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The Potential of Five Winter-grown Crops to Reduce Root-knot Nematode Damage and Increase Yield of Tomato

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Abstract: Broccoli (*Brassica oleracea*), carrot (*Daucus carota*), marigold (*Tagetes patula*), nematode-resistant tomato (*Solanum lycopersicum*), and strawberry (*Fragaria ananassa*) were grown for three years during the winter in a root-knot nematode (*Meloidogyne incognita*) infested field in Southern California. Each year in the spring, the tops of all crops were shredded and incorporated in the soil. Amendment with poultry litter was included as a sub-treatment. The soil was then covered with clear plastic for six weeks and *M. incognita*-susceptible tomato was grown during the summer season. Plastic tarping raised the average soil temperature at 13 cm depth by 7°C.The different winter-grown crops or the poultry litter did not affect *M. incognita* soil population levels. However, root galling on summer tomato was reduced by 36%, and tomato yields increased by 19% after incorporating broccoli compared to the fallow control. This crop also produced the highest amount of biomass of the five winter-grown crops. Over the three-year trial period, poultry litter increased tomato yields, but did not affect root galling caused by *M. incognita*. We conclude that cultivation followed by soil incorporation of broccoli reduced *M. incognita* damage to tomato. This effect is possibly due to delaying or preventing a portion of the nematodes to reach the host roots. We also observed that *M. incognita* populations did not increase under a host crop during the cool season when soil temperatures remained low (< 18°C).

Key words: biofumigation, crop rotation, management, *Meloidogyne incognita*, *Solanum lycopersicum*.

Among the plant-parasitic nematodes that limit productivity of California vegetables, root-knot nematodes (*Meloidogyne* spp.) are economically the most important (Koenning et al., 1999). The use of fumigant pesticides, traditionally used to control root-knot nematodes and other soilborne pests and pathogens, has diminished due to regulatory restrictions and increased costs. Current use is highly regulated because of direct toxicity to humans and the environment, and because fumigants have been implicated as important contributors to the emission of volatile organic compounds (VOCs), leading to poor air quality in several growing areas of California. Under the 2007 Ozone State Implementation Plan, the California Department of Pesticide Regulation is required to reduce emission of smog forming VOCs from soil fumigants (Wang et al., 2009).

Therefore, there is an urgent need for economically feasible, non-polluting, and sustainable nematode management strategies. Examples of such strategies include the use of resistant crop varieties and crop rotation. However, these strategies are limited because there are only a few resistant varieties available and the wide host range of *Meloidogyne* spp. makes it difficult to design a practical and effective cropping sequence. Biofumigation has been proposed as another strategy to manage soilborne problems including weeds (Brown and Morra, 1995), fungal pathogens (Ramirez-Villapudua and Munnecke, 1988; Subbarao et al., 1999), and nematodes (Mojtahedi et al., 1991; Johnson et al., 1992).

Biofumigation occurs when volatile compounds with pesticidal properties are released into the soil during decomposition of plant material or animal by-products (Halbrendt, 1996; Kirkegaard and Sarwar, 1998; Bello et al., 2000a, 2000b). Most research on biofumigation has focused on using brassicaceous crops (Kirkegaard and Matthiessen, 2004). Upon tissue disruption, glucosinolate compounds in brassicas produce biocidal isothiocyanates that are released in the soil when the crop is shredded and incorporated (Chew, 1988; Brown et al., 1991). The suppressive effect of brassicaceous biofumigants on soil-borne pathogens, weeds, and plant-parasitic nematodes has been demonstrated in numerous laboratory, greenhouse, and field studies (Brown et al., 1991; McFadden et al., 1992; Mojtahedi et al., 1993; Spak et al., 1993; Angus et al., 1994; Boydston and Hang, 1995; Ploeg and Stapleton, 2001; Boydston and Vaughn, 2002). Because it may not be possible or practical to use brassicaceous biofumigants in all environments, use of other crops or locally available agro-industrial residues as biofumigants may be used (Bello et al., 2000a, 2000b, 2004). For example, nitrogen-rich material such as manure can be added to act as an "activator" in the decomposition process (Bello et al., 2004).

A complication with growing cover crops as biofumigants is that they may host the target *Meloidogyne* spp. population (McLeod et al., 2001; Stirling and Stirling, 2003), resulting in a population increase during cover crop cultivation when conditions are favorable (i.e. high soil temperatures). To avoid this, resistant or non-host cover crop varieties can be grown (Stirling and Stirling, 2003; Pattison et al., 2006), or cover crops can be cultivated when soil temperatures are low enough to prevent nematode activity (Roberts, 1987). In greenhouse experiments we showed that amending soil with shredded leaves and stems of broccoli (*Brassica oleracea*), tomato (*Solanum lycopersicum*), or melon (*Cucumis melo*),

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reduced the ability of *M. incognita* to infest tomato under high (30°C) soil temperatures (López-Pérez et al., 2005). In that study, broccoli was the most effective amendment material under moderate soil temperatures (25°C), and none of the amendments were effective at lower (20°C) soil temperatures (López-Pérez et al., 2005). However, as the crops were not grown in nematode-infested treatment soils, possible effects due to differences in host status of these crops to *M. incognita* were not included (López-Pérez et al., 2005).

The objective of this field study was to compare the long-term effects of five crops, grown as winter cover crops and subsequently incorporated, on *M. incognita* population levels, and on nematode infestation and yield of a following summer tomato crop. Crops included *M. incognita*-host crops and poor or non-host crops. The effect of adding a nitrogen-rich "activator" (poultry litter) on the aforementioned parameters was also evaluated.

Materials and Methods

Nematode origin: *Meloidogyne incognita* race 3, originally isolated from cotton in the San Joaquin Valley, CA, USA, was maintained and increased on tomato 'Pixie' grown in steam-sterilized sand in a greenhouse (25 – 32°C with natural light). Species and race were determined by isozyme and differential host tests (Eisenback and Triantaphyllou, 1991). The trial was conducted at the University of California South Coast Research and Extension Center, Irvine, CA, USA, and the soil was a sandy-loam (12.5% sand, 75.5% silt, 12% clay, 0.5% organic matter, pH 7.3). Five years prior to the initiation of the trial, the field was fumigated with methyl bromide by a commercial applicator. The soil was then inoculated with eggs extracted from the roots of 'Pixie' tomato plants by injecting the egg suspension through buried drip tubing. Susceptible crops [carrot (*Daucus carota*), melon (*C. melo*), tomato (*S. lycopersicum*), and bell pepper (*Capsicum annuum*)] were grown in sequence during the summer for four years to increase *M. incognita* populations.

Experimental design and treatments: In August 2006, the field was divided into 30 plots. Each plot was three beds wide (bed width 64 cm), 6 m long, with 30 cm between beds. Along the beds, plots were separated by a 90 cm border. Each plot was subsequently divided into two subplots, each 3 m long and three beds wide. The experiment was a randomized block split-plot design, with six main treatments (five winter-grown crops and a fallow control), two sub-treatments (with or without poultry litter), and treatments were replicated five time.

The winter-grown crops were: 1) marigold (*Tagetes patula*) 'Single Gold' (Sahin Seeds, The Netherlands), seeded in the center of the beds (1.5 g seed/m bed). This variety was shown to reduce *M. incognita* (Ploeg, 2002); 2) strawberry (*Fragaria x ananassa*) 'Camarosa' (Crown Nursery LLC, Red Bluff, CA), one plant/15 cm in the center of the bed. In previous greenhouse tests we found strawberry 'Camerosa' to be a non-host for *M. incognita*; 3) tomato (*S. lycopersicum*) 'SunKing' (Seminis Vegetable Seeds, Oxnard, CA) 4-wk-old transplants, one plant/15 cm in center of bed. This variety is resistant to *M. incognita*. Although not normally grown during the winter season, this crop was included to represent a nematode-resistant vegetable crop; 4) carrot (*D. carota*) 'Avenger' (Seminis Inc., Saint Louis, MO) direct-seeded in center of beds (0.16 g seed/m). Carrot 'Avenger' is a host for *M. incognita*, and; 5) broccoli (*B. oleracea*) 'Liberty' (Seminis Vegetable Seeds, Oxnard, CA) transplants, one plant/15 cm in center of bed. This broccoli variety was shown to suppress *M. incognita* when used as a biofumigant (Ploeg and Stapleton, 2001; López-Pérez et al., 2005).

Crops were seeded or planted in mid September for three consecutive years in the same plots. Broccoli heads and strawberry fruits were harvested at maturity. Because of the poor growth of tomato during the winter, fruits were not harvested. Six months after planting, in March, the tops of all crops were cut, shredded in a wood chipper, weighed, and distributed over the plots. Carrots were dug and removed, but the leaves were left in the plots. Plant material from a 30 cm^2 area was collected from each plot, dried at 80°C for 48 h, and weighed. One of the subplots of each plot then received 3 kg (4,000 kg/ha) dried (11% moisture) and ground poultry litter (28.3% C, 4.8% N). Poultry litter was obtained from the same local egg farm each year. The crop residue and poultry litter was incorporated into the top 25 cm of the soil using a roto-tiller. The plots were watered with overhead irrigation to field capacity, and each of the subplots was covered with clear polyethylene plastic (0.1 mm thickness, The Home Depot Inc., USA) for 6 wk. Temperature readers (HOBO, Spectrum Technologies Inc., Plainfield, IL) were buried in the soil 13 cm deep in one of the tarped broccoli, no poultry litter subplots, and in one of the tarped fallow, no poultry litter subplots. Temperature was also recorded at 13 cm depth in two non-tarped fallow areas just outside the experimental field. Soil temperature data (13 cm depth) was also obtained from a weather station located at the Center.

After removal of the plastic, percentage weed cover was estimated visually for each of the subplots. The beds were re-shaped, making sure they were in the same location, and *M. incognita*-susceptible 4-wk-old tomato 'Peto98' transplants were planted over the entire field one week after plastic removal (one plant/30 cm within bed spacing). All crops were watered by drip tubing on the surface in the center of the beds. Summer tomato crops were fertilized according to standard practices (Hartz et al., 2008), and weeds were removed by hand. Tomatoes were grown to maturity, and the fruits from the inner eight plants of the center bed of each sub-plot were harvested three times at 2-wk intervals and total

TABLE 1. Dry green biomass remaining after harvest produced by winter-grown crops during a three-year field trial.

Winter Crop	Year 1	2	3	3 year average
	kg/ha (dry weight)			
Fallow (weeds)	0.1 (±0.02) f[a]	0.1 (±0.02) d	0.0 (±0.01) f	0.1 (±0.01) f
Broccoli	6.9 (±0.17) a	5.7 (±0.17) a	6.7 (±0.18) a	6.4 (±0.17) a
Carrot	3.5 (±0.22) c	3.4 (±0.43) b	2.8 (±0.15) c	3.2 (±0.18) c
Marigold	6.0 (±0.27) b	5.6 (±0.19) a	4.8 (±0.24) b	5.5 (±0.18) b
Strawberry	1.5 (±0.23) d	1.6 (±0.16) c	2.2 (±0.22) d	1.8 (±0.14) d
Tomato	0.8 (±0.16) e	0.4 (±0.11) d	1.2 (±0.15) e	0.8 (±0.11) e

[a] Values shown are the mean of 5 replicates (n = 5) ± standard error. Values in a column followed by different letters are significantly different ($P \leq 0.05$) according to Fisher's LSD-test.

fruit weight was determined. Roots from these plants were indexed for galling on a scale from 0 to 10 (0 = no galls, 10 = 100% galled; Bridge and Page, 1980). After harvest, the plant residue was incorporated, and beds were re-shaped for the next year of winter-grown crops. The winter-grown crops were grown in the same plots each year.

Meloidogyne incognita *analysis*: Soil samples for nematode analysis were collected from each subplot at the following times: 1) before planting/seeding of winter-grown crops, 2) at winter-grown crop incorporation, 3) after biofumigation, and 4) at summer-grown tomato harvest. Ten soil cores (2-cm-diam., 5 - 20 cm deep) were collected from the center bed of each sub-plot and pooled. Nematodes were extracted from two, 100 g soil sub-samples using a modified Baerman-funnel technique (Rodríguez-Kábana and Pope, 1981). Second-stage *M. incognita* juveniles (J2) were counted at 40x magnification, and the counts from the two sub-samples were averaged to give a nematode infestation level per sub-plot.

Statistical Analysis: Raw nematode data (number of *M. incognita* J2 recovered from soil) was $\log_{10}(x+1)$-transformed prior to analysis when necessary to meet assumptions of the statistical models used. Treatment and sub-treatment effects on *M. incognita* J2 levels, root galling, and fruit yields were analyzed in a split-plot analysis of variance (ANOVA) procedure, and means were compared using Fisher's protected least significant difference (LSD) test ($P \leq 0.05$) using SAS statistical software (SAS Institute, Cary, NC, USA). All data presented are nontransformed means ± standard errors.

RESULTS

General: The different winter-grown crops did not all grow well during the fall-winter season. Tomato initially grew well, but most plants died during the colder winter months, resulting in small amounts of green matter being incorporated. Broccoli produced the largest amount of green matter, followed by marigold, carrot, and strawberry, respectively (Table 1).

Average soil temperatures at 13 cm depth for the three years during the winter cropping period were 14.7, 15.7, and 17.3 °C, and during summer tomato were 23.6, 26.2 and 28.0 °C. Average soil temperatures at 13 cm depth under tarps ranged from 23 to 30°C over the three years, and were approximately 7°C higher than in non-tarped areas. Tarping raised the maximum temperatures by approximately 11°C.

Weed populations: Weed densities after removal of the plastic were relatively high in each year. In the first year, common purslane (*Portulaca oleracea*) was by far the most abundant weed species (> 90%). In the second and third years weeds consisted primarily of grasses. Weed densities were not affected by poultry litter [three year average with poultry litter 58%, without poultry litter 59% ($P > 0.05$)], but the different winter crops did affect weed densities (Table 2). Each year, broccoli

TABLE 2. Effect of cultivation and incorporation of winter-grown crops on estimated percentage weed coverage after removal of plastic tarp during a three-year field trial[a].

Winter Crop	Year 1	2	3	3 year average
	% weed coverage			
Fallow	48 (±5.7) abc[b]	85 (±3.0) a	76 (±1.6) a	70 (±3.6) a
Broccoli	19 (±8.4) d	60 (±7.0) b	37 (±4.0) c	39 (±4.9) c
Carrot	55 (±5.8) ab	79 (±4.8) a	58 (±4.7) ab	64 (±3.5) ab
Marigold	29 (±6.1) bcd	74 (±5.8) ab	52 (±5.7) bc	52 (±4.7) bc
Strawberry	58 (±6.3) a	81 (±3.5) a	68 (±3.6) ab	69 (±3.1) a
Tomato	25 (±9.9) cd	84 (±4.0) a	60 (±7.1) ab	56 (±6.1) ab

[a] Poultry litter amendment treatment did not have a significant effect ($P > 0.05$), therefore plots with and without poultry litter were combined for analysis.
[b] Values shown are the mean of ten replicates (n = 10) ± SE. Values in a column followed by different letters are significantly different ($P \leq 0.05$) according to Fisher's LSD-test.

significantly reduced weed densities compared to the fallow control. Averaged over the three years, broccoli and marigold resulted in significantly lower weed densities than in the fallow control (Table 2).

Meloidogyne incognita J2 *population levels and tomato root-galling*: At the start of the trial, *M. incognita* J2 population levels were low (average 6 J2/100g soil) and not significantly different among the treatments. In each year, the populations dramatically increased under susceptible summer tomato, declined under the winter-grown crops, and then declined further during the 6-wk tarping period (Table 3). Poultry litter did not affect *M. incognita* J2 population levels. The different winter-grown crops also failed to cause large or consistent effects on J2 population levels, and only three times were J2 population levels in the winter-grown crops significantly different from the fallow control. There were fewer nematodes in broccoli in March and May in year three and in tomato in March of year two compared to the fallow control (Table 3).

Galling caused by *M. incognita* on summer tomato was substantial, particularly in years two and three. There was no significant interaction between the winter-grown crop and poultry litter amendment, therefore the data was averaged over plus and minus poultry litter. In each year, the winter-grown crops affected the severity of galling on the following summer tomato crop. Galling on summer tomato was always lowest after broccoli, and significantly less than the fallow control in each year of the trial (Table 4). Other differences with the fallow control were in the first year, when the resistant tomato lowered galling, and in the third year when marigold lowered galling on the following susceptible tomato. Averaged over the three years, summer tomatoes following broccoli had significantly less galling than the other treatments. Amending soil with poultry litter did not affect galling in the first two growing seasons, but significantly increased galling in the third year. Averaged over the three years, poultry litter did not have an effect on tomato galling (Table 5).

Tomato yield: Each year there were significant differences in tomato yields between the different winter-grown crops. Broccoli resulted in the highest tomato yield each year, and significantly increased the yield over the fallow control in years two and three. Averaged over the three year trial period, summer tomato following broccoli yielded significantly more fruit than any of the other treatments (Table 6). Yield data roughly reflected the data on tomato galling, as the treatment that resulted in the lowest gall rating (broccoli) gave the highest yields, and the treatment with the highest gall ratings (strawberry) resulted in the lowest yields. Amending soil with poultry litter significantly increased tomato yields in the first and third years (from 1.9 to 2.2 kg/plant, and from 2.2 to 2.4 kg/plant respectively), and this effect was independent of the winter-grown crop. Averaged over the three-year period,

TABLE 3. Effect of winter-grown crops on soil population densities of second-stage *Meloidogyne incognita* juveniles (J2) per 100 g soil during a three-year field trial[a].

Winter Crop		Year								
		1			2			3		
	Sept (Pi)[b]	Mar	May	Sept	Mar	May	Sept	Mar	May	Sept
	M. incognita J2/100 g soil									
Fallow	7 (±3) a[c]	4 (±3) a	1 (±0) a	1449 (±519) ab	135 (±27) ab	11 (±2) a	1358 (±313) ab	35 (±7) a	4 (±1) ab	695 (±160) a
Broccoli	10 (±6) a	1 (±1) a	7 (±7) a	569 (±317) b	84 (±22) abc	7 (±2) a	1360 (±172) a	9 (±3) b	0 (±0) c	498 (±148) a
Carrot	6 (±4) a	2 (±1) a	2 (±2) a	2126 (±576) a	57 (±11) bc	11 (±2) a	1218 (±227) ab	17 (±4) a	7 (±3) a	613 (±131) a
Marigold	4 (±2) a	1 (±0) a	1 (±0) a	1890 (±448) a	104 (±24) abc	8 (±2) a	703 (±98) b	29 (±12) a	1 (±0) bc	638 (±113) a
Strawberry	8 (±3) a	2 (±1) a	0 (±0) a	2053 (±590) a	267 (±104) a	15 (±4) a	688 (±102) b	37 (±10) a	2 (±1) abc	503 (±108) a
Tomato	2 (±1) a	1 (±0) a	1 (±0) a	1088 (±446) ab	50 (±17) c	8 (±3) a	818 (±153) ab	27 (±6) a	3 (±1) abc	365 (±104) a

[a] Poultry litter amendment treatment did not have a significant effect ($P > 0.05$), therefore plots with and without poultry litter were combined for analysis.
[b] September samples were collected at harvest of susceptible summer tomato, March samples were collected at harvest of winter-grown crop, and May samples were collected after winter-grown crop incorporation and 6-wk tarping but prior to summer tomato planting.
[c] Values shown are the mean of ten replicates (n = 10) ± SE. Values in a column followed by different letters are significantly different ($P \le 0.05$) according to Fisher's LSD-test. Raw data (nematode counts) were $\log_{10}(x+1)$-transformed prior to analysis; non-transformed data are presented.

TABLE 4. Effect of cultivation and incorporation of winter-grown crops on the root galling of summer tomato by *Meliodogyne incognita* during a three-year field trial[a].

Winter Crop	Year 1	Year 2	Year 3	3 year average
	gall rating[b]			
Fallow	5.7 (±0.4) a[c]	7.7 (±0.1) a	6.4 (±0.5) a	6.6 (±0.2) ab
Broccoli	2.2 (±0.5) b	5.9 (±0.3) b	4.4 (±0.4) b	4.2 (±0.3) c
Carrot	5.7 (±0.4) a	7.7 (±0.2) a	5.9 (±0.6) ab	6.5 (±0.3) ab
Marigold	4.8 (±0.3) a	7.8 (±0.1) a	4.6 (±0.4) b	5.7 (±0.3) b
Strawberry	6.1 (±0.4) a	7.8 (±0.2) a	7.0 (±0.2) a	7.0 (±0.2) a
Tomato	3.2 (±0.5) b	7.5 (±0.4) a	6.4 (±0.5) a	5.7 (±0.4) b

[a] There was no significant interactive effect ($P > 0.05$) between the poultry litter amendment treatment and the winter crop treatment, therefore plots with and without poultry litter were combined for analysis.
[b] Galling index from 0 = no galling to 10 = 100% of root system galled.
[c] Values shown are the mean of ten replicates (n = 10) ± SE. Values in a column followed by different letters are significantly different ($P \leq 0.05$) according to Fisher's LSD-test.

poultry litter significantly increased yields from 2.0 to 2.1 kg/plant.

DISCUSSION

Meloidogyne incognita J2 population densities were generally not different at harvest of the different winter-grown crops and declined to similar levels both under a host crop (carrot), a nematode-resistant crop (tomato), or an antagonistic crop (marigold). Average soil temperatures at 13 cm depth during the winter period for the three years were 14.7, 15.7, and 17.3°C. Studies on temperature requirements for *M. incognita* activity and reproduction showed that motility and root penetration of J2 was very limited below 18°C, and consequently that reproduction below this temperature also was very low (Ploeg and Maris, 1999a; Roberts et al., 1981; Roberts, 1987). Thus, it is not surprising that the populations did not increase under the carrot host. The failure of marigolds to reduce *M. incognita* J2 populations could also be attributed to the low soil temperatures, as it was suggested that the nematodes need to be active for the antagonistic effect to occur (Ploeg and Maris, 1999b). In the absence of a host, in this study the fallow and strawberry treatments, overwintering populations of *M. incognita* usually decline, but survive as J2 and eggs in the soil (Jeger et al., 1993), which explains why population levels never declined to zero under these two treatments. Nematode populations declined further during the tarping period, but generally were not different among treatments. Stepanyan and Ploeg (2001) evaluated the host status of several weed species common in Southern California for *M. incognita*, and found that grasses in general were poor or non-hosts, but that common purslane was a moderately good host. However, this study did not show that common purslane, the most common weed at time of removal of the plastic tarp in the first year, resulted in an *M. incognita* increase.

Brassicas have been suggested to be particularly effective as biofumigants (Kirkegaard and Matthiessen, 2004), and although results in this study suggest that this may be true with respect to inhibition of weeds, incorporating broccoli residue was no more effective in lowering *M. incognita* J2 populations than the other treatments. Others (Chindo and Khan, 1990; Kaplan and Noe, 1993; Riegel et al., 1996) have reported that amending soil with poultry litter reduced *Meloidogyne* spp. populations in soil or infection of a susceptible crop. The mode-of-action of poultry litter or chicken manure is thought to be based primarily on the release of toxic levels of ammonium and on stimulation of nematode-antagonistic fungi and bacteria (Lazarovits et al., 2001; Riegel et al., 1996; Riegel and Noe, 2000). In our trial, we did not observe a clear impact of amending soil with poultry litter on *M. incognita* populations in soil, or on galling of a subsequently grown susceptible tomato crop. Similar results were obtained by Everts et al. (2006). In their three-year field trial, amending a sorghum sudangrass cover crop with poultry

TABLE 5. Effect of poultry litter amendment on root galling caused by *Meloidogyne incognita* of summer tomato during a three-year field trial.

Poultry litter	Year 1	Year 2	Year 3	3 year average
	gall rating[b]			
Yes	4.5 (±0.36) a[b]	7.4 (±0.21) a	6.1 (±0.32) a	6.0 (±0.21) a
No	4.7 (±0.39) a	7.3 (±0.18) a	5.5 (±0.31) b	5.8 (±0.21) a

[a] Galling index from 0 = no galling to 10 = 100% of root system galled.
[b] Values shown are the mean of 30 replicates (n = 30) ± SE. Values in a column followed by different letters are significantly different ($P \leq 0.05$) according to Fisher's LSD-test.

TABLE 6. Effect of cultivation and incorporation of winter-grown crops on the yield of following summer tomato during a three-year field trial[a].

Winter Crop	Year			
	1	2	3	3 year average
	-kg fruit / plant-			
Fallow	2.10 (±0.20) ab[b]	1.71(±0.08) b	2.36 (±0.10) b	2.06 (±0.09) b
Broccoli	2.52 (±0.12) a	2.33 (±0.16) a	2.71 (±0.08) a	2.52 (±0.08) a
Carrot	1.90 (±0.22) b	1.65 (±0.07) b	2.23 (±0.18) b	1.93 (±0.10) b
Marigold	2.17 (±0.13) ab	1.60 (±0.07) b	2.14 (±0.06) b	1.97 (±0.07) b
Strawberry	1.77 (±0.15) b	1.60 (±0.07) b	2.14 (±0.07) b	1.84 (±0.07) b
Tomato	1.97 (±0.17) b	1.73 (±0.09) b	2.24 (±0.11) b	1.98 (±0.08) b

[a] There was no significant interactive effect ($P > 0.05$) between the poultry litter amendment treatment and the winter crop treatment, therefore plots with and without poultry litter were combined for analysis.
[b] Values shown are the mean of ten replicates (n = 10) ± SE. Values in a column followed by different letters are significantly different ($P \leq 0.05$) according to Fisher's LSD-test.

litter did not result in additional suppression of *M. incognita*. In an earlier greenhouse pot trial we concluded that amending *M. incognita*-infested soil with chicken manure was effective in lowering galling and infestation of tomato grown in this soil, when soil temperatures increased from 20 to 25 to 30°C (López-Pérez et al., 2005). Although in this field trial the soil temperatures after the poultry litter amendment under the plastic tarp ranged between 23-30°C for the three years, the positive effects seen in the previous pot trials were not observed here. The variability in results between different studies involving organic amendments and nematode control has been attributed to differences in environmental conditions, particularly the soil environment. Thus, the composition and level of the native soil microbial community, which includes nematode-antagonistic organisms, probably plays an important role in the level of nematode control that can be achieved by amending soil with organic material such as poultry litter (MacGuidwin and Lane, 1995; Evers et al., 2006).

Although there were no direct effects of the different winter-grown crops on soil *M. incognita* population levels, the crops did result in differences in the severity of galling on the subsequent summer tomato crop. Preceding tomato by broccoli resulted in the lowest galling, but differences among the other winter-grown crops were not consistent over the three-year period. Thus, although J2 population levels after broccoli at planting of summer tomato were generally not lower than in the other treatments, broccoli did reduce galling. Furthermore, averaged over the three-year trial, broccoli also significantly increased tomato yields over the other treatments.

This suggests that cultivating and incorporating broccoli had a nematostatic rather than a direct nematicidal effect, reducing the infectivity of the remaining *M. incognita* population, possibly by interfering with the nematodes' ability to migrate to, or penetrate into the tomato roots. This hypothesis is supported by a recent study (Zasada et al., 2009) that showed that activity and infectivity of *M. incognita* J2 exposed to sublethal levels of benzyl isothiocyanate, a product from degradation of brassicaceous plant material, was reduced. It is unlikely that the effect can be attributed simply to the greater amount of biomass that was incorporated after broccoli, as there was no obvious relation between amounts of organic matter incorporated and galling for the other treatments. In a pot study, López-Pérez et al. (2005) also showed that incorporating broccoli tissue was more effective in protecting tomato against *M. incognita* than using tomato or melon tissue at a soil temperature of 25°C. The exact mechanism by which decomposing brassica tissue reduces plant-parasitic nematode damage remains unknown. For example, Kirkegaard and Matthiesen (2004) refer to nematodes as an example where amounts of glucosinolates in brassicaceous tissue often do not predict the efficacy of the crop for nematode control, and suggest that non-glucosinolate toxic compounds or indirect effects such as an increase in nematode antagonist populations may play an important role.

Amending soil with poultry litter resulted in higher tomato yields in two of the three years and when averaged over the three-year period, but since it did not affect galling or *M. incognita* populations, this can probably be attributed to the extra nitrogen input. Everts et al. (2006) who obtained similar results, also attributed higher yields associated with poultry litter amendment to increased nutrient levels.

This study showed that winter-grown broccoli, followed by incorporating the crop residue into the soil, benefited a following *M. incognita*-susceptible vegetable crop. When grown during the cool season when average soil temperatures are expected to remain close to or below 18°C, the risk of increasing *M. incognita* populations is low, even under suitable host crops. However, to further increase the potential and flexibility of brassicas as crops that can be used in the management of *Meloidogyne* spp., research should focus on identifying crop cultivars that have high nematode-suppressive efficacy and are non-hosts or resistant to the target nematodes. In addition to potentially reducing *M. incognita* damage, benefits of winter-grown cover crops such as improved soil structure and water infiltration, and reduced winter runoff, soil erosion, and nutrient loss have been reported (Hartz et al., 2005).

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