a randomized complete block design with 4 replications. Each experimental plot was 2.4 m × 6 m.

Trial I: Sunn hemp was seeded in rows on each side of drip irrigation lines with a row spacing of 1.2 m wide, and intra-row spacing of 20 cm on 21 September 2009. Control treatment plots remained fallow with weeds. All plots except SOL were drip irrigated as needed. SHSOL plots were irrigated only during the cover cropping period. Weeds in plots planted with SH were removed manually. On average, 25±3% sunn hemp seedlings were damaged by birds, thus rows were reseeded as needed. Sunn hemp foliage in SHSOL plots was cut at ground level 10 wk after sunn hemp planting (7 December 2009). To compensate for the bird damage, the amount of sunn hemp biomass reduction from each SHSOL plots was estimated by length of row missing of sunn hemp. External sunn hemp biomass collected from another field site planted at the same time was used to replace biomass missing in each plot. Sunn hemp foliage in SHSOL plots was soil incorporated using hand hoes, and two strips of 1.2-m wide solarization mulch were laid per plot. At 4 mon after sunn hemp planting (21 January 2010), sunn hemp in SH plots was cut at ground level and the foliage was soil incorporated using a rototiller. Clear plastic solarization mulch on SOL and SHSOL plots were removed immediately at 16 and 6 wk after solarization, respectively, corresponding to the termination of SH treatment. Soil in SH and C was tilled whereas that in SOL and SHSOL was not tilled, to maintain the SOL effect. Two irrigation lines were reinstalled in each plot on 1.2 m distance, flushed with water to stimulate weed germination and sprayed with glyphosate (Gly Star Plus, Ankeny, IA) at 17 ml/liter water prior to cowpea planting. The cowpeas planted after pre-plant treatments (on 22 April 2010) were to serve as bioassay for reniform nematode infection. To prevent the cowpea seedlings from bird damage, all plots were protected by garden nets (Diamond Netting, National Netting, Inc, GA) for 2 wk. Weeds grown between plots were periodically sprayed with glyphosate or hand weeded. Cowpea bioassay was terminated by cutting the plants at the soil level at 10 wk after planting.

Trial II: One day after termination of Trial I (1 July 2010), glyphosate was sprayed on the entire experimental site to kill weeds. The same experimental plots in Trial I were used in Trial II. Sunn hemp was seeded in SH and SHSOL plots, and plots were covered with solarization mulch on 7 July, 2010. Two mo after sunn hemp planting (8 September 2010), sunn hemp in SHSOL plots was soil incorporated and covered with solarization mulch. These preplant treatments were terminated on 6 October 2010, and all plots were planted with cowpea (on 20 October 2010) for 10 wk and biomass was harvested on 6 January 2011.

Soil temperature: The soil temperature of SOL and SHSOL plots was recorded at depths of 5 and 15 cm for the entire solarization period using data loggers (SpecWare 8 Basic, Spectrum Technologies, Inc., Il). Cumulative lethal hrs for nematodes (> 42 °C soil temperature) were calculated for SOL, SHSOL, and C, as described by Wang and McSorley (2008).

Nematode assay: Soil samples were taken before initiation of the experiment, at termination of sunn hemp and soil solarization, and at cowpea harvest. Six soil cores at 20-cm deep were systematically collected from each plot, composited into one sample, and transported to the laboratory. Nematodes were extracted from a 250-cm^3 subsample by elutriation (Byrd et al., 1976) followed by centrifugal flotation (Jenkins, 1964). All nematodes extracted were identified to genus level whenever possible and counted under an inverted microscope (Fluovert, Leitz Wetzlar, Germany). Nematodes were categorized into six trophic groups: algivores, bacterivores, fungivores, herbivores, omnivores or predators (Yeates et al., 1993; Okada et al., 2005). Nematode richness was determined by total number of taxa (mostly at the genus level with the exception of Rhabditidae). Additional nematode community indices calculated included the Simpson index of diversity (Simpson, 1949), maturity index (MI) (Bongers and Bongers 1998), enrichment index (EI), structure index (SI), and channel index (CI) (Ferris et al., 2001).

Weed coverage: Weeds commonly present were fireweed (*Erigeron canadensis*), goosegrass (*Eleusine indica*), ageratum (*Ageratum conyzoides*), emilia (*Emilia sonchifolia*), and violet crabgrass (*Digitaria violascens*) (Wang et al., 2003). Weed coverage was rated 1-wk after cowpea planting (29 April 2010), at cowpea harvest in Trial I, at cowpea planting and 5-wk after cowpea planting (24 November 2010) in Trial II using a Horsfall and Barrett (1945) scale of 1 to 12 where 1 = 0%, 2 = 1-3%, 3 = 4-6%, 4 = 7-12%, 5 = 13-25%, 6 = 26-50%, 7 = 51-74%, 8 = 75-87%, 9 = 88-93%, 10 = 94-96%, 11 = 97-99%, and 12 = 100% of ground covered.

Sunn hemp and cowpea biomass: Sunn hemp biomass was estimated from three 0.09 m^2 quadrants in each SH and SHSOL plot before soil amendment of sunn hemp foliage. Cowpea plants were cut at soil level and cowpea foliage per plot was weighed at harvest (24 November 2010 in Trial I, and 06 January 2011 in Trial II).

Statistical analysis: Data were subjected to one-way analysis of variance (ANOVA) using the general linear model (GLM) procedure in Statistical Analysis System (SAS Institute, Cary, NC). Nematode abundance and nematode community indices were log (x +1) or arsin (sqrt(x/100))-transformed, respectively based on PROC UNIVARIATE in SAS prior to ANOVA. Only untransformed arithmetic means are presented. Means were separated by Waller-Duncan k-ratio (k=100) t-test wherever appropriate.

Results

Sunn hemp biomass: Biomass of sunn hemp production differed between Trial I and Trial II. Sunn hemp fresh biomass in Trial I were 1.8±0.2 and 3.6±0.4 Mt/ha in SH and SHSOL plots, respectively; whereas, those in Trial II were 4.0±0.2 and 2.6±0.4 Mt/ha in SH and SHSOL plots, respectively.

Soil temperature and heat units: Heat accumulation in the soil for each treatment also differed between Trial I and Trial II. In Trial I, SOL and SHSOL had similar maximum temperatures at the two soil depths (5 and 15 cm) and were higher than those in SH and C. However, in Trial II, SHSOL generated more heat than SOL. Insufficient heat was accumulated at both soil depths when solarization was conducted during the cooler months in Trial I. In Trial II which was conducted during warmer months, SOL and SHSOL generated 378 and 175 hours above 42 °C, respectively at the 5-cm soil depth, exceeding the lethal heat (14 hours of > 42°C) needed to kill *R. reniformis* and *M. incognita* (Heald and Robinson, 1987; Wang and McSorley, 2008) (Table 1). However, no lethal heat units were accumulated at the deeper soil layer (15-cm soil depth) in SH and SHSOL plots.

Impact of SH or SOL on plant-parasitic nematodes: The most dominant plant-parasitic nematode at the experimental site was *R. reniformis* followed by *Meloidogyne* spp. Before the beginning of the experiment, nematode population densities were similar among treatments ($P >$ 0.05). In Trial I, SHSOL suppressed *R. reniformis*, and *Meloidogyne* numbers compared to C at the end of the cover cropping or solarization period (Pi) ($P < 0.05$) (Table 2). However, SHSOL only suppressed *R. reniformis* at cowpea harvest (Pf) ($P < 0.05$). SHSOL did not reduce abundance of *R. reniformis* as compared to SH alone in both trials. On the other hand, SH, SOL and SHSOL suppressed *Meloidogyne* population densities in Trial II but not in Trial I ($P < 0.05$) (Table 2).

Impact of SH or SOL on free-living nematodes: No difference was found in the abundance of free-living nematode genera and trophic groups among treatments prior to the beginning of the experiment. After the SH or SOL treatments, their impacts on free-living nematodes varied between Trial I and Trial II (Tables 3 and 4). Although SH enhanced abundance of bacterivorous nematodes at Pi and that of omnivorous nematodes at Pf in Trial II ($P <$ 0.05, Table 4), it did not affect these nematodes in Trial I. On the other hand, SOL only suppressed omnivorous nematodes at Pi in Trial I ($P < 0.05$, Table 3), but suppressed bacterivorous, fungivorous, and omnivorous nematodes at Pi, and omnivorous nematodes at Pf in Trial II ($P < 0.05$, Table 4).

As anticipated, integration of SH and SOL (SHSOL) reduced the negative impact of SOL on nematode

Table 1. Maximum soil temperature and lethal hours accumulated at the end of preplant treatment in sunn hemp (SH), soil solarization (SOL), integration of sunn hemp and soil solarization (SHSOL), and weedy fallow control (C) plots measured at 5 and 15 cm soil depth during the solarization period in two trials.

	5 cm		15 cm	
Treatments	Lethal hrs[a]	Max temp °C	Lethal hrs	Max temp °C
		Trial I		
SH	0	28.0	0	27.5
SOL	1	42.5	0	33.0
SHSOL	0	39.0	0	30.0
C	0	30.5	0	27.5
		Trial II		
SOL	378	53.0	10	43.0
SHSOL	175	59.0	5	46.0
C	0	34.5	0	30.5

[a] Lethal hrs are cumulative hours with temperature > 42° C (Wang and McSorley, 2008).

TABLE 2. Effects of sunn hemp (SH), soil solarization (SOL), integration of SH and SOL (SHSOL), and weedy fallow control (C) plots on abundance of plant-parasitic nematodes/250 cm^3 soil at termination of SH and SOL (Pi), and at cowpea harvest (Pf) in two trials.

Treatments	Trial I		Trial II	
	Pi	Pf	Pi	Pf
	Rotylenchulus reniformis			
SH	687[a] ab	2412 ab	808 a	375 a
SOL	850 ab	4567 a	550 a	1415 a
SHSOL	205 b	925 b	1223 a	715 a
C	927 a	333 a	1470 a	1593 a
	Meloidogyne spp.			
SH	92 a	457 a	8 b	8 b
SOL	5 b	162 a	0 b	13 b
SHSOL	12 b	100 a	13 b	70 b
C	92 a	325 a	70 a	300 a

[a] Means are average of 4 replications. Means in a column for each nematode genus followed by the same letter(s) do not differ according to Waller-Duncan *k*-ratio (*k*= 100) *t*-test based on log(x+1) transformed values. Only untransformed values are presented.

communities both in Trial I and Trial II. At Pi in Trial I and Trial II, population densities of total fungivorous nematodes were consistently higher in SHSOL compared to SOL ($P < 0.05$, Tables 3 and 4). Additionally, at Pi in Trial I, SHSOL enhanced population densities of fungivorous and bacterivorous nematodes compared to all other treatments ($P < 0.05$, Table 3). However, this effect of SHSOL dissipated at Pf of both trials (Tables 3 and 4).

Nematode community analysis: No difference was observed among pre-plant soil treatments for all the nematode community indices prior to the beginning of the experiment. Positive impact of SH was more obvious in Trial II than in Trial I. At Pi in Trial I, all the nematode community indices measured were not different between SH and the C (Table 5). However, in Trial II, SH enhanced % bacterivores, reduced % herbivores as compared to C at Pi ($P < 0.05$, Table 6) and supported higher EI ($P < 0.05$; Table 6) than C from Pi to Pf. Moreover, at Pf in Trial II, higher % omnivores and SI was recorded in SH than in C ($P < 0.05$; Table 6). On the other hand, SOL at Pi in Trial I reduced nematode richness as compared to the C ($P < 0.05$; Table 5). Negative impact of SOL on nematode communities in terms lower % omnivores and richness compared to C was recorded at Pi in Trial I, and was found at both Pi and Pf in Trial II ($P < 0.05$; Table 6). Integration of SHSOL resulted in higher % bacterivores but lower % herbivores than the other pre-plant treatments ($P < 0.05$) at Pi in Trial I (Table 5). SHSOL also had lower F/(F+B) ratio than C ($P < 0.05$) at Pi in Trial I. However, at Pi in Trial II, no difference in all nematode community indices was found between SHSOL and C (Table 6). At Pf in Trial II, similar nematode community indices were recorded in SOL and SHSOL. However, there was a comparable % of higher free-living nematode trophic groups in SHSOL as compared to SOL (Table 6).

Impacts on weed coverage: Weeds recorded at the experimental site were similar among treatments (Table 7). At 1-wk after cowpea planting in Trial I, both solarization treatments (SOL and SHSOL) suppressed broad leaf, grasses and total weed coverage compared to C ($P < 0.05$, Table 8). However, towards the end of the cowpea crop in Trial I, grasses were suppressed in both sunn hemp treated plots (SH and SHSOL) ($P < 0.05$), whereas total weeds were suppressed by SH, SOL and SHSOL compared to C ($P < 0.05$, Table 8). Unlike Trial I, broad leaf weed coverage was equally suppressed by SH, SOL and SHSOL compared to C at cowpea planting in Trial II ($P < 0.05$, Table 8). At 5-wk after cowpea planting, SH, SOL, and SHSOL suppressed broad leaf, grasses and total weeds compared to C ($P < 0.05$). However, broad leaf and total weeds coverage in SH was more abundant than that in SOL and SHSOL at 5 wk after cowpea planting ($P < 0.05$). The weed suppressive effect of SOL and SHSOL was similar throughout Trial II ($P > 0.05$, Table 8).

Impacts on cowpea growth: Sunn hemp plots produced less cowpea fresh biomass compared to C and SOL ($P < 0.05$) in Trial I, but no difference was detected among

TABLE 3. Effects of sunn hemp (SH), soil solarization (SOL), integration of SH and SOL (SHSOL), and weedy fallow control (C) plots on abundance of free-living nematode trophic groups at termination of SH and SOL (Pi), and at cowpea harvest (Pf) in Trial I.

Trophic group	SH	SOL	SHSOL	C
	.... Nematode abundance/250 cm^3 soil			
	At Pi (28 January 2010)			
Bacterivores	690[a] b	597 b	4577 a	702 b
Fungivores	190 b	122 b	497 a	220 b
Omnivores	52 a	5 b	35 a	37 a
Predators	2 a	0 a	0 a	0 a
Total nematodes	965 b	755 b	5150 a	973 b
	At Pf (01 July 2010)			
Bacterivores	3695 a	4447 a	2447 a	4120 a
Fungivores	860 a	562 a	462 a	485 a
Omnivores	47 a	62 a	45 a	72 a
Predators	2 a	2 a	5 a	7 a
Total nematodes	4630 a	5097 a	2975 a	4702 a

[a] Means are average of 4 replications. Means in a row followed by the same letter(s) do not differ according to Waller-Duncan *k*-ratio (*k*= 100) *t*-test based on log(x+1) transformed, and non-transformed values for abnormally and normally distributed data, respectively.

TABLE 4. Effects of sunn hemp (SH), soil solarization (SOL), integration of SH and SOL (SHSOL), and weedy fallow control (C) plots on abundance of free-living nematode trophic groups at termination of SH and SOL (Pi), and at cowpea harvest (Pf) in Trial II.

Trophic group	SH	SOL	SHSOL	C
	.... Nematode abundance/250 cm^3 soil			
	At Pi (20 October 2010)			
Bacterivores	2663[a] a	420 c	584 bc	1195 b
Fungivores	578 a	145 b	315 a	388 a
Omnivores	30 ab	10 b	21 ab	45 a
Predators	18 a	3 a	3 a	5 a
Total nematodes	3310 a	600 c	957 bc	1655 ab
	At Pf (30 December 2010)			
Bacterivores	1212 ab	585 b	1062 ab	1857 a
Fungivores	255 ab	155 b	237 ab	637 a
Omnivores	345 a	50 b	130 b	198 b
Predators	13 a	8 a	18 a	10 a
Total nematodes	1830 ab	808 b	1468 ab	2735 a

[a] Means are average of 4 replications. Means in a row followed by the same letter(s) do not differ according to Waller-Duncan *k*-ratio (*k*= 100) *t*-test based on log(*x*+1) transformed, and non-transformed values for abnormally and normally distributed data, respectively.

C, SOL and SHSOL (Table 9). Cowpea biomass was not different among all treatments in Trial II ($P > 0.05$, Table 9). In general, cowpea growth in Trial II was lower than that in Trial I.

DISCUSSION

In this experiment, solarization treatment did not suppress the more abundant plant-parasitic nematode, *R. reniformis*, but did suppress the less abundant *Meloidogyne* sp. It had been known that *M. incognita* J2s and *R. reniformis* juveniles can be killed at 42 °C within 13.8 cumulative hrs (Heald and Robinson, 1987; Wang and McSorley, 2008). Solarization in Trial I was conducted during fall to winter, and thus did not accumulate sufficient lethal hrs to kill plant-parasitic nematodes. Possibly, the insufficient lethal hrs in Trial I had only a sublethal effect on nematodes. Although solarization

TABLE 5. Effects of sunn hemp (SH), soil solarization (SOL), integration of SH and SOL (SHSOL), and weedy fallow control (C) plots on nematode community indices at termination of SH and SOL (Pi), and at cowpea harvest (Pf) in Trial I.

Index	SH	SOL	SHSOL	C
	At Pi (28 January 2010)			
% Bacterivores	36.35[a] b	35.34 b	82.56 a	34.57 b
% Fungivores	10.98 a	6.98 a	10.73 a	10.39 a
% Herbivores	46.59 a	55.88 a	5.27 b	52.74 a
% Omnivores	4.12 a	0.26 b	0.61 b	1.66 ab
% Predators	0.16 a	0.00 a	0.00 a	0.00 a
F/(F+B)	0.22 ab	0.17 ab	0.11 b	0.26 a
Richness	22 a	14 b	20 a	20 a
Dominance	0.21 a	0.24 a	0.31 a	0.24 a
Diversity	6.39 a	4.53 a	4.10 a	4.81 a
Maturity index	1.02 a	2.12 a	1.56 a	2.20 a
Enrichment index	71.41 a	41.46 b	80.46 a	58.45 ab
Structure index	46.03 a	34.83 a	27.75 a	54.18 a
Channel index	20.34 a	44.51 a	6.12 a	35.27 a
	At Pf (01 July 2010)			
% Bacterivores	45.66 a	43.28 a	58.85 a	43.58 a
% Fungivores	11.84 a	5.30 a	10.00 a	5.72 a
% Herbivores	41.43 a	50.59 a	29.64 a	49.01 a
% Omnivores	0.60 a	0.54 a	0.94 a	1.26 a
% Predators	0.04 a	0.03 a	0.13 a	0.15 a
F/B	0.26 a	0.12 a	0.17 a	0.18 a
F/(F+B)	0.19 a	0.11 a	0.14 a	0.14 a
Richness	19 a	20 a	18 a	21 a
Dominance	0.25 a	0.32 a	0.29 a	0.37 a
Diversity	4.20 a	3.20 a	3.69 a	2.92 a
Maturity index	1.42 a	1.32 a	1.41 a	1.49 a
Enrichment index	86.82 a	91.57 a	89.34 a	85.72 a
Structure index	17.04 a	21.56 a	23.48 a	34.93 a
Channel index	8.30 a	3.61 a	5.28 a	7.57 a

[a] Means are average of 4 replications. Means in a row followed by the same letter(s) do not differ according to Waller-Duncan *k*-ratio (*k*= 100) *t*-test based on arsin(sqrt(*x*/100)) transformed, and non-transformed values for abnormally and normally distributed data, respectively.

TABLE 6. Effects of sunn hemp (SH), soil solarization (SOL), integration of SH and SOL (SHSOL), and weedy fallow control (C) plots on nematode community indices at termination of SH and SOL (Pi) and, at cowpea harvest (Pf) in Trial II.

Index	SH	SOL	SHSOL	C
		At Pi (20 October 2010)		
% Bacterivores	58.12[a] a	29.00 b	28.60 b	32.11 b
% Fungivores	12.16 a	09.66 a	13.01 a	09.40 a
% Herbivores	28.55 b	58.74 a	55.88 ab	56.35 a
% Omnivores	0.52 ab	0.37 b	0.52 ab	01.30 a
% Predators	0.28 a	0.34 a	0.05 a	0.09 a
F/B	0.20 b	0.39 ab	00.50 a	0.32 ab
F/(F+B)	0.17 b	0.25 ab	0.32 a	0.23 ab
Richness	19 a	14 b	15 ab	18 a
Dominance	0.26 a	0.25 a	0.24 a	0.26 a
Diversity	03.87 a	04.39 a	04.77 a	04.00 a
Maturity index	01.42 b	01.76 a	01.76 a	01.79 a
Enrichment index	87.28 a	65.21 b	69.19 b	72.57 b
Structure index	14.87 a	12.35 a	12.80 a	27.07 a
Channel index	06.53 b	19.06 a	21.97 a	14.84 ab
		At Pf (30 December 2010)		
% Bacterivores	45.20 a	27.20 a	35.73 a	35.65 a
% Fungivores	10.13 a	4.91 ab	8.15 b	11.39 a
% Herbivores	27.56 b	63.75 a	49.91 ab	48.26 ab
% Omnivores	16.09 a	2.98 b	4.77 b	3.87 b
% Predators	0.68 a	0.21 a	0.73 a	0.19 a
F/B	0.22 a	0.30 a	0.22 a	0.34 a
F/(F+B)	0.18 a	0.21 a	0.18 a	0.24 a
Richness	20 a	16 b	22 a	22 a
Dominance	0.16 a	0.26 a	0.16 a	0.15 a
Diversity	6.58 a	5.25 a	6.46 a	6.98 a
Maturity index	2.10 a	1.98 a	1.93 a	1.94 a
Enrichment index	87.55 a	74.49 ab	76.19 ab	67.64 b
Structure index	80.42 a	54.92 ab	53.70 ab	42.14 b
Channel index	8.05 a	13.32 a	10.92 a	19.05 a

[a] Means are average of 4 replications. Means in a row followed by the same letter(s) do not differ according to Waller-Duncan *k*-ratio (k= 100) *t*-test based on arsin(sqrt(x/100)) transformed, and non-transformed values for abnormally and normally distributed data, respectively.

accumulated lethal hrs far exceeded that required to kill plant-parasitic nematodes in Trial II, which was conducted during the summer, less than 10 lethal hrs accumulated at deeper soil depths (> 15 cm). High clay content in Hawaii might have contributed to low heat accumulation deeper in the soil after solarization. High clay content (68-76% by mass) in soil of Oahu, HI (Mohanram et al., 2010) might have prevented transmission of heat deeper into the soil. A common dilemma of soil solarization is the inability for the solar heat to penetrate deep into the soil (25-cm) even in sandy soils (97% sand) of Florida (Chellemi et al., 1993; Wang and McSorley, 2008). This temperature data could explain the ineffectiveness of solarization to suppress the high abundant *R. reniformis* in both of these trials. Furthermore, future studies on effects of soil moisture on heat conduction in Oahu soil could explain additional causes of the ineffectiveness of soil solarization on *R. reniformis* suppression.

On the other hand, SH treatment although showing a trend to having lower abundance of *R. reniformis* than C, but did not suppress *R. reniformis* population densities significantly. These results were not consistent with earlier findings where sunn hemp cover cropping suppressed *Meloidogyne* spp. (Marahatta et al., 2010; Wang et al., 2011) and *R. reniformis* (Wang et al., 2001; 2002). The amount of SH biomass produced in this experiment was low compared to the 7 Mt/ha dry biomass produced under optimum conditions (Rotar and Joy, 1983), and might have contributed to poor *R. reniformis* suppression in both trials. More research is underway to estimate minimum biomass of SH required for suppression of plant-parasitic nematodes.

Although it is anticipated that integration of SH and SOL could suppressed *R. reniformis* and *Meloidgyne* more effectively than either of these treatments alone, SHSOL only suppressed plant-parasitic nematodes in this experiment at Pi in Trial I when the SH biomass was > 3Mt/ha. Difference in plant-parasitic nematode suppressive effect of SHSOL found in Trial I and Trial II was most likely due to differences in SH biomass, and not due to solarization heat accumulation.

The SHSOL treatment effect in Trial I supported our hypothesis that integrating SH and SOL would reduce the negative impact of SOL on free-living nematodes. In the current experiment, % omnivores, richness and EI were sensitive in detecting the negative impact of solarization on nematode communities. These negative effects of SOL on nematode communities were reduced when integrated with SH in Trial I, but not in Trial II.

Table 7. Common weeds recorded in experimental site, Whitmore, Oahu, Hawaii, USA.

Family	Scientific name	Common name
Araceae	*Caladium* sp.	Caladium
Compositae	*Ageratum conyzoides*	Ageratum
	Erechtites hieracifolia	Fireweed
	Emilia sonchifolia	Flora's paintbrush
	Conyza sp.	Horseweed
	Sonchus oleraceus	Sow Thistle
Cyperaceae	*Cyperus brevifolius*	Green kyllinga
	Cyperus rotundus	Purple nutsedge
Euphorbiaceae	*Euphorbia hitra*	Garden spurge
Gramineae	*Cymbopogon refractus*	Barbwire / soap grass
	Eragrostis pectinacea	Carolina lovergrass
	Chloris radiate	Radiate finger / plush grass
	Agrostis alba	Red top
	Digitaria violascens	Smooth / violet crabgrass
	Chloris divaricata	Star grass
	Panicum torridum	Torrid panic grass / kakonakona
	Andropogon bicornis	West Indian foxtail
	Elusine indica	Wiregrass / goose grass
Leguminosae	*Caesalpinia sepiaria*	Cats claw
	Mimosa pudica	Sensitive plant
Melastomataceae	*Clidemia* sp.	Clidemia
Polypodiaceae	*Polypodium aureum*	Hares-foot fern

High temperature (maximum of 59°C at 5-cm soil depth) in SHSOL plots in Trial II might have caused more negative impact on the nematode community than that in Trial I (maximum of 39 °C at 5-cm soil depth). Another possibility for these differences in SHSOL could be due to higher sunn hemp biomass in SHSOL plots in Trial I than Trial II. Low soil pH at the experimental site caused difficulties in establishing the growth of this cover crop despite adding 4 tons/acre of agricultural lime to the site. Perhaps a longer waiting period was needed for the adjustment of soil pH.

Table 8. Effects of sunn hemp (SH), soil solarization (SOL), integration of SH and SOL (SHSOL), and weedy fallow control (C) plots on weed coverage in four sampling times.

Weed type	SH	SOL	SHSOL	C
Trial I: 1 wk after cowpea planting (29 April 2010) [y]				
Broad leaves	4.50 [a] a	1.00 b	1.75 b	4.75 a
Grasses	2.50 ab	1.50 b	1.25 b	3.00 a
Total weeds	4.50 a	2.25 b	1.25 b	4.75 a
Trial I: At cowpea harvesting (01 July 2010)				
Broad leaves	2.00 a	2.00 a	2.25 a	3.25 a
Grasses	1.00 b	1.50 ab	1.25 b	2.25 a
Total weeds	4.50 b	3.25 c	3.00 c	5.50 a
Trial II: At cowpea planting (20 October 2010)				
Broad leaves	1.50 b	1.50 b	1.50 b	3.00 a
Grasses	1.25 a	1.00 a	1.25 a	2.00 a
Total weeds	1.75 a	1.50 a	1.50 a	3.00 a
Trial II: 5 wk after cowpea planting (24 November 2010)				
Broad leaves	7.50 b	4.75 c	5.00 c	9.25 a
Grasses	1.75 b	1.50 b	1.75 b	2.75 a
Total weeds	7.75 b	4.75 c	5.25 c	9.75 a

[a] Means are average of 4 replications. Means in a row followed by the same letter(s) do not differ according to Waller-Duncan *k*-ratio (k = 100) *t*-test.
[y] Weed coverage was recorded by using Horsfall-Barratt scale 1-12 scale (1=no weed, 12=100% weed).

Table 9. Effects of sunn hemp (SH), soil solarization (SOL), integration of SH and SOL (SHSOL), and weedy fallow control (C) plots on cowpea biomass at cowpea harvest.

Trial	SH	SOL	SHSOL	C
	........Cowpea biomass (t / ha)........			
Trial I	13.66[a] b	21.79 a	17.13 ab	21.24 a
Trial II	7.31 a	9.75 a	10.01 a	6.34 a

[a] Means are average of 4 replications. Means in a row followed by the same letter(s) do not differ according to Waller-Duncan *k*-ratio (k= 100) *t*-test.

Weed suppressive effect of SOL and SHSOL in both trials was similar to the sunn hemp and solarization study conducted by McSorley et al. (2008) and the solarization trials conducted by Chase et al. (1998). This weed suppressive effect of SOL and SHSOL lasted up to crop harvest in Trial I and up to 5 wk after cowpea planting in Trial II, and may be promising for reducing herbicide application frequency.

Reduction of cowpea biomass by SH in Trial I was possibly due to a long SH cover cropping period (4 mo) that might have resulted in SH residues with high C:N ratio. Higher C:N ratio in the residues of SH incorporated into the soil may have eventually resulted in a period of nutrient starvation (Ingham et al., 1985; Hessen, 1990; Wang et al., 2004b; Wang and McSorley, 2005). In Trial II, cover cropping period was short and a cowpea biomass produced in SH and SHSOL was relatively higher as compared to BG though no significant differences were observed in Trial II.

In conclusion, effect of the integration of sunn hemp cover cropping and soil solarization on plant-parasitic nematodes varies. It did not suppress population densities of *R. reniformis* compared to sunn hemp cover cropping alone, but did suppress *R. reniformis* compared to solarization and weedy fallow when cover crop biomass was higher. Furthermore, integration of sunn hemp and solarization reduced the negative impact of solarization on nematode communities. While solarization alone or in combination with sunn hemp could suppress weeds better than sunn hemp or a weedy fallow control, sunn hemp cover cropping alone is more effective in suppresing *R. reniformis,* and enhancing free-living nematodes than the integration of sunn hemp and soil solarization.

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