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Strip-tilled Cover Cropping for Managing Nematodes, Soil Mesoarthropods, and Weeds in a Bitter Melon Agroecosystem

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Abstract: A field trial was conducted to examine whether strip-tilled cover cropping followed by living mulch practice could suppress root-knot nematode (*Meloidogyne incognita*) and enhance beneficial nematodes and other soil mesofauna, while suppressing weeds throughout two vegetable cropping seasons. Sunn hemp (SH), *Crotalaria juncea*, and French marigold (MG), *Tagetes patula*, were grown for three months, strip-tilled, and bitter melon (*Momordica charantia*) seedlings were transplanted into the tilled strips; the experiment was conducted twice (Season I and II). Strip-tilled cover cropping with SH prolonged *M. incognita* suppression in Season I but not in Season II where suppression was counteracted with enhanced crop growth. Sunn hemp also consistently enhanced bacterivorous and fungivorous nematode population densities prior to cash crop planting, prolonged enhancement of the Enrichment Index towards the end of both cash crop cycles, and increased numbers of soil mesoarthropods. Strip-tilled cover cropping of SH followed by clipping of the living mulch as surface mulch also reduced broadleaf weed populations up to 3 to 4 weeks after cash crop planting. However, SH failed to reduce soil disturbance as indicated by the Structure Index. Marigold suppressed *M. incognita* efficiently when planted immediately following a *M. incognita*-susceptible crop, but did not enhance beneficial soil mesofauna including free-living nematodes and soil mesoarthropods. Strip-tilled cover cropping of MG reduced broadleaf weed populations prior to cash crop planting in Season II, but this weed suppression did not last beyond the initial cash crop cycle.

Key words: Crotalaria juncea, free-living nematodes, living mulch, *Meloidogyne incognita*, mesoarthropods, *Momordica charantia*, nematode community analysis, *Tagetes patula*.

Societal demand for environmentally friendly crop production practices has increased the need for pest suppressive cover crops (Costello and Altieri, 1995). However, most studies aimed at examining the impact of cover crops on crop pests have examined weed, nematode, or insect pests separately (McSorley and Gallaher, 1992; Hooks and Johnson, 2002; Ngouajio et al., 2003). Unfortunately, cover cropping strategies used to mitigate one pest may have a negative impact on pest suppression with regards to other pest complexes. Populations of insect pests are normally reduced by cover crops if the cash crop is interplanted with living leguminous cover crops such as strawberry clover (*Trifolium fragiferum*) and white clover (*Trifolium repens*) (Costello and Altieri, 1995; Hooks and Johnson, 2001; 2002; 2004). However, suppression of plant-parasitic nematodes by cover crops is either through mechanisms resulting from the incorporation of organic material (Wang et al., 2001), preplanting of allelopathic cover crops (Ploeg, 2000), or by serving as a trap crop prior to incorporation (Gardner and Caswell-Chen, 1994). On the other hand, suppression of weeds by cover crops is mainly through allelopathy (Hutchinson and McGiffen, 2000) or establishment of surface mulch that physically suppress weeds (Ngouajio et al., 2003). Thus, to use cover crops for the suppression of multiple pests requires a truly integrated strategy.

To achieve suppression of multiple pests using cover cropping systems, an initial step is to select cover crops that are suppressive to targeted plant-parasitic nematodes. Two cover crops with distinct mechanisms for suppressing plant-parasitic nematodes are sunn hemp (SH; *Crotalaria juncea* L.) (Wang et al., 2004) and French marigold (MG; *Tagetes patula* L.) (Ploeg, 2002). Sunn hemp is a rapid growing legume that is used mainly as a green manure in tropical regions (Rotar and Joy, 1983). It is a non- or poor host for many plant-parasitic nematodes including root-knot nematodes, *Meloidogyne* spp. (Wang et al., 2002), reniform nematode, *Rotylenchulus reniformis* Linford and Oliveira, 1940 (Wang et al., 2001; Marla et al., 2009), and soybean cyst nematode, *Heterodera glycines* Ichinohe, 1952 (Warnke et al., 2008). Sunn hemp produces monocrotaline, which is toxic to many plant-parasitic nematodes (Rodriguez-Kabana et al., 1992; Wang et al., 2001; Jourand et al., 2004) especially when incorporated into the soil (Wang et al., 2004). In addition to being suppressive to plant-parasitic nematodes, SH can produce 147 to 180 kg/ha of total nitrogen and 10.4 t dry biomass/ha within 60 days when planted at 40 kg seed/ha under optimum growing conditions in Hawaii (Rotar and Joy, 1983; K.-H. Wang, unpublished). When incorporated into the soil, SH can enhance the abundance of free-living nematodes that play important roles in soil nutrient cycling (Wang et al., 2004; Wang and McSorley, 2005) and increase populations of nematode-trapping fungi (Wang et al., 2001, 2004). *Tagetes* spp. also suppresses multiple genera of plant-parasitic nematodes including *Meloidogyne* (Ploeg, 2002), lesion nematodes, *Pratylenchus* spp. (Evenhuis et al., 2004), and *R. reniformis* (Caswell et al., 1991). The main allelopathic compound in *Tagetes* spp. responsible for nematode suppression is α-terthienyl (Gommers and Bakker, 1988). However, *Tagetes* spp., suppresses plant-parasitic nematodes differently than SH.

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Unlike SH, *Tagetes* spp., kill nematodes as a standing cover crop and is ineffective after soil incorporation. Jagdale et al. (1999) supported this hypothesis by demonstrating that nematicidal activity of *Tagetes* spp. was only detected in root exudates but not in homogenized extracts of roots and leaves.

Conventional cover cropping systems usually incorporate nematode antagonistic plants into the soil as green manures. Although this practice may enhance populations of free-living nematodes (Wang et al., 2003a) and soil mesoarthropods (Kautz et al., 2006), it can disturb soil organisms that are higher in the soil food web hierarchy (Wang et al., 2006). To mitigate this effect, cover crops in combination with conservation tillage practices may increase organisms higher in the hierarchy of the soil food web such as omnivorous and predacious nematodes, collembolans, and mites that also contribute to soil nutrient cycling (Coleman, 1996). For example, living mulches can be used in strip-till cover cropping systems for insect management purposes (Hooks and Johnson, 2001). In addition, continuous clipping of a SH living mulch as surface mulch provided additional benefits of slower release of nutrients and physical weed suppression (Wang et al., 2008).

The experiment described here is part of a larger project aimed at developing cover cropping strategies to manage above- (insect and weeds) and below- (nematode and mites) ground organisms concurrently. This experiment was conducted in a bitter melon (*Momordica charantia* L.) production system. Bitter melon is a popular vegetable among the Asian ethnic group in Hawaii but had received limited research attention. Currently, farmers struggle to grow bitter melon due to damage caused by *M. incognita* (Kofoid & White, 1919). The specific objectives of the experiment were to determine the impact of a strip-tilled cover crop planting systems on 1) the suppression of plant-parasitic nematodes, 2) the abundance of beneficial soil mesofauna including nematodes and soil mesoarthropods, 3) weed suppression, and 4) crop growth and yield.

Materials and Methods

A field experiment was conducted on a commercial farm in Kunia, HI (21° 28' N, 158 ° 04' W) in 2007 (Season I) and repeated in 2008 (Season II). The soil at the study site was a Kunia silty clay (fine parasesquic, isohyperthermic oxic dystrustepts) with a pH ~ 5. The study site was historically infested with high populations of *M. incognita*. The experiment had three cover crop treatments: 1) *C. juncea* 'Tropic Sun' (SH) (seeded at 40 kg/ha), 2) *T. patula* 'Single Gold' (MG) (seeded at 2 kg/ha), and 3) bare ground (BG). Treatments were arranged in a randomized complete block design with four replications and each experimental plot was 11×11 m^2.

Season I: Cover crops were grown from October 2007 to January 2008. Cover crops were sown in 0.6-m spaced rows (i.e. 18 rows/plot). At the end of the cover cropping period, SH was mowed to a height of 10-cm using a flail mower. Marigold plots were not mowed because of its short plant stature. Sunn hemp and MG biomass was estimated prior to mowing by cutting cover crop stems at the soil surface from three 0.18-m^2 quadrates, randomly located in each treatment plot. Plant material was oven dried at 70 °C for 3 d, and weighed.

Alternate SH and MG rows were then incorporated into the soil using a hand-held tiller; untilled cover crop rows remained as living mulches. Two wk after cover crop incorporation, 3-wk-old bitter melon seedlings were transplanted into the tilled strips. Nine rows with 6 bitter melon seedlings per row were planted per plot. A trellis consisting of wooden poles and nylon nets was built in each row to accommodate the aerial growth of bitter melon vines. Bitter melon plants were fertilized with urea (46-0-0) and 10-20-20 N-P-K fertilizer (Gaviota high grade fertilizer, Brewer Chemical Corporation, Honolulu, HI) at 67 kg/ha 1 and 6 wk after transplanting, respectively, which is equivalent to 38 kg/ha of N, 13 kg/ha of P_2O_5, and 13 kg/ha of K_2O throughout each cropping cycle. Plots were drip irrigated and spot treated with glyphosate as necessary. Due to heavy infestation with melon fly, *Bactrocera cucurbitae*, the melon fly bait GF-120 (Dow AgroSciences LLC, Indianapolis, IN) was sprayed weekly beginning at 6 wk after transplanting on weeds surrounding the experimental plots. Bitter melon fruits were harvested from whole plot between 12 to 21 wk after transplanting, and fruit number and fruit weight were recorded.

Season II: Treatments in season II were superimposed on the same plots established in Season I to maintain treatment integrity and determine the cumulative impact of each treatment over two cropping seasons. Bitter melon plants from the initial crop were manually removed from each treatment plot. On 7 July 2008, MG was reseeded immediately into the MG plots after removal of bitter melon plants. Other treatments were left weedy fallow for 2 mon. Sunn hemp was sown on 15 August 2008. On 7 October 2008, cover crop biomass was estimated and alternate rows of cover crops were tilled as described for Season I. Learning from the experience in Season I that flail mowing of SH at low height did not allow SH to grow back as living mulch, and also to avoid the effort to reconstruct the trellis for the bitter melon crop, alternate SH rows were not mowed but were trimmed to approximately 30-cm height and were kept as living mulch in Season II. Sunn hemp was trimmed three times (1, 6, and 13 wk after bitter melon planting) to avoid shading of the cash crop and also to provide surface mulch on cash crop rows. Management of MG remained the same as in Season I. The experiment was maintained similar to that described in Season I except that malathion 5 EC (Micro Flo Company LLC, Memphis, TN) was applied at a rate of 17 ml/liter in addition to the weekly GF-120 applications to protect the crop from melon flies.

Nematode assay: Soil samples were taken before the beginning of the experiment (22 October 2007), at cover crop termination (3 February 2008 in Season I; 21 November 2008 in Season II), and at bitter melon termination (16 May 2008 in Season I; 24 February 2009 in Season II). Six soil cores (2.5-cm diam. × 20-cm deep) were collected from each plot and combined into one composite sample. Nematodes were extracted from a 250-cm^3 subsample of soil by elutriation followed by centrifugal flotation (Jenkins, 1964). Nematodes were identified to genus level whenever possible and counted using an inverted microscope (Fluovert, Leitz Wetzlar, Germany). Nematodes were categorized into five trophic groups: bacterivores, fungivores, herbivores, omnivores, or predators (Yeates et al., 1993). Nematode richness was determined by total number of taxa (mostly at genus level with the exception of the family Rhabditidae). Additional nematode community indices calculations included Simpsons 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). Species of *Meloidogne* were identified by esterase phenotype (Esbenshade and Triantaphyllou, 1985).

Five bitter melon plants were removed from each plot at the end of each season for root gall rating. Root galling was rated on a modified scale of 0 to 7 where 0 = no galls, 1 = <1% of root system galled (1 or 2 galls present), 2 = 1% (3 to 10 galls present), 3 = 5-10% of root system galled (11 to 30 galls), 4 = < 25% of root system galled, 5 = 25% to 50% root system galled and not functioning, 6 = 50% to 75% root system galled and not functioning, 7 = >75% of root system galled (Taylor and Sasser 1978; Netscher and Sikora, 1990).

Soil mesoarthopod assay: One hundred g soil subsamples of from each collected sample were incubated in a Berlese trap (Kim and Jung, 2008) for 3 d using 25 watt bulbs (soft while, GE lightening, General Electric Company, OH). Soil mesoarthropods were collected in glass jars containing 70% ethyl alcohol, identified to order under a stereo microscope (Nikon, Serco Technical Services, CA), and categorized into trophic groups (Coleman, 1996).

Weed biomass and coverage: Weed biomass was estimated during the cover crop growing season (19 December 2007) in Season I by clipping weeds at the soil surface from three, 0.37-m^2 quadrats randomly placed in 3 areas per plot, oven dried at 70°C for 3 d and weighed. However, in Season II weeds were monitored by Horsfall and Barratt (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. The Horsfall and Barratt scale was also used to monitor weed coverage approximately one month after bitter melon planting in both seasons, but weeds were not monitored beyond 1 mon after bitter melon planting as herbicide was applied to maintain treatment integrity.

Plant growth: Five bitter melon plants per plot were randomly selected 2 wk after transplanting. Throughout the growing season, stem diameters were measured at 2-wk intervals using a digital caliper (Digimatic Caliper Mitutoyo Corporation, Kanagawa, Japan).

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 and soil mesoarthropod abundance data were log-transformed [log (x +1)] prior to ANOVA to normalize the data distribution. Untransformed arithmetic means of all data are presented. Data for all community indices and weed monitoring were not transformed prior to analysis. Means for specific sampling times were separated by Waller-Duncan k-ratio (k =100) t-test wherever appropriate.

Results

Biomass of cover crops: Sunn hemp dry biomass generated at the end of the cover cropping period in Season I and II was 5,895 ± 2,406 and 5,618 ± 1,529 kg/ha, respectively. Whereas, dry biomass of MG at the end of the cover cropping period was ≤ 200 and 865 ± 314 kg/ha in season I and II, respectively.

Meloidogyne incognita: Because *M. incognita* was the most prevalent and damaging plant-parasitic nematode found at the study site, only the abundance of *M. incognita* with respect to plant-parasitic nematodes is reported. Before the beginning of the experiment, nematode population densities were not different among treatments (data not shown). In Season I, population densities of *M. incognita* were not suppressed by SH at cover crop incorporation (Pi), but were suppressed by SH by the end of the bitter melon crop (Pf) ($P < 0.05$, Table 1). In Season II, population densities of *M. incognita* were suppressed by SH and MG at cover crop incorporation ($P < 0.05$), but not at bitter melon termination ($P > 0.05$, Table 1). Root-gall index at termination of the bitter melon crop was reduced only by SH in Season I, but was reduced by both SH and MG in Season II ($P < 0.05$); no difference was observed between SH and MG (Table 2).

Table 1. Population densities of *Meloidogyne incognita* in a strip-tilled cover cropping system with marigold (MG) and sunn hemp (SH), as well as bareground (BG) at cover crop incorporation (Pi) and at termination (Pf) in a bitter melon (*Momordica charantia*) crop during two seasons.

	Number of *M. incognita*/250 cm^3 soil			
	Season I		Season II	
Treatments	Pi	Pf	Pi	Pf
BG	50 a	568 a	55 a	292 a
MG	63 a	558 a	25 b	145 a
SH	15 a	68 b	26 b	206 a

Means are an average of four replications. Means in a column followed by the same letter do not differ according to Waller-Duncan k-ratio (k = 100) t-test based on log(x+1) transformed values.

TABLE 2. *Meloidogyne incognita* root gall indices on bitter melon (*Momordica charantia*) in a strip-tilled cover cropping system with marigold (MG) and sunn hemp (SH), as well as bareground (BG) in two seasons.

	Root-gall index (0-7 scale)[a]	
Treatments	Season I	Season II
BG	6.55[b] a	6.26 a
MG	5.80 ab	3.65 b
SH	3.90 b	2.57 b

[a] Root gall index (0-7 scale; 0 = no galls, 7 = >75% of root system galled).
[b] Means are an average of four replications. Means in a column followed by the same letter(s) do not differ according to Waller-Duncan *k*-ratio ($k = 100$) *t*-test.

Nematode community analysis: Several genera of free-living nematodes were significantly higher in SH than BG at Pi but no treatment differences were observed at Pf (Table 3). Population densities of bacterivorous and fungivorous nematodes at Pi were higher in SH than BG during both seasons ($P < 0.05$), but were not different between MG and BG (Table 3). Bacterivorous nematodes enhanced by SH compared to BG at Pi were *Acrobeloides*, *Cephalobus*, and Rhabditidae in Season I, and *Eucephalobus*, *Prismatolaimus*, and Rhabditidae in Season II. Except for Rhabditidae and *Acrobeloides* in Season II, population densities of all taxa of bacterivores in SH were similar to BG at Pf in both seasons. On most sampling dates, MG did not affect population densities of bacterivorous or fungivorous nematodes. However, Rhabditidae numbers were enhanced by MG at Pf during Season I ($P < 0.05$; Table 3). Abundances of most bacterivorous and fungivorous genera were not different between SH and MG except for a few genera where SH had higher abundances than MG ($P < 0.05$; Table 3). Population densities of omnivorous and predacious nematodes were relatively low throughout the study and no differences were detected among treatments.

Nematode richness, the number of nematode taxa, was not impacted by SH or MG during either seasons. Although nematode diversity was reduced by both cover crops as compared to BG at Pi in Season I ($P < 0.05$), nematode diversity recovered to levels similar to BG at Pf and was not different from BG in Season II (Table 4). No difference in MI was detected among treatments during Season I and II. The EI was consistently higher

TABLE 3. Population densities of free-living nematode genera in a strip-tilled cover cropping system with marigold (MG) and sunn hemp (SH), as well as bareground (BG) at cover crop incorporation (Pi) and at termination (Pf) in a bitter melon (*Momordica charantia*) crop during two seasons.

		Nematode genera/250 cm^3 soil					
		Pi			Pf		
Nematode	c-p value[a]	BG	MG	SH	BG	MG	SH
				Season I			
Bacterivores							
Acrobeloides	2	20[b] b	80 ab	123 a	0 a	10 a	0 a
Cephalobus	2	60 b	118 ab	175 a	175 a	252 a	388 a
Cervidellus	2	58 ab	25 b	95 a	6 a	0 a	6 a
Drilocephalobus	2	68 a	60 ab	3 b	56 a	19 a	31 a
Rhabditidae	1	230 b	493 ab	880 a	113 b	238 a	500 a
Total		790 b	1,130 ab	1,625 a	931 a	1,094 a	1,794 a
Fungivores							
Aphelenchus	2	288 b	475 ab	1,365 a	506 a	250 a	469 a
Total		405 b	573 b	1,488 a	681 a	338 a	763 a
Total omnivores		58 a	25 a	108 a	81 a	19 a	56 a
Total nematodes		1,252 b	1,727 ab	3,220 a	1,693 a	1,450 a	2,612 a
				Season II			
Bacterivores							
Acrobeloides	2	2 a	2 a	6 a	25 c	70 a	43 b
Cephalobus	2	172 a	57 b	271 a	140 a	200 a	127 a
Eucephalobus	2	367 b	310 b	738 a	472 a	297 a	298 a
Prismatolaimus	3	32 b	197 ab	241 a	165 a	220 a	270 a
Rhabditidae	1	287 b	177 b	618 a	302 b	342 ab	671 a
Total		1,235 b	1,012 b	2,281 a	1,435 a	1,430 a	1,731 a
Fungivores							
Aphelenchoides	2	35 b	62 ab	213 a	92 a	115 a	150 a
Aphelenchus	2	242 ab	207 b	383 a	237 a	135 a	268 a
Filenchus	2	5 b	40 ab	78 a	70 a	37 a	41 a
Psilenchus	2	0 a	0 a	3 a	0 b	0 b	3 a
Total		282 b	320 b	698 a	410 a	315 a	473 a
Total omnivores		35 a	25 a	32 a	45 a	40 a	65 a
Total nematodes		1,552 b	1,357 b	3,012 a	1,890 a	1,785 a	2,270 a

[a] See Bongers and Bongers (1998).
[b] Data are untransformed arithmetic means of four replications. Means in a row within each sampling time followed by the same letter(s) are not differ according to Waller-Duncan *k*-ratio ($k = 100$) *t*-test based on $\log(x+1)$ transformed values.

TABLE 4. Nematode community indices in a strip-tilled cover cropping system with marigold (MG) and sunn hemp (SH), as well as bareground (BG) at cover crop incorporation (Pi) and at termination (Pf) in a bitter melon (*Momordica charantia*) crop during two seasons.

	Nematode community indices			
	Season I		Season II	
Treatments	Pi	Pf	Pi	Pf
		Diversity		
BG	8.53 a	6.47 a	5.66 a	7.40 a
MG	5.95 b	5.93 a	6.34 a	7.55 a
SH	4.42 b	5.95 a	6.69 a	7.08 a
		Maturity index		
BG	1.98 a	2.08 a	1.95 a	1.99 a
MG	1.76 a	2.04 a	2.05 a	1.95 a
SH	1.72 a	1.84 a	1.91 a	1.85 a
		Enrichment index		
BG	59.50 b	45.74 b	50.74 a	53.31 b
MG	69.41 a	54.83 a	49.87 a	57.55 b
SH	70.50 a	57.91 a	58.68 a	72.47 a
		Channel index		
BG	33.51 a	58.31 a	20.74 b	27.35 a
MG	21.07 a	36.75 a	29.75 a	20.84 ab
SH	29.42 a	27.45 a	23.58 ab	15.55 b
		Structure index		
BG	33.86 a	29.12 ab	17.70 a	29.76 a
MG	17.04 a	43.09 a	32.98 a	35.01 a
SH	5.92 a	12.67 b	23.51 a	32.62 a

Means are an average of four replications. Means in a column within a community index followed by the same letter(s) do not differ according to Waller-Duncan *k*-ratio ($k = 100$) *t*-test.

TABLE 5. Population densities of mesoarthropods in a strip-tilled cover cropping system with marigold (MG) and sunn hemp (SH), as well as bareground (BG) at cover crop incorporation (Pi) and at termination (Pf) in a bitter melon (*Momordica charantia*) crop during Season II.

	Number of mesoarthropods/100 g soil			
	Pi		Pf	
Treatments	Predators[a]	Fungivores/ detritivores[b]	Predators	Fungivores/ detritivores
BG	10[c] b	4 b	8 a	1 b
MG	25 a	5 ab	7 a	3 b
SH	20 a	8 a	9 a	6 a

[a]Predator refers to mites, Actinedida, Astigmata, Prostigmata, and Mesostigmata and spiders.
[b]Fungivores and detritivores include Oribatida, and collembolan.
[c]Means are an average of four replications. Means in a column 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.

in SH and MG than BG throughout Season I ($P < 0.05$), but was only higher in SH compared to BG at Pf in Season II ($P < 0.05$). The CI was not different among treatments in Season I, but was higher in MG compared to BG at Pi in Season II ($P < 0.05$), and lower in SH compared to BG at Pf in Season II ($P < 0.05$). Cover crops did not affect SI during the experiment ($P > 0.05$).

Soil mesoarthropod populations: Population densities of soil mesoarthropods were low and did not differ among treatments in Season I. However, densities of mesoarthropods increased in Season II. The majority of these soil mesoarthropods were predatory mites (Actinedida, Astigmata, Prostigmata, Mesostigmata), fungivorous or detritivorous mites (Oribatida), spiders (predators), and springtails or Collembola (fungivorous). Relative to BG, population densities of predatory mesoarthropods were higher in SH at Pi, and population densities of fungivorous or detritivorous mesoarthropods were higher at Pi and Pf ($P < 0.05$, Table 5). Predatory mesoarthropods were only higher in MG compared to BG at Pi in Season II ($P < 0.05$).

Weeds: Total weed densities were lower in SH plots before bitter melon planting in Season I. Broadleaf weeds densities were lower in SH at one month after bitter melon planting in both seasons, and prior to planting in Season II ($P < 0.05$; Table 6). When comparing MG to BG, broadleaf weed densities were lower ($P < 0.05$) before bitter melon planting, but grass densities were higher ($P < 0.05$) at one month after bitter melon planting in Season II (Table 6).

Bitter melon plant growth and yield: In Season I, bitter melon growth was severely impacted by *M. incognita* infestation and fruits were severely damaged by melon flies in all treatments, resulting in no yield differences among treatments. Despite no yield difference among treatments in Season II, stem diameter of bitter melon

TABLE 6. Weed biomass or coverage in a strip-tilled cover cropping system with marigold (MG) and sunn hemp (SH), as well as bareground (BG) in a bitter melon (*Momordica charantia*) crop during two seasons.

	Weed coverage		
Treatments	Grass	Broad leaves	Total
		Season I	
		Before crop planting[a]	
		Biomass (g/m^2)[b]	
BG	-	-	206.80 a[c]
MG	-	-	116.36 ab
SH	-	-	50.45 b
		After crop planting[d]	
		Horsfall-Barratt scale	
BG	2.17 a	2.17 a	3.08 ab
MG	2.33 a	1.58 ab	4.00 a
SH	2.00 a	1.50 b	2.25 b
		Season II	
		Before crop planting[a]	
BG	2.00 a	4.08 a	4.50 a
MG	1.27 a	2.16 c	4.08 a
SH	4.08 a	3.16 b	5.41 a
		After crop planting[b]	
BG	3.25 b	3.33 a	4.25 a
MG	4.75 a	3.08 ab	5.33 a
SH	2.83 b	1.91 b	3.00 b

[a]At termination of cover crops but before mowing or strip-tilling of cover crops.
[b]Biomass of weeds are an average of three quadrates composed of grasses and broadleaf weeds.
[c]Means are an average of four replications. Means in a column followed by the same letter(s) do not differ according to Waller-Duncan *k*-ratio ($k = 100$) *t*-test.
[d]At 3 and 4 wk after bitter melon crop planting in Season I and II, respectively.

measured prior to fruiting stage was greater in SH and MG than in BG ($P < 0.05$, Fig. 1).

Discussion

The strip-tilled SH cover cropping system tested in these experiments suppressed *M. incognita* until the end of the bitter melon crop in Season I. McSorley et al. (2009) examined the effect of SH in a strip-tilled cover cropping system and reported that SH suppressed stunt nematodes (*Quinisulcius acutus*) until the end of a squash crop. However, *M. incognita* population densities were similar in SH and BG at the end of Season II and may have been due to healthier plants and associated root growth of bitter melon grown after a SH cover crop. Similar results were also observed in a SH amendment experiment in the greenhouse where enhancement of cash crop growth by SH resulted in greater numbers of *M. incognita* at the end of the experiment (Wang et al., 2004). Although continuous clipping of SH living mulch throughout the bitter melon crop in Season II was hypothesized to provide longer-term suppression of plant-parasitic nematodes than that of BG, we did not observe this effect. Use of SH residues as surface mulch did not suppress population densities of *M. incognita* (Wang et al., 2008), and using SH in a no-till system also failed to suppress *Meloidogyne* spp. (Chellemi, 2006). Thus, based on these findings, use of SH cover crop in a strip-tilled system followed by using its residues as surface mulch will not provide additional plant-parasitic nematode suppression compared to that obtained in a conventional tillage system. However, we were more interested in the additional benefits of SH strip-tilled cover cropping system in terms of enhancing beneficial mesofauna and suppressing weeds.

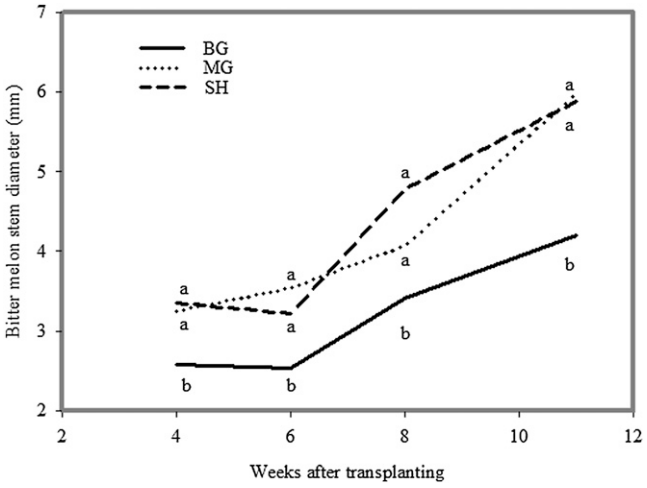

Fig. 1. The effect of strip-tilled cover cropping on bitter melon (*Momordica charantia*) stem diameter in Season II. Means within each sampling date followed by the same letter are not different according to Waller-Duncan *k*-ratio ($k = 100$) *t*-test. BG = bareground, MG = marigold, and SH = sunn hemp.

Suppression of *M. incognita* by strip-tilled MG cover cropping was inconsistent in this study. Strip-tilled MG did not suppress *M. incognita* in Season I when MG was planted after a fallow period, whereas it did suppress *M. incognita* in Season II when MG was seeded immediately after the termination of the bitter melon crop. This immediate reseeding of MG was based on the assumption that the allelopathic effect of MG on *M. incognita* can be enhanced if MG is planted when *M. incognita* juveniles are active in soil. It is possible that MG is ineffective in suppressing *M. incognita* when planted into a field that has been fallow for a lengthy period because juvenile nematodes may have entered a survival stage (Oka and Mizukubo, 2009). Since only living MG root systems exhibit nematicidal properties, incorporation of MG residues into the soil does not suppress *M. incognita* (Jagdale et al., 1999; Ploeg, 2000). Planting MG immediately after a bitter melon crop allowed MG to release allelopathic compounds against active *M. incognita*, and thus was more effective. The removal of bitter melon plants prior to planting MG in Season II may have reduced the pressure from *M. incognita* as suggested by LaMondia (2008) who reported that the reproductive factor of tobacco cyst nematode, *Globodera tabacum* Lownsberry & Lownsberry, 1954, was reduced after destruction of stalks, stumps, and roots of the previous crop. Additionally, the earlier sowing date of MG in Season II may have allowed better establishment and greater biomass production of MG than in Season I which also may have contributed to greater suppression of *M. incognita* by MG in Season II. However, MG did not reduce *M. incognita* population densities compared to BG at termination of the bitter melon crop in Season II possibly due to better plant growth of the bitter melon crop in MG.

Most conventional cover cropping system using leguminous plants fail to enhance omnivorous and predatory nematodes over a vegetable cropping season when compared to fallow with weeds (Wang et al., 2006). We anticipated that strip-tilled cover cropping with SH and MG would reduce soil disturbance and therefore enhance nematodes with higher c-p values such as omnivorous and predacious nematodes. However, an impact of reduced soil disturbance on nematode communities was not observed in the rhizosphere of bitter melon in these experiments. In contrast, SI which reflects abundances of omnivorous and predacious nematodes was lowest in SH at Pf of Season I. This lack of increase in the abundance of predacious nematodes in SH was most likely due to disturbance in the strip-till zone and negligible initial populations of these nematodes. A similar strip-tilled cover cropping experiment was conducted at Homestead, FL at a location where predacious nematodes were abundant initially (McSorley et al., 2009). However, strip-tilled SH only increased omnivorous and predacious nematodes at termination of the cover crop, and this effect did not

persist during the subsequent squash crop (McSorley et al., 2009). Thus, initial populations of omnivorous or predacious nematodes are not the limiting factor but reduction of soil disturbances could maximize the benefits of strip-tilled cover cropping. The integration of conservation tillage and continuous inputs of organic matter could increase SI as compared to conservation tillage in a non-organic farming system (Sánchez-Moreno et al., 2009). In addition, no-till practices further increased SI in an organic system compared to a strip-tilled system. More time may be required to enhance omnivorous or predacious nematodes at sites that have been exposed to severe disturbances from conventional tillage practices (Okada and Harada, 2007).

Abundances of bacterivorous and fungivorous nematodes is often used as indicator of soil nutrient enrichment or depletion (Bongers and Bongers, 1998; Ferris et al., 2001). Sunn hemp consistently increased the abundances of bacterivorous and fungivorous nematodes at cover crop incorporation, but this effect did not last until the end of the bitter melon crop. We were anticipating that strip-tilled cover cropping could prolong the enhancement of bacterivorous nematodes over a longer period of time, i.e. at least until harvest of the cash crop. Previously, Wang et al. (2003a) reported bacterivorous nematode abundance could be enhanced after planting squash in a SH amended soil for two months if the initial numbers of bacterivorous nematodes were low (< 250/250 cm^3 soil) initially. The number of bacterivorous nematodes in BG at this experimental site were relatively high (790 and 1,235/250 cm^3 soil in Season I and II, respectively).

A more sensitive soil nutrient indicator, EI (Ferris et al., 2001), was used to evaluate soil nutritional enrichment. The EI was enhanced by SH strip-tilled cover crop practice throughout the two cropping seasons compared to BG. However, previous studies using SH as a soil amendment in greenhouse pots failed to enhance EI two months after squash planting in three different soils (Wang et al., 2003a). It is possible that continuous inputs of surface organic mulch by clipping of the SH living mulch in the current study might have sustained higher EI throughout the cropping season compared to BG. Wang et al. (2008) demonstrated that planting SH alone or leaving SH residues as surface organic mulch without soil incorporation did not enhance EI. The current strip-tilled SH cover cropping system allowed partial incorporation of SH residues, and partial surface organic mulch, thus, increasing the chances of soil enrichment.

The CI is used to access the primary decomposition pathways; a higher CI indicates a dominance of fungal decomposition and is often associated with more stressful soil conditions (Ferris et al., 2001). In general, EI increased whereas CI decreased from Season I to Season II, indicating that continuous strip-tilled cover cropping, especially with green manure crops like SH, increased soil nutrient enrichment, and reduced soil stress. A stressful soil condition generally infers that the soil is disturbed, dominated by fungal decomposition while lacking bacterial decomposition, has a degraded soil food web with low biodiversity, and is undergoing nutrient depletion (Ferris et al., 2001). On the other hand, soil health is the capacity of a soil to function within ecosystem boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health (Doran et al., 1996). A healthy soil should be able to support life processes such as plant anchorage and nutrient supply, retain optimal water and soil properties, support soil food webs, recycle nutrients, maintain microbial diversity, remediate pollutants, and sequester heavy metals. All of these conditions are difficult to measure by soil nutrient analysis, and will require reliable bioindicators such as nematode community indices (Wang and McSorley, 2005). Sunn hemp only reduced CI at Pf in Season II indicating that reduction of soil stress through strip-tilled cover cropping takes time. Further research is needed to continue monitoring nematode community indices to confirm the longer-term impact of strip-till cover cropping.

Marigold did not enhance any free-living nematodes. Additionally, most of the nematode community indices after MG cover crop did not differ from those in BG. This result is different from findings of Yuhara (1971) where different organic amendments including wild MG enhanced the abundance of free-living nematodes. However, similar to our finding, MG 'Single Gold' as a summer cover crop did not enhance bacterivorous, fungivorous, or omnivorous nematodes on a winter squash crop compared to that of BG (McSorley et al., 2009). The amount of MG biomass produced in the current experiment was probably insufficient to enhance free-living nematodes. However, *T. erecta* as a cover crop also did not enhance free-living nematodes in a pineapple agroecosystem where biomass of *T. erecta* was relatively high (Wang et al., 2003b) Further research is need to test if higher biomass of MG enhances free-living nematodes. It was clear that MG did not produce toxic compound against free-living nematodes in this study similar to that reported by Ball-Coelho et al. (2001).

Another goal of this research was to assess the impact of strip-tilled cover cropping on other organisms in the agricultural ecosystem. Population densities of soil mesoarthropods at Pf of Season I were low, likely due to poor biological activity after a prolong period of fallow and a previous history of extensive cultivation. However, strip-tilled cover cropping of both SH and MG increased predacious and fungivorous/detritivorous soil mesoarthropods at Pi of Season II. This result is consistent with previous findings which showed that the abundances of fungivorous and detritivorous soil mesoarthropods were positively correlated with soil organic matter inputs (Kim and Jung, 2008). Strip-tilled MG failed to sustain higher population densities of soil

mesoarthropods until the end of bitter melon crop in Season II most probably because MG cover crop started to senesce prior to completion of the primary crop growth season. However, the SH living mulch continued to supply more organic surface mulch through clippings, thus SH continued to increase fungivorous/detritivorous soil mesoarthropods at Pf of Season II.

Strip-tilled cover cropping of SH reduced broadleaf weeds but not grass weeds in this experiment, similar to when SH was used as surface organic mulch (Wang et al., 2008). Weed suppression by SH lasted until 3-4 weeks after bitter melon planting. However, MG suppressed broadleaf weeds only during the cover crop growing stage, prior to bitter melon transplanting. Longer weed suppression from SH probably occurred because SH clippings were added during the cash crop growing period. Herbicide sprays may need to be integrated into this strip-tilled SH cover cropping system to manage weed populations towards the end of the cash crop season.

Due to severe fruit fly damage on bitter melon, the benefits of strip-tilled cover cropping on cash crop yield could not be evaluated. However, larger stem diameter of cucurbit has been shown to be correlated with crop yield (Maršić and Jakše, 2010). Bitter melon growth was highest in SH and this was most likely due to green manure effects. In this study, two cropping seasons were required to see a benefit of cover cropping on plant growth.

In conclusion, the current work demonstrated that strip-tilled cover cropping with SH did not provide additional plant-parasitic nematode suppression, but did provide additional weed suppression, and improved soil health conditions over two cropping seasons compared to MG. Further research is needed to reduce soil disturbance by strip-tilled cover cropping to maximize the benefits of this system.

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