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Grafting and Paladin Pic-21 for Nematode and Weed Management in Vegetable Production

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Abstract: Two years of field trials conducted in a *Meloidogyne incognita*-infested field evaluated grafting and Paladin Pic-21 (dimethyl disulfide:chloropicrin [DMDS:Pic] 79:21) for root-knot nematode and weed control in tomato and melon. Tomato rootstocks evaluated were; 'TX301', 'Multifort', and 'Aloha'. 'Florida 47' was the scion and the nongrafted control. A double crop of melon was planted into existing beds following tomato harvest. Melon rootstocks, *C. metulifer* and 'Tetsukabuto', were evaluated with nongrafted 'Athena' in year 1. In year 2, watermelon followed tomato with scion variety 'Tri-X Palomar' as the control and also grafted onto 'Emphasis' and 'Strongtosa' rootstocks. Four soil treatments were applied in fall both years under Canslit metalized film; Paladin Pic-21, methyl bromide:chloropicrin (MeBr:C33, 67:33), Midas (iodomethane:chloropicrin 50:50), and a herbicide-treated control. *M. incognita* J_2 in soil were highest in herbicide control plots and nongrafted tomato. All soil treatments produced similar tomato growth, which was greater than the herbicide control. All treatments reduced *M. incognita* J_2 in roots compared to the herbicide control. 'Multifort' rootstock produced the largest and healthiest roots; however, the number of *M. incognita* isolated from roots did not differ among the tomato rootstocks tested. Galling on tomato was highest in herbicide control plots and nongrafted plants. In melon, *M. incognita* J_2 in soil did not differ among melon rootstocks, but numbers isolated from melon rootstocks increased in 'Tetsukabuto' compared with *C. metuliferus*. 'Tetsukabuto' were larger root systems than nongrafted 'Athena'. All fumigants provided protection for all melon rootstocks against galling by *M. incognita* compared to the herbicide control. Galling on *C. metuliferus* rootstock was less in all fumigant treatments compared with nongrafted 'Athena' and 'Tetsukabuto'. In watermelon, *M. incognita* in soil and roots did not differ among soil treatments or watermelon rootstocks, and yield was lower in both grafted rootstocks compared with the nongrafted control. All soil treatments increased average fruit weight of watermelon compared with the herbicide control, and provided effective weed control, keeping the most predominant weed, purple nutsedge (*Cyperus rotundus* L.), density at or below 1/m row. Grafting commercial scions onto *M. incognita*-resistant rootstocks has potential for nematode management combined with soil treatments or as a stand-alone component in crop production systems.
Key words: dimethyl disulfide, *Meloidogyne incognita*, methyl bromide, root-knot nematodes.

Research focus has begun to shift from single tactic chemical fumigant controls for pathogenic nematodes and weeds to combinations of approaches which include more environmentally sustainable practices including grafting. The soil fumigant methyl bromide (MeBr) has been replaced by other products including dimethyl disulfide and allyl isothiocyanate for nematode and weed control in high-value vegetable production in Florida (Kokalis-Burelle et al., 2014). In order for soil treatments to remain commercially viable in the current regulatory environment, they must remain commercially available, be highly efficacious in controlling soilborne pests (comparable to MeBr), have no negative impact on yield, and be economically feasible (Rosskopf et al., 2005; Jacoby, 2012; Belova et al., 2013). Meta-analysis on 78 studies comparing MeBr fumigation, a chemical alternative, and an untreated control treatment determined that various MeBr alternatives were comparable to MeBr for strawberry production in CA and Spain (Belova et al., 2013). Results were inconclusive for tomato and strawberry production in FL. However, only studies that compared MeBr to other chemical fumigants or various formulations were evaluated, while studies that included nonchemical treatments and combinations of alternatives and nonchemical treatments were omitted. The discrepancy observed in Florida could highlight the possibility that approaches that focus on a drop-in replacement for MeBr are not sufficient (Yates et al., 2002).

Grafting of vegetable crops to control plant diseases has been practiced for centuries in Asia (Kubota et al., 2008), and has been used for tomato production in Mediterranean regions for nematode and soilborne pathogen control (Besri, 2007). This approach has potential to provide resistance to multiple soilborne pathogens, and resistant rootstocks can be coupled with currently available commercial scion cultivars. Sources of resistant rootstocks include closely related species, hybrids, and weeds. Although root-knot nematode resistance has not yet been identified in melons (*Cucumis melo*), *C. metuliferus* E. Mey. Ex Naud. and hybrids of *C. melo* L. and *C. metuliferus* have proven to be good candidates for root-knot nematode resistant rootstocks suitable for grafting onto commercial melon cultivars (Igarashi et al., 1987, cited in Kubota et al., 2008; Sigüenza et al., 2005). Attempts to incorporate this nematode resistance into *C. melo* using traditional plant breeding approaches have not been successful (Chen and Adelberg, 2000). Thies and Levi (2007) found that wild watermelon lines (*Citrullus lanatus* [Thunb.] Matsum. & Nakai var. *citroides* [L.H. Bailery] Mansf.), and a commercial wild watermelon rootstock (*C. lanatus*) had significantly less galling than 'Fiesta' a diploid seeded watermelon, the squash hybrid rootstock *Cucurbita moschata* Duchesne × *C. maxima* Duchesne, and bottle gourd rootstocks. Further work by Thies et al.

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(2010) confirmed that wild watermelon germplasm derived from *C. lanatus* var. *citroides* may be useful as rootstocks for managing root-knot nematodes in watermelon. Other commercial rootstocks available for use with seedless watermelons include a Lagenaria-type 'Emphasis', and an interspecific squash hybrid type 'Strong Tosa' (Syngenta Seeds, Inc.).

Previous research on vegetable grafting for root-knot nematode control includes greenhouse and microplot trials conducted over a 3-yr period to evaluate bell pepper (*Capsicum annuum* L.), tomato (*Solanum lycopersicum* L.), melon (*C. melo* L.), and watermelon (*C. lanatus*) for *Meloidogyne incognita* (Kofoid & White) Chit. management. In bell pepper, several rootstocks were identified as either consistently resistant to galling by *M. incognita*, or consistently susceptible to galling (Kokalis-Burelle et al., 2009). In 2 yr of microplot studies, *M. incognita* J_2 in soil were similar among all tomato rootstocks, but J_2 in roots were increased in the nongrafted 'Florida 47' when compared to all grafted rootstocks. In melon, only *C. metuliferus* rootstock reduced galling in nematode-infested soil. 'Tetsukabuto' did not reduce numbers of *M. incognita* J_2 in either soil or roots either year. There were no differences in nematode numbers, galling, or plant growth among watermelon rootstocks tested (Kokalis-Burelle and Rosskopf, 2010).

Combining grafting with other approaches for nematode and pathogen control and yield enhancement is practiced in Spain and Morocco, where grafted plants are used in conjunction with other strategies including alternative fumigants, solarization, and biofumigation (Besri, 2007). The objective of this project was to evaluate grafting in combination with the soil fumigant Paladin Pic-21, and to compare results with previous industry standard fumigants and nongrafted plants for management of root-knot nematodes (*M. incognita*) and weeds in tomato and melon double-crop production in Florida.

Materials and Methods

Experimental design

Field trials were conducted at the USDA-ARS farm in Fort Pierce, FL, in a location infested with *M. incognita*. Soil at the site was Oldsmar sand. A split plot experiment with four replications was used to evaluate rootstock/scion combinations in fumigated and herbicide-only treated soil. The herbicide-only treatment will be referred to as the herbicide control, and was included in order to enable the production of crops by controlling weeds in the nonfumigated plots, and to assess the effect of grafting on *M. incognita* without a soil fumigant treatment. No additional herbicides or soil pesticides were applied to plots receiving fumigant treatments. Four soil treatments were applied under metalized film (32 μm thick, silver on white, Canslit, Inc. Montreal, Quebec, Canada). Treatments were dimethyl disulfide with chloropicrin (468 L/ha, 79:21 Paladin Pic-21 [DMDS:chloropicrin], Arkema, Colombes Cedex, France), MeBr with chloropicrin (MeBr:C33) 225 kg/ha, 67:33 methyl bromide:chloropicrin; TriEst Ag Group, Inc, Palmetto, FL), iodomethane with chloropicrin (IM:C50) (112 kg/ha, 50:50 iodomethane:chloropicrin, Midas, Arysta LifeScience Corp. no longer registered in the United States), and the herbicide control described below. Fertilizer (15–0–25 N–P–K) was broadcast applied to the field before bed formation. All soil fumigants were applied to pre-formed beds at 30-cm depth using a standard, nitrogen-pressurized fumigation rig with three chisels per bed. Immediately following the injected fumigant, beds were reformed. The herbicide-only treatment was applied to formed beds using a CO_2 powered, tractor-mounted sprayer with an 8004 flat-fan nozzle and beds were covered with film without incorporation. The herbicide combination included: S-metolachlor (Dual Magnum, Syngenta Crop Protection, 1.4 L/ha); rimsulfuron (Matrix, DuPont 140 ml/ha); and halosulfuron (Sandea, Gowan Co. 35 ml/ha). Bed areas were marked and soil treatments were applied in the same manner to the same areas for the second year of trials.

Subplot treatments in the primary tomato crop consisted of 'Florida 47' (Asgrow Seed, Monsanto Co., St. Louis, MO) as the scion grafted onto three rootstocks reported to be resistant to *M. incognita;* 'TX301', (Syngenta Seeds, Wilmington, DE), 'Multifort' (De Ruiter Seeds, Lakewood, CO), and 'Aloha' (American Takii Seed, Salinas, CA), and the nongrafted scion, 'Florida 47'. Main plots were 30-m long and were split into 7.6-m subplots for each tomato rootstock.

In year 1, a double crop of melon (*C. melo*) was planted into the existing beds following the first tomato crop, which was physically removed after harvest. Two melon rootstocks; *C. metulifer* (Trade Wind Fruit Co.), and 'Tetsukabuto' (*C. maxima* × *C. moschata*), (Takii Seed, Salinas, CA), were grafted with 'Athena' (Syngenta Seeds, Inc., Rogers Brand Vegetable Seeds, Boise, ID) as the scion. 'Athena' was also evaluated as the nongrafted control. Three melon plants on each rootstock were planted into subplots previously planted with the four tomato rootstocks in each of the fumigant treatments.

In year 2, watermelon was substituted for melon due to the unavailability of grafted melon. Watermelon variety 'TriX Palomar' (Syngenta Seeds, Inc., Rogers Brand Vegetable Seeds, Boise, ID) was used as the scion and the nongrafted control. Watermelon rootstocks evaluated were 'Emphasis' (Syngenta Seeds, Inc., Rogers Brand Vegetable Seeds, Boise, ID), a Lagenaria hybrid rootstock used for grafting seedless watermelon, and 'StrongTosa' (Syngenta Seeds, Inc., Rogers Brand Vegetable Seeds, Boise, ID), an interspecific squash hybrid (*C. moschata* × *C. maxima*) used for grafting watermelon and specialty melons. Grafted watermelon seedlings were provided by the Full Count program from Syngenta Seeds. Tomato, melon, and watermelon crops were managed using recommended commercial practices for Florida tomato and melon production.

Grafted plant production

For the first year of trials, grafted tomato and melon plants were purchased from a commercial production house (Speedling Inc., Alamo, TX). Transplants for the second year of trials were produced at the USDA facility in Ft. Pierce, FL. Grafted watermelon transplants for the second year of trials were supplied by Rogers Brand Vegetable Seeds (Syngenta Seeds, Inc., Boise, ID). Second year tomato scion and rootstock seedlings were germinated in 128-cell trays in a peat-based potting media. Grafting was performed when the plants had two to three true leaves. Seedlings were grafted using the tube grafting method (Rivard and Louws, 2006; Kubota et al., 2008). Grafting was performed by hand when seedlings reached the two to three true leaf stage. Immediately after grafting, seedlings were placed in a high humidity (approximately 95%) healing chamber, at 75° C, in the dark for 24 hr, followed by 7 days with 12 hr of light and 12 hr of dark. Grafted seedlings were then moved to the greenhouse for 7 days, followed by a 2- to 4-day hardening period outside of the greenhouse before planting in the field.

Nematode, weed, and disease assessments

All treatments were assessed for plant growth, root disease, soil and root nematode populations, weed emergence and season-end weed biomass, and marketable yield. Weeds emerging through planting holes and plastic for a 30-m area in each plot were counted and identified to species. Above-ground weed biomass was collected at harvest in each year and weighed.

Data on soil nematode populations, gall ratings, and plant growth were collected from 4, 1-m long sample areas within each replication. Nematode populations in soil were assessed immediately before fumigation, and at approximately 2, 10, and 16 wk after fumigation. Ten 15-cm soil cores were taken in each plot using a 1.75-cm-diam. soil probe and combined. A 100-cm^3 subsample was used for nematode extraction. Nematodes were extracted from both soil and roots using the Baermann funnel technique and *Meloidogyne* spp. and nonparasitic (microbivorous and predatory) nematodes identified. Gravid females were extracted from roots and identified based on enzyme phenotypes as *M. incognita* using the Phast system (GE Healthcare Bio-Sciences Corp., Piscataway, NJ) (Esbenshade and Triantaphyllou, 1985; 1990). At 16 wk after fumigation, plants were destructively sampled. Roots were evaluated for galling and root condition, and nematodes were extracted from roots. Plant growth measurements, including shoot weight and root weight were recorded. Root condition ratings were used as an indicator of root disease on a scale 0 to 5 with 0 to 1.0 = 0% to 20% discolored roots, 1.0 to 2.0 = 21% to 40%, 2.0 to 3.0 = 41% to 60%, 3.0 to 4.0 = 61% to 80%, and 4.0 to 5.0 = 81% to 100%. Root galling was assessed using a root gall index based on a scale of 0 to 10, with 0 representing no galls and 10 representing severe (100%) galling (Bridge and Page, 1980).

Yield assessments

Tomatoes were harvested three times during each season from 10 marked plants in each plot. Total number of fruit, total weight per fruit, average size (mm), and color class (http://www.floridatomatoes.org/retail/tastier-tomatoes/), with fruit picked at breaker stage and riper was recorded. Melons were harvested at half-slip and total number of fruit and individual fruit weights were recorded.

Statistical analysis

Data were statistically analyzed according to standard procedures including SAS analysis of variance (ANOVA) and least significant difference (SAS Institute, Cary, NC). Disease incidence data were arcsin square root transformed before analysis to meet model assumptions for normality. All other data were analyzed with mixed models ANOVA using the PROC MIXED procedure in SAS for either a randomized complete block or a split-plot design. Plant growth, disease assessments, nematodes data, yield, and weed data constituted random variables, while soil treatment and rootstocks constituted fixed variables. Unless otherwise stated, all differences referred to in the text were significant at the 5% level of probability.

Results

Year 1 tomato

Root-knot nematode and nonparasitic nematodes in soil did not differ among soil treatments in either the postfumigation sample or the midseason sample. No *M. incognita* were isolated from soil at either sampling time, while nonparasitic nematodes ranged between 100 and 300 nematodes/100 cm^3 soil (data not presented). *M. incognita* and nonparasitic nematode numbers in soil did not differ among tomato rootstocks early in the season (data not presented).

Paladin Pic-21 was similar to MeBr:C33 for most plant growth variables measured (Table 1). All soil treatments produced larger tomato root systems than the herbicide control (Table 1), and reduced numbers of *M. incognita* isolated from roots at the end of the season (Table 1). There were no differences among soil treatments or rootstocks for nonparasitic nematodes in soil at the end of the season (data not presented). 'Multifort' and 'TX-301 rootstocks were the largest and 'Multifort' had less root discoloration as measured by root condition ratings (Table 1).

Galling by *M. incognita* was highest in the herbicide control plots planted with nongrafted Florida 47 tomatoes (Fig. 1). Interactions occurred between soil

TABLE 1. Effect of soil treatments and rootstock on grafted tomato plant growth, nematode populations, and root disease in year 1.

Soil treatment	*M. incognita* (J_2/g root)	Nonparasitic (No./g root)	Height (cm)	Diameter (mm)	Shoot weight(kg)	Root weight (g)	Root condition[a]
Herbicide control	3.89 a	11.63 ab	71.22 b[b]	14.14 c	1.36 b	34.20 b	0.08 b
Paladin Pic-21	0.00 b	15.80 a	78.82 a	16.00 b	1.62 a	40.08 a	0.28 a
MeBr:C33	0.00 b	5.17 b	82.24 a	17.55 a	1.62 a	38.21 a	0.43 a
Midas	0.00 b	8.84 b	78.62 a	16.11 b	1.61 a	39.61 a	0.10 b
LSD (0.05)	2.94	6.87	4.31	1.08	0.20	3.27	0.16
Rootstock							
Nongrafted 'Florida 47'	2.16 a	10.23 b	75.75 b	14.45 b	1.45 bc	33.91 b	0.33 a
'TX301'	1.52 a	6.58 b	78.94 b	16.18 a	1.63 ab	41.78 a	0.21 ab
'Multifort'	0.10 a	5.89 b	85.99 a	17.02 a	1.81 a	40.05 a	0.08 b
'Aloha'	0.10 a	18.73 a	70.22 c	16.15 a	1.33 c	36.35 b	0.27 a
LSD (0.05)	2.94	6.87	4.31	1.08	0.20	3.27	0.16

[a] Root Condition rating: 0 to 1.0 = 0% to 20% discolored roots, 1.0 to 2.0 = 21% to 40%, 2.0 to 3.0 = 41% to 60%, 3.0 to 4.0 = 61% to 80%, and 4.0 to 5.0 = 81% to 100% of the root system is diseased and/or necrotic.
[b] Means with the same letter are not significantly different at $P \leq 0.05$.

treatments and rootstocks with regard to galling by *M. incognita*. The highest level of root galling occurred in herbicide control plots and in subplots containing nongrafted plants. 'Multifort' and 'Aloha' rootstocks in herbicide control plots had lower gall index values the nongrafted 'Florida 47'. No differences in galling occurred among rootstocks in treated soils (data not presented).

The number of purple nutsedge (*Cyperus rotundus*) emerging through the plastic was low, but was significantly different between fumigant/herbicide control treatments ($P = 0.0027$) with Paladin Pic-21, MeBr:C33, and the herbicide control treatment all being equivalent with <1 purple nutsedge shoot per 30 m of bed, and the Midas treatment averaging 1 shoot for every 30 m of bed.

Yield of tomato in year 1 of the trials was highest in the Midas treatment as reflected in higher total number of fruit/plot and total fruit weight compared with the herbicide control (Fig. 2). Midas also had higher total fruit weight than MeBr:C33 (data not presented). There were no differences in total number of fruit/plot and total fruit weight/plot among the tomato rootstocks (data not presented).

Year 1 melon

When melon was planted into the same beds following tomato in the first year, vine growth was higher in all

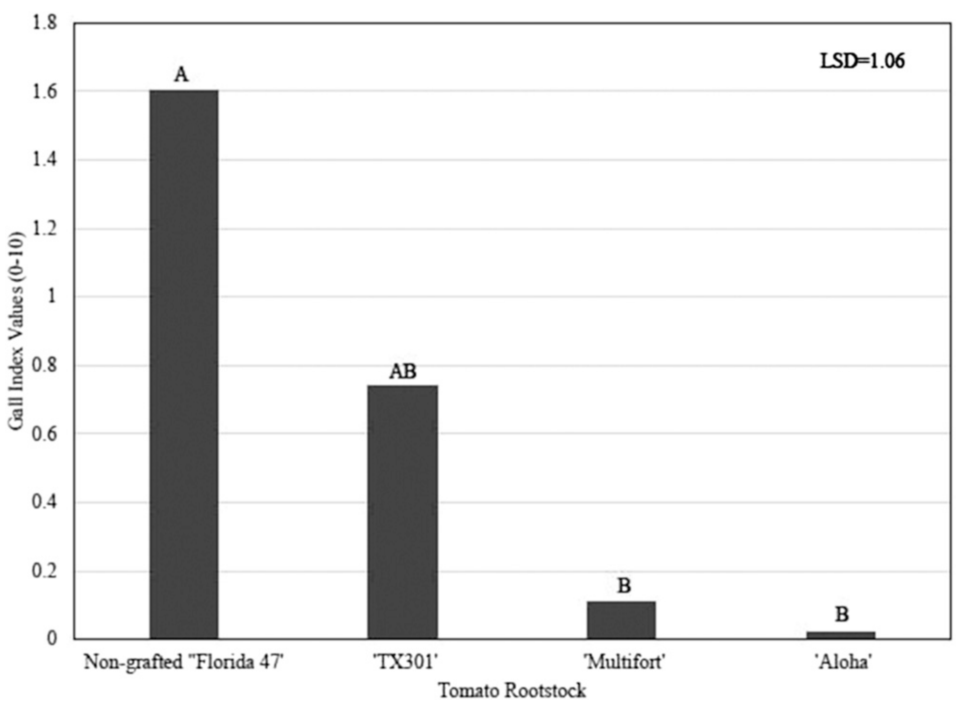

FIG. 1. Gall index values for tomato rootstocks in herbicide only treated control plots in year 1. Gall rating scale (0-10): 0 = no galling and 10 = root system completely galled (Bridge and Page, 1980). Bars with the same letter are not significantly different at $P \leq 0.05$.

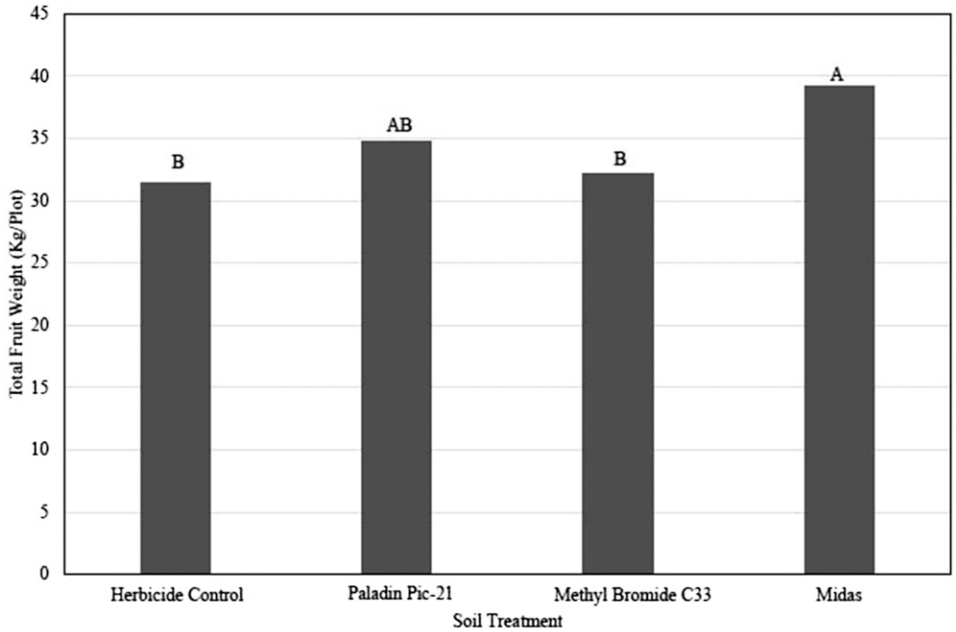

FIG. 2. Tomato yield in year 1 in response to soil treatments. Bars with the same letter are not significantly different at $P \leq 0.05$. Yield did not differ among tomato rootstocks tested.

soil treatments early in the season compared to the herbicide control, and *C. metuliferus* exhibited the most growth of the rootstocks tested (data not presented). At the end of the season, there were no differences among soil treatments for *M. incognita* in soil or melon plant root weight (Table 2). The number of *M. incognita* J_2 isolated from melon roots was reduced with Paladin Pic-21 compared with the herbicide control (Table 2). Nonparasitic nematodes were more abundant in roots and soil in the herbicide control than all other soil treatments at the end of the season (Table 2). *C. metuliferus* rootstock increased vine length early in the season compared with the nongrafted 'Athena' and 'Tetsukabuto' (data not presented), and had fewer *M. incognita* J_2 in soil compared with nongrafted 'Athena', and fewer *M. incognita* J_2 isolated from roots than 'Tetsukabuto' (Table 2). *C. metuliferus* rootstock reduced galling in all soil treatments (Table 3) and improved root condition ratings in the herbicide control and MeBr:C33 soil treatments (Table 3). 'Tetsukabuto' did not reduce galling compared to the nongrafted 'Athena' (Table 3). Paladin Pic-21 had the lowest gall rates of all the soil treatments tested. All soil treatments increased melon yield compared to the herbicide control plots, whereas both melon rootstocks increased yield compared to nongrafted 'Athena' plants (Fig. 3).

Soil treatment had a significant effect on purple nutsedge emerged through the plastic ($P = 0.0448$), bedstraw (*Galium aparine* L.; $P = 0.0306$) and Florida pusley (*Richardia scabra* L.; $P = 0.0079$) in the planting holes. Although statistically greater in the herbicide control, weed density was low with less than 1 nutsedge shoot or weed in a plant hole per 30-m bed. Melon rootstock had no effect on weeds.

Year 2 tomato

Soil treatments and rootstocks were placed in the same location in the fall of year 2 as in the fall of year 1,

TABLE 2. Effect of soil treatments and rootstock on plant growth, nematode populations in soil, and roots of grafted melon in year 1.

Soil treatment	*M. incognita* (J_2/100 cm^3 soil)	Nonparasitic (No./100 cm^3 soil)	Root Weight (g)	*M. incognita* (J_2/g root)	Nonparasitic (No./g root)
Herbicide control	115.76 a[a]	1723.7 a	28.70 a	9.37 a	286.36 a
Paladin Pic-21	43.63 a	368.6 b	16.09 a	1.02 b	34.93 b
MeBr:C33	205.18 a	419.3 b	27.48 a	4.46 ab	39.55 b
Midas	33.04 a	529.9 b	27.98 a	6.17 ab	57.12 b
LSD (0.05)	179.93	697.99	12.82	7.16	124.18
Rootstock					
Nongrafted 'Athena'	187.09 a	1241.4 a	19.44 b	5.12 ab	147.85 a
C. metuliferus	10.28 b	441.8 b	21.82 b	0.79 b	28.36 b
'Tetsukabuto'	100.84 ab	597.9 b	33.81 a	9.30 a	107.45 ab
LSD (0.05)	155.82	604.48	11.05	6.17	107.07

[a] Means with the same letter are not significantly different at $P \leq 0.05$.

TABLE 3. The effect of soil treatment on disease of melon cultivars in year 1. Due to significant interactions between soil treatment and rootstock.

Herbicide Control	Gall index[a]	Root condition[b]
Nongrafted 'Athena'	6.85 a[c]	3.69 a
C. metuliferus	2.72 b	2.20 b
'Tetsukabuto'	7.12 a	3.66 a
LSD (0.05)	1.33	0.62
Paladin Pic-21		
Nongrafted 'Athena'	0.93 a	1.39 a
C. metuliferus	0.11 b	1.47 a
'Tetsukabuto'	0.78 a	1.63 a
LSD (0.05)	0.66	0.25
MeBr:C33		
Nongrafted 'Athena'	1.38 a	1.43 ab
C. metuliferus	0.15 b	1.21 b
'Tetsukabuto'	1.04 a	1.63 a
LSD (0.05)	0.77	0.24
Midas		
Nongrafted 'Athena'	2.64 a	2.12 a
C. metuliferus	0.30 b	1.74 a
'Tetsukabuto'	2.41 a	1.93 a
LSD (0.05)	1.19	0.54

[a] Gall index scale (0-10): 0 = no galling and 10 = root system completely galled (Bridge and Page, 1980).
[b] Root Condition rating: 0 to 1.0 = 0% to 20% discolored roots, 1.0 to 2.0 = 21% to 40%, 2.0 to 3.0 = 41% to 60%, 3.0 to 4.0 = 61% to 80%, and 4.0 to 5.0 = 81% to 100% of the root system is diseased and/or necrotic.
[c] Means with the same letter are not significantly different at $P \leq 0.05$.

and soil treatments were reapplied before the tomato crop was planted. All soil treatments reduced *M. incognita* in soil at the end of the season compared to the herbicide control (Table 4). There were no additional effects of soil treatment on plant growth including stem diameter, shoot weight, root weight, or root condition (Table 4). However, Paladin Pic-21 had higher yield than the herbicide control, and 'Aloha had the highest yield compared to all other rootstocks and the nongrafted

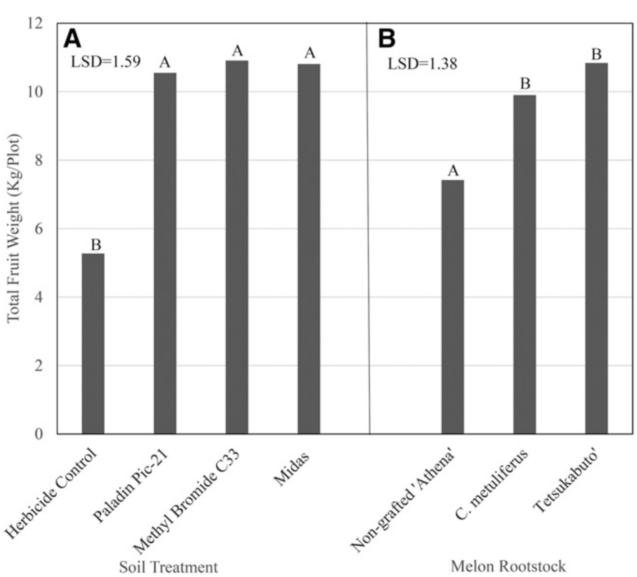

FIG. 3. Effects of soil treatment (3a), and rootstock (3b), on yield of grafted melon in year 1. Bars with the same letter are not significantly different at $P \leq 0.05$.

control (Table 4). However, 'Mutifort' rootstock did have a positive effect on plant growth and root condition compared with the nongrafted 'Florida 47' (Table 4). Paladin Pic-21 improved the number of fruit, and fruit weight per plant compared with the herbicide control, and 'Aloha' rootstock increased both of those yield parameters compared with nongrafted 'Florida 47' (Table 4).

For some variables, including plant height, *M. incognita* J_2/g root, root gall index, and average fruit size and weight, there were interactions among soil treatments and rootstocks (Table 5). When separated by tomato rootstock and soil treatment due to interactions between these factors, all soil treatments and rootstocks provide acceptable control of *M. incognita* J_2 in roots and galling at the end of the season with the exception of 'Florida 47' nongrafted plants in herbicide control plots (Table 5).

Midseason plant health ratings and stand counts showed that no differences occurred among soil treatments for wilted plants, virus symptoms, and plant vigor (data not presented). Also, no differences occurred in missing (dead) plants, wilted plants, virus symptoms, or plant vigor among rootstocks (data not presented). By the first harvest, bacterial wilt caused by *Ralstonia solanacearum* had spread farther than in the first year of tomato production, and was significantly influenced by treatment ($P = 0.0145$) with Midas having 22%, MeBr:C33 19%, herbicide control 11%, and Paladin Pic-21 with 6% of the plants wilted due to bacterial wilt. There was no effect of rootstock on the incidence of this disease.

Few weeds emerged during the second tomato season and for those that did, only Florida pusley was significantly different between soil treatments ($P = 0.0216$), with the herbicide control treatment having an average of 1.5 pusley plants per 30-m of bed, and the other soil treatments having none. All others weeds remained below 1 plant per 30 m.

Year 2 watermelon

None of the soil treatments applied before the fall tomato crop provided control of nematodes in soil early (data not presented) or late in the watermelon growing season (Table 6). Neither of the rootstocks tested for nematode control in watermelon reduced numbers of *M. incognita* J_2 in soil late in the season compared to the nongrafted 'Tri-X Palomar' control (Table 6). 'Emphasis' rootstock increased J_2 in soil compared to both the nongrafted control and 'Strongtosa' in the late-season sample (Table 6). Root weights did not differ among the soil treatments or rootstocks at harvest (data not presented). Soil treatment and watermelon rootstock had an impact on total fruit weight and average fruit weight of watermelon (Table 6). Highest yields of watermelon were achieved with MeBr:C33 as the soil treatment and nongrafted 'Tri-X Palomar' as the melon cultivar (Table 6). Nongrafted 'Tri-X Palomar' had overall higher yields than both grafted watermelons (Table 6). No differences occurred among soil treatments in *M. incognita* and

TABLE 4. Effect of soil treatments and rootstock on nematode populations in soil, plant growth, disease, and yield of grafted tomato at the end of the season in year 2.

Soil Treatment	*M. incognita* (J_2/100 cm^3 soil)	Nonparasitic (No./100 cm^3 soil)	Stem diameter (mm)	Shoot weight (kg)	Root weight (g)	Root condition[a]	Number of fruit/plant	Fruit weight/plant (kg)
Herbicide Control	9.21 a[b]	132.89 a	16.13 a	1.56 a	40.87 a	0.93 a	21.42 b	1.84 b
Paladin Pic-21	1.84 b	176.07 a	15.90 a	1.94 a	37.41 a	0.49 a	27.44 a	2.76 a
MeBr:C33	0.35 b	113.40 a	15.64 a	1.83 a	33.80 a	0.45 a	26.19 ab	2.55 ab
Midas	0.36 b	126.32 a	15.88 a	1.57 a	34.43 a	0.45 a	27.19 a	2.63 ab
Rootstock								
Nongrafted 'Florida 47'	5.68 a	131.28 ab	14.99 b	1.51 c	32.19 b	0.77 a	24.78 b	2.29 b
'TX301'	2.84 a	139.27 ab	15.72 ab	1.95 a	39.85 a	0.57 ab	24.00 b	2.13 b
'Multifort'	0.78 a	165.80 a	16.57 a	1.85 ab	38.49 a	0.41 b	24.21 b	2.12 b
'Aloha'	2.48 a	112.34 b	16.26 a	1.60 bc	35.99 ab	0.58 ab	29.25 a	3.24 a

[a] Root Condition rating: 0 to 1.0 = 0% to 20% discolored roots, 1.0 to 2.0 = 21% to 40%, 2.0 to 3.0 = 41% to 60%, 3.0 to 4.0 = 61% to 80%, and 4.0 to 5.0 = 81% to 100% of the root system is diseased and/or necrotic.
[b] Means with the same letter are not significantly different at $P \leq 0.05$.

non-parasitic nematode populations in soil late in the season sampling (Table 6). However, watermelon rootstock 'Emphasis' had significantly more *M. incognita* J_2 isolated from soil than the 'Tri-X Palomar' nongrafted control and 'Strongtosa' (Table 6).

There were no differences among the soil treatments or rootstocks with respect to the number of *M. incognita* J_2 isolated from watermelon roots, except in untreated soil, where more J_2 were isolated from 'Strongtosa' roots than from the nongrafted 'Tri-X Palomar' control (Fig. 4). There were no differences among the soil treatments or watermelon rootstocks with respect to the galling caused by *M. incognita* (data not presented).

Weed populations were effectively controlled by all of the soil treatments, with few significant differences. Nightshade (*S. americanum* Mill.; $P = 0.0314$), bedstraw ($P = 0.035$), and Florida pusley ($P < 0.0001$) were better controlled ($P \leq 0.05$) by the fumigant treatments than by the herbicide control treatment, but even this application resulted in only an average of two of each of these weeds in the melon plant hole per 30 m of bed. There were no significant differences in control of any of the grass weeds present, including southern crabgrass [*Digitaria ciliaris* (Rets.) Koeler] and goosegrass [*Eleusine indica* (L.) Gaertn.]. There were no differences attributable to soil treatment in the final weed fresh weights, averaging between 2 and 4 kg per plot at final watermelon harvest.

DISCUSSION

Although grafting of both tomatoes (Rivard et al., 2010; Kunwar, et al., 2014) and melons (Thies et al., 2010; Guan et al., 2013) has gained momentum in the

TABLE 5. Growth, disease, and yield of tomatoes in year 2 analyzed within each fumigant. Due to a significant interaction between fumigant and rootstock the data is presented accordingly.

	Plant height (cm)	*M. incognita* (J_2/g root)	Gall index[a]	Average fruit size (mm)	Average fruit weight (g)
Herbicide Control					
Nongrafted 'Florida 47'	71.51 ab[b]	35.81 a	2.86 a	71.85 ab	178.99 b
'TX301'	65.26 b	0.47 b	1.18 b	72.40 a	185.54 ab
'Multifort'	71.40 ab	0.23 b	0.33 b	70.80 b	170.18 c
'Aloha'	75.86 a	0.28 b	0.18 b	72.35 a	186.41 a
Paladin Pic-21					
Nongrafted 'Florida 47'	73.86 a	2.14 a	0.15 a	71.67 b	176.56 b
'TX301'	80.74 a	0.28 a	0.08 ab	73.13 a	188.90 a
'Multifort'	80.03 a	0.00 a	0.05 b	71.01 b	170.93 b
'Aloha'	75.51 a	0.00 a	0.09 ab	70.77 b	175.54 b
MeBr:C33					
Nongrafted 'Florida 47'	76.29 bc	0.00 a	0.34 a	70.03 b	169.30 b
'TX301'	86.23 a	0.00 a	0.09 a	71.94 a	179.51 a
'Multifort'	81.01 ab	0.00 a	0.06 a	70.30 b	165.61 b
'Aloha'	71.05 c	0.00 a	0.20 a	70.97 ab	177.29 a
Midas					
Nongrafted 'Florida 47'	75.40 b	0.00 a	0.19 ab	70.43 a	170.72 a
'TX301'	83.21 ab	0.56 a	0.23 a	70.88 a	173.15 a
'Multifort'	86.06 a	0.00 a	0.10 b	70.74 a	170.17 a
'Aloha'	77.63 ab	0.00 a	0.23 a	70.46 a	173.04 a

[a] Gall index scale (0-10): 0 = no galling and 10 = root system completely galled (Bridge and Page, 1980).
[b] Means with the same letter are not significantly different at $P \leq 0.05$.

TABLE 6. Early and late season nematode populations in soil, yield root disease, and root weight of watermelon at end of season in year 2.

Soil treatment	*M. incognita* (J_2/100 cm^3 soil)	Nonparasitic (No./100 cm^3 soil)	Root condition[a]	Total fruit weight (kg)	Average fruit weight (kg)
	Late season		End of season		
Herbicide Control	58.59 a[b]	403.04 a	2.50 a	2.40 c	1.88 c
Paladin Pic-21	20.54 a	291.83 a	1.81 ab	4.89 bc	3.34 b
MeBr:C33	21.62 a	190.42 a	1.15 b	10.12 a	4.58 a
Midas	123.17 a	396.41 a	1.32 b	6.53 b	3.39 ab
Melon Cultivar					
Nongrafted 'Tri-X Palomar'	19.49 b	338.43 ab	1.08 b	8.75 a	4.37 a
'Emphasis'	119.7 a	385.91 a	2.12 a	4.25 b	2.67 b
'Strongtosa'	29.11 b	236.93 b	1.88 b	4.95 b	2.85 b

[a] Root Condition rating: 0 to 1.0 = 0% to 20% discolored roots, 1.0 to 2.0 = 21% to 40%, 2.0 to 3.0 = 41% to 60%, 3.0 to 4.0 = 61% to 80%, and 4.0 to 5.0 = 81% to 100% of the root system is diseased and/or necrotic.
[b] Means with the same letter are not significantly different at $P \leq 0.05$.

United States with the establishment of businesses providing commercially-available grafted plants, there is still some variability in the performance of rootstocks under different conditions. This study reiterated that not all resistant rootstocks are effective for controlling nematodes in soil or roots, or increasing yield. Previous studies have shown that the benefits of grafting might be site-specific and several factors need to be considered when selecting rootstocks for pathogen management, such as pathogen pressure, dynamics of pathogens, and environmental and soil conditions (Louws et al., 2010; Buller et al., 2013; Rysin an Louws, 2015). In previous studies, it was reported that intermediate and moderately nematode-resistant rootstocks had low incidence of galling throughout a 2-yr field trial, and *M. incognita* populations in the soil under susceptible tomato cultivars increased compared with the resistant rootstocks throughout a 2-yr experiment (Rivard et al., 2010). Also, from the first to final harvest, *M. incognita* decreased in nonfumigated soil, while it increased in fumigated soil. In the study presented here, a decrease in *M. incognita* was also observed in plots planted with resistant tomato rootstocks. Furthermore, plots planted with the 'Multifort' rootstock had higher subsequent double-crop melon yields than those planted with nongrafted susceptible tomatoes.

In grafted tomatoes, the rootstocks 'Aloha' and 'Multifort' both reduced root galling, but did not reduce the number of J_2 extracted from roots. In melon, *M. incognita* J_2 in soil did not differ among the rootstocks but the number of J_2 isolated from roots was increased in 'Tetsukabuto' compared with *C. metuliferus*, resulting in reduced galling on *C. metuliferus* rootstock and improved general root condition with *C. metuliferus* compared with either the nongrafted melon or 'Tetsukabuto' rootstock.

With regard to soil treatments, control of purple and yellow nutsedge has been a significant challenge with

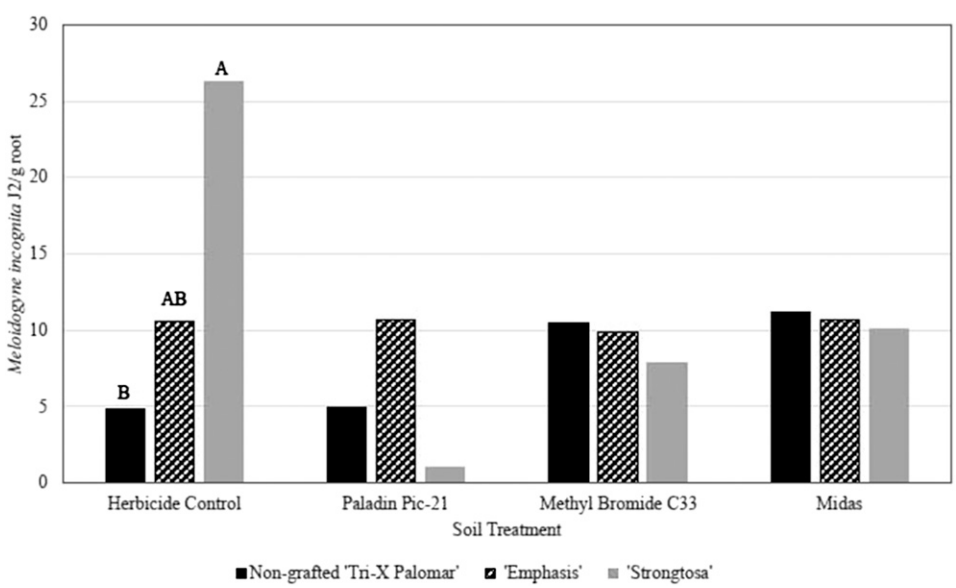

FIG. 4. Effect of soil treatment and watermelon rootstock on *Meloidogyne incognita* J_2/g watermelon root at harvest. Bars with the same letter are not significantly different at $P \leq 0.05$.

the loss of MeBr:C33. Yield losses in tomato resulting from interference from purple nutsedge (*Cyperus rotundus* L.) can be greater than 50% under common commercial production weed pressure (Gilreath and Santos, 2004). In the current study, weed populations in a field with a history of heavy purple nutsedge pressure were effectively controlled in all seasons with Paladin Pic-21, and this control was comparable to that achieved with MeBr:C33. There were few differences in weed control between treatments, with only a few weed species more effectively controlled by the fumigants than by the herbicide-only control. Although the number of weeds was significantly different for bedstraw and Florida pusley in both seasons, the overall weed populations were still minimal and there were no differences among soil treatments in either the fresh or dry biomass of weeds collected at either melon harvest. Florida pusley is a problematic weed in direct-seeded tomatoes (Glaze, 1988), but it is not considered competitive with transplanted tomatoes, particularly at the low numbers remaining after the treatments applied here. Similarly, *Galium spurium* was reported to have a negative impact on the yield of canola, but significant plant density was $100/m^2$ (Malik and Vanden Born 1987), much higher than seen in the current trial. Neither of these weeds present known secondary problems, as neither are reported as hosts of root-knot nematodes.

Several studies have accentuated the need for employing multiple strategies for managing pest and weed pressure. A recent study performed in China evaluated various alternatives to MeBr, and found that fumigation with a combination of 1,3-dichloropropene and chloropicrin resulted in root-knot nematode control similar to MeBr, yet only moderately controlled weeds for tomato production (Qiao et al., 2015). The authors recommended adding herbicides to the two-fumigant combination. In another study, thymol applied as soil fumigant, combined with a foliar application of Acibenzolar-S-methyl, a plant activator that enhances plant resistance, (Actigard 50 WG, Syngenta, Basel, Switzerland), significantly reduced the number of nematode J_2 in susceptible tomato plants (Ji et al., 2007), and increase yield in susceptible and moderately bacterial wilt-resistant tomato plants (Ji et al., 2007; Hong et al., 2011).

The need for integrated systems continues to drive the development of new approaches for management of soilborne pests, including registration of new chemicals, such as the biofumigant Dominus (allylisothiocyanate, IsaGro USA), which can be combined with other fumigants or herbicides, as well as nonchemical approaches such as grafting. Another alternative approach to chemical fumigants for pathogen control is anaerobic soil disinfestation (ASD), a biologically based, nonchemical pre-plant treatment. ASD incorporates a labile carbon source, covering the rows with a polyethylene mulch, and saturating the soil with water. The soil becomes anaerobic, allowing anaerobic bacteria to flourish and produce organic acids and other antimicrobial compounds. ASD has been proven to control weeds and plant pathogens including bacteria, fungi, nematodes, and oomycetes (Butler et al., 2012; Momma et al., 2013; Shennan et al., 2014). This method could also be paired with vegetable grafting to manage diseases not controlled by ASD.

The efficacy of soil fumigants such as MeBr as nematicides has long been established (Hutchinson et al., 1999; Rosskopf et al., 2005). However, use of MeBr has been phased-out and all registrations for US products containing methyl iodide were voluntarily cancelled by the registrant (EPA, 2012). From the research presented here, nematode and weed control with Paladin Pic-21 was comparable to these disallowed fumigants. Although efficacious for nematode and weed control, Paladin Pic-21 continues to have limitations for applications in densely populated areas due to the need for odor mitigation. Research on reducing the odor associated with this compound is on-going. The combination of grafting and Paladin Pic-21, or other new techniques such as ASD could provide the pathogen and weed control needed in vegetable production. The continued regulatory and public scrutiny of fumigants demonstrates the need to have a wide array of tools for soilborne pest management rather than dependency on a single tactic approach.

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