Soil Solarization and Biological Control for Managing *Mesocriconema xenoplax* and Short Life in a Newly Established Peach Orchard

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Abstract

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The effects of soil solarization, with and without a *Pseudomonas* spp. cocktail or wheat rotation as alternatives to chemical control of *Mesocriconema xenoplax*, were investigated from 2004 to 2011. Preplant solarization and soil fumigation (67% methyl bromide + 33% chloropicrin mixture; henceforth, referred to as MBr) was initiated in 2004 in an orchard infested with *M. xenoplax* and a history of peach tree short life (PTSL). Plots consisted of nine treatments: (i) nonsolarized soil-alone, (ii) nonsolarized soil with bacteria cocktail (nonsolar-bacteria), (iii) nonsolarized soil with wheat (nonsolar-wheat), (iv) nonsolarized soil with bacteria cocktail and wheat (nonsolar-bacteria-wheat), (v) solarized soil-alone, (vi) solarized soil with bacteria cock-

tail (solar-bacteria), (vii) solarized soil with wheat (solar-wheat), (viii) solarized soil with bacteria cocktail and wheat (solar-bacteria-wheat), and (ix) preplant MBr fumigation. Peach trees were planted into all plots in 2005. Nematode populations were suppressed 20 months longer after orchard establishment in solar-alone and solar-wheat plots than solar-bacteria and solar-bacteria-wheat plots. *Pseudomonas* spp. cocktails did not have a pronounced effect in suppressing *M. xenoplax* in this study. Fumigation effect on *M. xenoplax* population density dissipated 24 months after application. Solar-wheat-treated soil was as effective as preplant MBr fumigation in increasing tree survival from PTSL for at least 6 years after orchard establishment.

In the southeastern United States, the productive life span of peach (*Prunus persica* (L.) Batsch) trees does not exceed 6 to 10 years on some sites due to premature tree death (1). Two causes of early tree mortality are a disease complex known as peach tree short life (PTSL) and Armillaria root rot (12,19). PTSL is caused by a predisposition of trees to cold injury, bacterial canker (*Pseudomonas syringae* pv. *syringae* van Hall), or a combination of both, which results from parasitism by the ring nematode *Mesocriconema xenoplax* (Raski, 1952) Loof & de Grisse, 1989 (= *Cricronemoides xenoplax* (Raski, 1952) Loof and de Grisse, 1967) (1,18,24). In closed-end field microplots, peach trees died of cold injury after 4 years of parasitism by *M. xenoplax*, whereas trees in noninfested soil survived (18). Moreover, development of PTSL on land that had not been planted with peach trees for ≥ 75 years varied with exposure of trees to cumulative population levels of *M. xenoplax* (16). Such evidence indicates that PTSL complex is a nematode-associated disease and that the presence of *M. xenoplax* is required for the disease to occur. Additionally, *M. xenoplax* has been shown to make peach trees ('Suwanee') more susceptible to bacterial spot (*Xanthomonas arboricola* pv. *pruni*) (21). Trees growing in *M. xenoplax*-infested soil show evidence of more severe bacterial spot damage than trees exposed to low ring nematode populations.

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Preplant nematicides for ring nematode control are available in the Southeast (6). The current preplant nematicide recommendation for managing this nematode pathogen includes soil fumigation with Telone II (1,3-D) or Vapam (metam-sodium) (6). These are the only two preplant soil fumigants available to peach growers since the importation and manufacture of methyl bromide (MBr) was banned in the United States and Western Europe after January 2005 (4), due to its role in ozone depletion. As a result of reduced availability of pre- and postplant nematicides and the need for disease management practices that are less hazardous to humans, cheaper, and more environmentally safe, other nematode control options, such as biological control agents and soil solarization, are being investigated (8,10).

Soil solarization is the hydrothermal heating of moist soils under clear polyethylene plastic during summer to achieve temperatures detrimental to soilborne pathogens and weeds (8,22). Soil solarization, alone or in combination with other disease management practices, has been shown to be effective in reducing the inoculum density of many soilborne, disease-causing organisms, including plant-parasitic nematodes (22). Other beneficial effects of solarization include enhancement of competitive, thermotolerant populations of resident bacteria and fungi which limit subsequent colonization by less-competitive, antagonistic bacteria that were introduced into the system following solarization (5). Kluepfel et al. (10) substantiated this in an orchard study in which the native microbial community was significantly lowered both quantitatively and qualitatively by solarization. Furthermore, preplant soil solarization was effective in lowering the population density of *M. xenoplax* near economic threshold levels for up to 2 years on a PTSL site (10).

Pseudomonas sp. BG33R; a naturally derived, rifampin-resistant strain of BG33 isolated from a peach orchard site suppressive to PTSL, was demonstrated to suppress ring nematode reproduction in field soil under greenhouse conditions, as well as to inhibit egg hatch of the ring nematode in vitro (10). Seven additional fluorescent pseudomonad strains isolated from this same peach orchard inhibited ring nematode reproduction by more than 50% compared

with the control treatment. All seven strains were identified as *Pseudomonas* spp. based on fatty acid analysis using MIDI Microbial Identification System (Microbial ID, Inc., Newark, DE) and subsequent 16S rDNA sequence analysis (10,25). Additional research is needed to investigate utilization of soil solarization alone and in combination with a cocktail of *Pseudomonas* strains delivered through irrigation system to manage ring nematode and PTSL.

The objective of this research was to evaluate efficiency of a cocktail of *Pseudomonas* spp. strains, alone or in combination with soil solarization or wheat, to suppress *M. xenoplax* populations and aid tree health during establishment of a young peach orchard.

Materials and Methods

Bacterial strains, media, and growth. Five *Pseudomonas* spp. strains previously demonstrated to suppress *M. xenoplax* multiplication were evaluated collectively (i.e., *Pseudomonas* spp. cocktail) under field conditions in this study (9,10,26). The five *Pseudomonas* spp. culture strains included (i) *Pseudomonas* sp. BG33R (i.e., rifampin-resistant and known to kill *M. xenoplax* eggs), (ii) *Pseudomonas* sp. 134, (iii) *Pseudomonas* sp. 135, (iv) *Pseudomonas* sp. 136, and (v) *Pseudomonas* sp. 137. Each of these strains was grown separately in 14 liters of sterile *Pseudomonas* F Broth (tryptone at 10 g/liter, proteose peptone number 3 at 10 g/liter, dipotassium phosphate trihydrate at 1.5 g/liter, magnesium sulfate heptahydrate at 1.5 g/liter, and glycerol 10 g/liter). The broth for *Pseudomonas* sp. BG33R also included 140 ml of filter-sterilized rifampin (10 mg/ml). Cultures were incubated for 24 h at 28°C in 19-liter carboys positioned horizontally on an orbital shaker, followed by addition of 140 ml of a solution containing filter-sterilized 10% sorbitol and 10% inositol. Incubation then continued for another 24 h under the same conditions. Exposure to light was kept to a minimum during the 48 h of incubation. The cultures were transported to the field site, then combined and delivered through the irrigation system, as described below.

Field plot establishment. Various combinations of soil solarization, wheat rotation, and *Pseudomonas* spp. cocktail application treatments were compared with preplant MBr fumigation in a field experiment designed to investigate suppression of *M. xenoplax* populations and tree survival in a PTSL site over time. Plots were established in May 2004 at the United States Department of Agriculture–Agricultural Research Service Southeastern Fruit and Tree Nut Research Laboratory in Byron, Georgia. The study was conducted on a Faceville sandy loam soil (78% sand, 14% silt, 8% clay [pH 5.7], and 1.79% organic matter) with a previous history of PTSL. Peach trees had been growing on this site since 1998 and were removed in May 2004. Immediately following tree removal in May, the test site was subsoiled (approximately 81 cm-deep) and rototated. The test site was divided into six adjacent blocks (planting rows) each measuring 87 by 6.1 m, with treatment plots arranged in a randomized linear configuration down each of the six planting rows. Within each block, there were nine preplant soil treatment plots, which included (i) nonsolarized soil (nonsolar-alone), (ii) nonsolarized soil with bacteria cocktail (nonsolar-bacteria), (iii) nonsolarized soil with wheat (nonsolar-wheat), (iv) nonsolarized soil with bacteria and wheat (nonsolar-bacteria-wheat), (v) solarized soil-alone, (vi) solarized soil with bacteria cocktail (solar-bacteria), (vii) solarized soil with wheat (solar-wheat), (viii) solarized soil with bacteria and wheat (solar-bacteria-wheat), and (ix) MBr fumigation, which served as the positive control. Plots within a block were 8.5 by 3.1 m. Treatments were arranged in a randomized complete block design with six blocks. Care was taken not to transport soil between the plots throughout all phases of the study.

The plots were re-rototated on 22 June 2004, and a 4.0-mil (0.1 mm), clear polyethylene tarp (approximately 8.5 by 3.0 m) (NC420; Armin Plastics, City of Industry, CA) was stretched across the soil surface of all solarized plots and held in place by burying the edges. The plots were solarized from 23 June until 29 October. The nonsolarized plots in each replication were left fallow during the solarization period and weeds were controlled using

glyphosate at label rates (Roundup; Monsanto, St. Louis). Soil temperatures were recorded Monday through Friday at approximately 3:00 p.m. using Tel-Tru thermometers (Cross System Components, Conyers, GA) that were placed in four solarized and four nonsolarized plots at depths of 10.2 and 30.5 cm during the period of solarization. At the end of the solarization period, tarps were slit with a knife (to release heat), and left in place until after MBr application to plots designated for fumigation.

Soil fumigant (67% MBr, 33% chloropicrin) was applied (455 kg/ha; Hendrix and Dail, Inc., Tifton, GA) in a strip (3.1 m wide) under tarp on 10 November 2004. Soil moisture (10- to 15-cm depth) was adequate for fumigation such that, when the soil was compressed in the hand, it formed a ball that was easily broken with little disturbance (50 to 70% available soil moisture; 23). Tarps were removed from all plots on 19 November 2004.

Presolarization and prefumigation *M. xenoplax* populations in soil were determined on 22 June 2004 from four soil cores (2.5 cm in diameter by 30 cm deep) collected within each plot throughout the test site. The four soil cores were composited by plot within each block for a total of 54 samples. The nematodes were extracted from a 100-cm³ soil subsample with a semi-automatic elutriator (2) and centrifugal flotation (7), and counted.

All plots were planted to 'Dixiland' peach on Nemaguard rootstock at a tree spacing of 1.5 by 6.1 m in March 2005. Each plot had eight trees, the outer two of which served as borders with the six center trees as the experimental unit. All border trees were planted first. Using shovels, the remaining trees were planted by treatment in the following order: MBr fumigation, nonsolar-alone, nonsolar-wheat, solarized soil-alone, solar-wheat, solar-bacteria, solar-bacteria-wheat, nonsolar-bacteria, and nonsolar-bacteria-wheat. All shovels were dipped in an approximately 1.05% NaOCl solution (20% Clorox) and rinsed with water between use in planting trees in each experimental unit. Trees planted in all bacteria-treated plots were first placed in an 18.9-liter bucket (i.e., six trees per bucket) containing approximately 10.8 liters of a combined bacterial suspension of the five *Pseudomonas* spp. strains (i.e., cocktail). The tree roots were submerged in the bacterial cocktail for approximately 30 minutes prior to planting. Total mean populations of the *Pseudomonas* spp. cocktail in each bucket were 6.55×10^8 CFU/ml. Each planting hole also received approximately 1.8 liters of the cocktail solution, obtained from the bucket, before covering the tree roots with soil. All non-bacteria-treated trees were soaked in water alone prior to planting.

In addition to preplant applications, postplant applications of the *Pseudomonas* spp. cocktail were made in a 1.5-m radius area on both sides of each treated tree on 6 July, 8 September, 13 October, 8 November, and 8 December 2005; 4 April, 4 May, 8 June, 14 September, 19 October, and 16 November 2006; 12 April, 5 June, 2 July, 6 September, 10 October, 20 November, and 20 December 2007; and 14 April, 20 May, 12 June, and 1 July 2008. Our hypothesis was that, by delivering the *Pseudomonas* spp. cocktail at regular intervals through the irrigation system to trees established in solarized and nonsolarized soils, populations of the introduced pseudomonads would be enhanced. This would result in improved soil and rhizosphere colonization and subsequent control of *M. xenoplax* populations. Postplant applications of the *Pseudomonas* spp. cocktail were made by applying the bacteria through a dedicated irrigation line fitted with a chemical injector. A second, water-only irrigation line that bypassed the injector applied only water to the noninoculated treatment trees. This allowed all treatment trees to receive equal volumes of water during the day of inoculation. Seven Supernet microjet-sprinklers (Netafim Irrigation, Inc., Fresno, CA) with a flow rate of 20.4 liters/h were installed in the tree row half-way between each test tree. Each microjet-sprinkler wetted a 3.0-m-diameter area. Total mean populations of the *Pseudomonas* spp. cocktail incorporated into the irrigation water were 4.04×10^9 CFU/ml, with a mean dilution rate of 3.21×10^8 CFU/ml during a 4-h irrigation period. Water at approximately 142.9 liters/h was applied to each *Pseudomonas* spp. cocktail plot during the 4-h application period; the equivalent to wetting the top

soil to a depth of 30.5 cm, where the majority of plant-parasitic nematodes resided. Bacterial presence was confirmed in randomly selected, bacteria-treated plots during each application by collecting emitter water. The water samples were then serially diluted in sterile water and plated onto *Pseudomonas* Agar F (PAF; Difco Laboratories, Detroit).

All trees received annual applications of fertilizer (10-10-10 and 34-0-0 N-P-K), insecticides, fungicides, and herbicides, and were commercially pruned as recommended by the Georgia Cooperative Extension Service. Application rates of all applied materials were according to the schedule outlined in the guidelines for nonbearing and bearing trees (6,11).

The preplant population density of *M. xenoplax* was determined on 2 March 2005 from six soil cores collected from within each plot throughout the test site, as described above for the presolarization and prefumigation sampling. Postplant population density of *M. xenoplax* was determined on 9 June, 6 September, and 2 December 2005; 29 March, 7 June, 12 September, and 15 November 2006; 9 March, 5 June, 4 September, and 12 December 2007; 27 March, 10 June, 17 September, and 9 December 2008; 12 March, 8 June, and 2 September 2009; and 13 January, 23 March, 9 June, 2 September, and 3 December 2010 from one soil core collected within the drip line of each of six test trees of each experimental unit. The six soil cores were composited and nematodes were extracted from a 100-cm³ subsample as described above.

The area within the plots designated for wheat was shallow disked (10.0 cm) before AGS-2010 wheat was planted at a seeding rate of 136 kg/ha with an EV-N-SPRED broadcast spreader (Earthway Products, Inc., Bristol, IN) on 23 November 2005, 7 December 2006, 19 November 2007, 22 October 2008, 17 November 2009, and 15 December 2010. Wheat plots did not receive supplemental fertilizer other than that used in fertilizing the trees. The purpose of interplanting the wheat around the peach trees was not to suppress the *M. xenoplax* populations (14) but, rather, to have the wheat (roots) serve as an overwintering host for the bacteria (D. Kluepfel, *unpublished*) while peach trees were dormant. The wheat was allowed to reach maturity; then, the stalks were mowed with a weed-eater and the stubble was allowed to remain on the soil surface throughout the summer months, until the soil was disked in the fall each year.

Trunk diameters were measured at 20.3 cm above the soil surface on 24 February 2006, 28 February 2007, 12 February 2008, 29 January 2009, 1 February 2010, and 21 January 2011. Tree mortality as a result of bacterial canker infection or cold injury was recorded on 24 May 2006, 2 May 2007, 22 May 2008, 14 May 2009, 3 June 2010, and 2 May 2011 to monitor PTSL in the site.

Statistics. Nematode data were subjected to analysis of variance (ANOVA) with the general linear models procedure of SAS (SAS Institute, Cary, NC). For the presolarization and prefumigation

sampling dates, nematode population densities were compared among the nine designated treatments—(i) nonsolarized soil, (ii) nonsolarized soil with bacteria, (iii) nonsolarized soil with wheat, (iv) nonsolarized soil with bacteria and wheat, (v) solarized soil alone, (vi) solarized soil with bacteria, (vii) solarized soil with wheat, (viii) solarized soil with bacteria and wheat, and (ix) MBr fumigation—before the soil was solarized or fumigated. For the preplant sampling date (before the *Pseudomonas* spp. cocktail and wheat treatments were applied), nematode densities were compared among solarized, nonsolarized, and MBr-treated plots. For the postplant sampling dates, nematode densities were compared among all nine treatments, except on the first postplant sampling date (June 2005), when only nonsolarized soil alone, solarized soil alone, and MBr plots were compared (because the *Pseudomonas* spp. cocktail and wheat plots were not yet established at the time of sampling). Nematode density means for the presolarization and prefumigation sampling and postplant sampling dates were compared according to the Fisher protected least significant difference (LSD) test, following a significant *F* test. For the preplant sampling dates, nematode density means for the combined solarized and nonsolarized treatments were compared with the MBr treatment using Dunnett's test, following a significant *F* test. Treatment effects on tree trunk diameter means also were determined by ANOVA, followed by the Fisher protected LSD test, following a significant *F* test. Finally, the proportion of peach tree survival within each experimental unit for the solarized, nonsolarized, and MBr soil fumigation treatments were tested for mean separation for each sampling date by ANOVA. Only significant differences (*P* ≤ 0.05) will be discussed unless stated otherwise.

Results and Discussion

Soil temperatures. Maximum soil temperatures reached 48.3°C at 10.2 cm and 38.3°C at 30.5 cm depth in the solarized plots in July, compared with 43.3°C at 10.2 cm (July) and 37.8°C at 30.5 cm (August) depth in the nonsolarized plots (Table 1). Furthermore, the 5-month average daily soil temperature in the solarized plots was approximately 4°C greater at both the 10.2- and 30.5-cm depths compared with the nonsolarized plots.

Using heat to manage nematode populations is one of the oldest physical methods known (3). Nematodes are known to be sensitive to heat, with most life-stage mortality thresholds occurring between 44.4 and 48.0°C. In contrast, populations of pathogenic fungi have been reported to be greatly reduced at temperatures between 40 and 50°C (8). In our study, soil temperatures >44°C only occurred in solarized plots at 10.2 cm in July (10 days) and August (5 days) during the 18.3-week solarization period (*data not shown*). Only during one day in July at 10.2 cm was the soil temperature >48°C. Soil temperatures >44°C did not occur at the 30.5-cm depth in the solarized or nonsolarized plots. In the present study, the soil temperatures in solarized plots at 10.2 cm were

Table 1. Soil temperatures at 10.2- and 30.5-cm depths in solarized and nonsolarized plots, June through August 2004, Byron, GA^x

Month	Depth (cm) ^z	Soil temperature (°C) ^y			
		Mean		Maximum	
		Solarized	Nonsolarized	Solarized	Nonsolarized
June	10.2	36.5	32.3	42.2	35.0
	30.5	31.8	28.2	33.3	28.9
July	10.2	41.0	38.1	48.3	43.3
	30.5	35.3	32.0	38.3	37.2
August	10.2	38.2	34.2	46.1	42.8
	30.5	34.1	30.2	37.8	37.8
September	10.2	34.0	29.7	41.1	37.8
	30.5	30.0	26.3	34.4	32.2
October	10.2	30.7	26.2	38.3	31.1
	30.5	27.3	22.9	31.7	25.6

^x Temperatures were recorded daily at approximately 3:00 p.m. using a soil thermometer. Temperature data were collected from 24 June to 29 October 2004 (excluding weekends).

^y Mean daily temperature and highest temperature recorded for the respective month.

^z Thermometers were buried at each depth (i.e., 10.2 or 30.5 cm) in four randomly selected solarized and four nonsolarized plots in the test site.

within the efficacious range for killing plant-parasitic nematodes and some pathogenic fungi. It is possible that, by delivering efficacious temperatures to depths greater than 10.2 cm, further suppression of ring nematode populations could result in additional reductions in PTSL incidence.

***M. xenoplax* evaluation.** The mean population density of *M. xenoplax* prior to soil solarization and MBr treatment for six replications was 60 ± 8.3 (standard error)/100 cm³ of soil in June 2004. In March 2005, the nematode population density following establishment of the solarized and MBr fumigation plots but prior to replanting peach trees was greatest ($P \leq 0.05$) in the nonsolarized plots (21 *M. xenoplax*/100 cm³ of soil), intermediate in the solarized plots (6 *M. xenoplax*/100 cm³ of soil), and lowest in MBr-fumigated plots (0 *M. xenoplax*/100 cm³ of soil). Furthermore, the 4°C differential in soil temperature between solarized (36.1°C at 10.2 cm and 31.7°C at 30.5 cm) and nonsolarized (32.1°C at 10.2 cm and 27.9°C at 30.5 cm) plots mentioned previously may also explain the approximate temperature threshold needed to significantly lower ring nematode populations prior to orchard establishment.

Three months after orchard establishment (June 2005), nematode populations were greater in nonsolar-alone plots than in the solarized soil-alone and MBr-fumigated plots (Table 2). No differences in ring nematode population were detected between the solarized soil-alone and MBr fumigation. Furthermore, 12 months after orchard establishment (March 2006), all nonsolar plots had greater ($P \leq 0.05$) nematode populations than all solarized and MBr-fumigated plots. No differences in ring nematode population were detected among any of the solarized plots and MBr fumigation. Presence of the *Pseudomonas* spp. cocktail or wheat did not suppress ($P \leq 0.05$) *M. xenoplax* population density as well as soil solarization. Therefore, postplant bacterial cocktail applications were discontinued after July 2008. The lack of nematode suppression in the presence of the *Pseudomonas* spp. cocktail did not substantiate our observations in previous field studies with solarization combined with *Pseudomonas* sp. BG33R (10,15). In our first solarization test, *M. xenoplax* populations were significantly lower ($P \leq 0.05$) in solarized plots that were initially inoculated with *Pseudomonas* sp. BG33R at planting and again 8 months later compared with plots that were only solarized. However, this enhanced reduction in *M. xenoplax* populations in plots where *Pseudomonas* sp. BG33R was introduced decreased over time. One

possible explanation as to why no suppression in *M. xenoplax* population was observed in the presence of the *Pseudomonas* spp. cocktail in the current study is that competition or antagonism occurred among the five *Pseudomonas* spp. strains in the soil, thus limiting their individual, deleterious effects on nematode reproduction. In contrast, the suppressive effect of solarization on ring nematode populations was sustained for more than 1 year. In the present study, populations of *M. xenoplax* were lower in solarized plots for up to 17 months longer (March 2006) than in nonsolarized plots. During this same time, *M. xenoplax* populations were statistically similar among solarized and MBr-treated plots. Twenty-four months after MBr application (November 2006), the nematode population density in the fumigated plots did not differ from those in the nonsolar-alone, nonsolar-wheat, and four solarized treatment plots, even though no ring nematodes were detected immediately after fumigation. The lack of statistical significance may be attributable to high variability in *M. xenoplax* population densities between the nonsolar treatments and MBr fumigation plots on this sampling date. It was not until 28 months after MBr application (March 2007) that *M. xenoplax* was first detected in the MBr-fumigated plots. The advantage of using preplant fumigation, one component of the 10-Point Management Program (1) to control *M. xenoplax* in the PTSL disease complex, was confirmed in this study, given that MBr is a broad-spectrum pesticide that controls not only nematodes but also other microorganisms and certain weeds. However, it is not unusual for the effect of preplant fumigation to diminish over time. In South Carolina, Zehr and Golden (27) reported that managing *M. xenoplax* with a preplant application of 1,3-D was not effective for more than 2 years following initial treatment. Our results substantiated those of Nyczepir and Bertrand (13) and Sharpe et al. (20), who both reported that a resurgence in the mean *M. xenoplax* population density on 'Nemaguard' rootstock occurred approximately 25 months after a preplant treatment with MBr. At subsequent sampling dates from September 2007 to December 2008, the ring nematode population density in MBr-fumigated and the four solarized plots generally increased, compared with the four nonsolarized plots (Table 2), such that the *M. xenoplax* population density was greater ($P \leq 0.05$) on three of the five sampling dates in MBr-treated plots than in all four nonsolarized plots. One explanation for this occurrence may be that trees growing in solarized and MBr-fumigated soil were healthier early on, resulting in increased feeder root abun-

Table 2. Populations of *Mesocriconea xenoplax* in a peach orchard, as influenced by soil solarization, *Pseudomonas* spp. bacteria cocktail, wheat intercropping, or preplant fumigation with methyl bromide-chloropicrin, 2005 to 2008, Byron, GA^a

Treatments ^y	<i>M. xenoplax</i> per 100 cm ³ of soil									
	2005		2006		2007			2008		
	9 June ^w	2 December	29 March ^w	15 November ^x	9 March ^x	4 September ^w	12 December ^y	27 March ^w	17 September ^w	9 December ^w
Nonsolar-alone	75 a	70 a	113 a	123 ab	186 ab	207 bc	978 abc	501 cde	75 c	36 d
Nonsolar-bacteria-wheat	63 ^z	58 a	143 a	260 a	290 a	153 c	420 bc	186 e	57 c	78 cd
Nonsolar-wheat	58 ^z	33 a	128 a	88 ab	215 ab	210 bc	831 abc	306 de	87 c	135 bcd
Nonsolar-bacteria	13 ^z	30 a	168 a	235 a	339 a	168 c	309 c	117 e	51 c	135 bcd
Solar-wheat	10 ^z	0 a	13 b	40 b	253 a	920 a	832 abc	1,349 abc	704 ab	168 bcd
Solar-bacteria	8 ^z	5 a	3 b	128 ab	303 a	906 ab	1,622 a	977 bcde	340 bc	335 bc
Solar-bacteria-wheat	5 ^z	0 a	3 b	130 ab	243 a	1,162 a	1,564 ab	1,288 abcd	423 bc	368 b
Solar-alone	0 b	0 a	10 b	10 b	143 ab	828 abc	1,810 a	1,932 ab	630 ab	215 bcd
MBr	0 b	0 a	0 b	0 b	18 b	618 abc	1,533 ab	1,933 a	1,073 a	688 a

^a Data are means of six replications per treatment, except that 15 November 2006 to 9 December 2008 had five replicates for nonsolar-alone, and 4 September 2007 to 9 December 2008 had five replicates for nonsolar-bacteria-wheat, nonsolar-bacteria, and nonsolar-wheat.

^y Soil was solarized from 23 June until 29 October 2004. Wheat = wheat was planted at a seeding rate of 136 kg/ha on 23 November 2005, 7 December 2006, 19 November 2007, 22 October 2008, 17 November 2009, and 15 December 2010. Bacteria = *Pseudomonas* spp. cocktails were applied at a mean dilution rate of 3.21×10^8 CFU/ml during a 4-h irrigation period on 6 July, 8 September, 13 October, 8 November, and 8 December 2005; 4 April, 4 May, 8 June, 14 September, 19 October, and 16 November 2006; 12 April, 5 June, 2 July, 6 September, 10 October, 20 November, and 20 December 2007; and 14 April, 20 May, 12 June, and 1 July 2008. MBr = soil fumigant (67% methyl bromide:33% chloropicrin) was applied at a rate of 455 kg/ha; application date was 10 November 2004. Tarps were removed from all plots on 19 November 2004.

^w Nematode means within a column followed by the same letter are not different ($P \leq 0.05$) according to Fisher's least significant difference.

^x Nematode means within a column followed by the same letter are not different ($P < 0.10$) according to Fisher's least significant difference.

^y Nematode means within a column followed by the same letter are not different ($P = 0.12$) according to Fisher's least significant difference.

^z Treatment not included in analysis since the *Pseudomonas* spp. cocktail and wheat plots were not yet established at the time of sampling.

dance (i.e., food source), which supported increased nematode reproduction during this period of time. In contrast, trees growing in nonsolarized soil were weaker, resulting in a reduced food source, which is known to limit nematode reproduction (17). From June 2009 (55 months after MBr application) to December 2010 (73 months after MBr application), *M. xenoplax* population densities did not differ among any of the soil treatments, thus indicating stabilization in ring nematode population density as related to soil treatment effect. For example, in December 2010, mean ring nematode populations in the four nonsolarized, four solarized, and MBr-fumigated treatment plots were 123 *M. xenoplax*/100 cm³ of soil (range 84 to 156), 105 *M. xenoplax*/100 cm³ of soil (range 75 to 158), and 130 *M. xenoplax*/100 cm³ of soil, respectively. A second explanation as to why *M. xenoplax* became established in the solar and MBr plots over time may be the result of subsoiling that occurred during site preparation of the plots, as previously reported (16). Subsequently, over time, the roots among adjacent plots eventually grew down the subsoil furrows, which aided nematode movement and establishment of *M. xenoplax* into solar and MBr plots from other plots that already had established ring nematode populations. A third explanation may be the suppression of nematode antagonists by the nematicide and soil solarization process that also might have favored the increase of *M. xenoplax* in the MBr-fumigated and solarized plots.

Differences in trunk diameter were detected among some of the solarized, nonsolarized, and MBr fumigation treatments on five of six sampling dates (Table 3). In February 2006 (11 months after orchard establishment), trunk diameter was smallest ($P \leq 0.01$) in nonsolar-wheat plots, intermediate in solar-bacteria and solar-bacteria-wheat, and greatest in fumigated plots. Twenty-three months after orchard establishment (February 2007), tree growth again was greatest ($P = 0.10$) in the MBr-fumigated plots and lowest in nonsolar-wheat plots. The effect of solarization, *Pseudomonas* spp. cocktail, or wheat interplanting on tree growth at and after 23 months after orchard establishment (February 2007) was not apparent among the treatments. Tree growth at 46 months after orchard establishment (January 2009) and thereafter was generally greater in the nonsolarized plots than the solarized and MBr-fumigated plots. One possible explanation for this reversal in treatment effect on increased tree growth might be related to number of test trees surviving within the respective treatment plots. More test trees surviving in a particular treatment over time (i.e., MBr-fumigated and solarized plots; Table 3) would result in increased canopy and, therefore, increased competition for space and light among the trees, thus resulting in a slower-growing trees. In con-

trast, fewer living test trees resulting from increased PTSL tree mortality within a particular treatment (i.e., up to 71 % tree mortality in nonsolarized plots) would mean less competition for tree space, therefore resulting in larger trees. These remaining larger trees would, therefore, receive more pruning wounds per tree, which would also induce additional stress that may contribute to an increase in PTSL tree mortality. To circumvent pruning effect on PTSL incidences in this study, trees were always pruned after 15 February (2006 to 2011) (1,6).

Some of the experimental peach trees developed typical PTSL symptoms and died during the experiment. In May 2006 (14 months after orchard establishment), more ($P \leq 0.05$) trees in the nonsolarized soil-alone, nonsolar-bacteria, and nonsolar-wheat plots developed PTSL symptoms and died than in all four solarized and MBr-fumigated plots (Table 3). In May 2007 (26 months after orchard establishment), PTSL tree mortality in all nonsolarized soil plots was greater ($P \leq 0.05$) than in all solarized and MBr-fumigated plots. No differences in PTSL tree death were detected among all the solarized plots and the MBr-fumigated soil plots. Thirty-eight months after orchard establishment (May 2008), tree survival in solar soil-alone, solar-wheat, and solar-bacteria-wheat was comparable with trees growing in MBr-fumigated soil. In May 2009 (50 months after orchard establishment) and June 2010 (63 months after orchard establishment), tree survival was highest in MBr-fumigated soil (89%) and lowest in nonsolar-bacteria-wheat plots (29%). Although tree survival in solar-wheat plots (80%) was greater ($P \leq 0.05$) than tree survival in the four nonsolarized treatment plots, tree survival in solar-wheat plots did not differ from MBr-fumigated plots. In May 2011 (74 months after orchard establishment), four trees succumbed to PTSL death (i.e., three trees in solar-wheat plots and one tree in MBr-fumigated plots). However, tree survival in solar-wheat (71%) and MBr-fumigated soil (86%) generally remained statistically similar between and among treatments when compared with the previous two rating periods (Table 3). These results clearly demonstrate the benefit of suppression in ring nematode population density in extending peach tree longevity on a PTSL site. In addition, our results indicate that use of alternatives to MBr soil fumigation did not negatively impact long-term tree survival.

In general, peach growers in the southeastern United States would consider $\geq 50\%$ tree loss in a particular block unacceptable, and would remove the remaining live trees and replant or utilize the land for another crop. In our study, tree mortality of $\geq 50\%$ occurred in all four nonsolar treatment plots at 26 months after orchard establishment (May 2007). Greater early tree mortality in

Table 3. Effect of soil solarization, *Pseudomonas* spp. bacteria cocktail, wheat interplanting, or preplant fumigation with methyl bromide–chloropicrin on trunk diameter of peach trees (*Prunus persica* ‘Dixiland’/‘Nemaguard’) and tree mortality due to peach tree short life (PTSL), 2006 to 2011, Byron, GA^w

Treatment ^x	Trunk diameter (mm)					Cumulative PTSL mortality (%)						
	24 Feb 2006 ^y	28 Feb 2007 ^z	12 Feb 2008 ^y	29 Jan 2009 ^y	1 Feb 2010 ^y	24 Jan 2011 ^y	24 May 2006 ^y	2 May 2007 ^y	22 May 2008 ^y	14 May 2009 ^y	3 June 2010 ^y	2 May 2011 ^y
Nonsolar-alone	26.3 bc	49.2 bc	69.4 a	85.9 b	104.0 abc	114.9 bc	36 b	53 b	56 c	63 def	63 def	63 de
Nonsolar-bac-wheat	27.9 bc	50.3 abc	75.5 a	96.5 a	110.5 a	128.8 a	19 ab	56 b	63 c	71 f	71 f	71 e
Nonsolar-wheat	25.4 c	48.1 c	73.9 a	88.6 b	109.5 a	119.3 ab	36 b	56 b	61 c	66 ef	68 ef	68 e
Nonsolar-bac	27.5 bc	52.3 ab	74.3 a	89.7 ab	106.6 ab	117.8 abc	39 b	50 b	52 bc	58 cdef	58 cdef	58 cde
Solar-wheat	27.9 bc	48.9 bc	70.6 a	83.3 b	92.2 c	105.7 c	0 a	8 a	11 a	20 ab	20 ab	29 ab
Solar-bac	28.9 b	51.9 abc	74.1 a	88.8 b	99.7 abc	115.1 bc	0 a	16 a	27 ab	38 abcd	38 abcd	38 abcd
Solar-bac-wheat	29.6 b	51.5 abc	71.0 a	85.5 b	99.6 abc	111.9 bc	0 a	11 a	12 a	34 abc	34 abc	34 abc
Solar-alone	27.7 bc	49.5 bc	68.7 a	82.8 b	95.0 bc	106.7 bc	0 a	14 a	21 a	41 bcde	41 bcde	41 bcde
MBr	33.5 a	53.8 a	71.7 a	84.0 b	93.1 c	105.8 bc	0 a	0 a	3 a	11 a	11 a	14 a

^w Data are means of six replications per treatment, except for trunk diameter on 12 February 2008 to 24 January 2011, which had five replicates for nonsolar-alone, nonsolar-bacteria-wheat, and nonsolar-bacteria; and nonsolar-wheat and for solar-alone on 24 January 2011, which had five replicates.

^x Soil was solarized from 23 June to 29 October 2004. Wheat = wheat was planted at a seeding rate of 136 kg/ha on 23 November 2005, 7 December 2006, 19 November 2007, 22 October 2008, 17 November 2009, and 15 December 2010. Bac = *Pseudomonas* spp. bacteria cocktails were applied at a mean dilution rate of 3.21×10^8 CFU/ml during a 4-h irrigation period on 6 July, 8 September, 13 October, 8 November, and 8 December 2005; 4 April, 4 May, 8 June, 14 September, 19 October, and 16 November 2006; 12 April, 5 June, 2 July, 6 September, 10 October, 20 November, and 20 December 2007; and 14 April, 20 May, 12 June, and 1 July 2008. MBr = soil fumigant (67% methyl bromide:33% chloropicrin) was applied at a rate of 455 kg/ha on 10 November 2004. Tarps were removed from all plots on 19 November 2004.

^y Means within a column followed by the same letter are not different ($P \leq 0.05$) according to Fisher's least significant difference.

^z Means within a column followed by the same letter are not different ($P = 0.10$) according to Fisher's least significant difference.

the nonsolarized plots (50 to 56%) compared with the solarized (8 to 16%) and MBr-fumigated plots (0%) just 2 years postplanting could be attributed to a relatively high *M. xenoplax* population at the time of orchard establishment in March 2005 (Table 2). The experimental orchard site has a known history of PTSL, and has been replanted to peach four times over the past 40 years. It has been reported that PTSL development is dependent upon cumulative exposure of trees to increasing populations of *M. xenoplax* (16). In the present study, the ring nematode population density in most nonsolarized plots from 3 (June 2005) to 12 (March 2006) months after orchard establishment was higher than in solarized and MBr-fumigated plots (Table 2). Therefore, trees in nonsolarized plots were exposed to greater nematode-feeding-induced stress during a sensitive phenological time period, which resulted in elevated PTSL tree death.

Tree survival in the solar-wheat plots was not different ($P \leq 0.05$) from that in the MBr-fumigated plots 6 years after orchard establishment. We are uncertain of the mechanism or mechanisms by which the solar-wheat soil treatment suppressed PTSL tree mortality, because this aspect was not addressed in this study. However, preplanting wheat prior to orchard establishment was as effective as preplant MBr fumigation in increasing tree survival from PTSL (13), even though postplant wheat intercropping in newly planted or 4-year-old, well-established peach trees did not suppress ($P \leq 0.05$) ring nematode populations after 3 years (14).

In summary, preplant soil solarization was found to impart long-lasting suppression of *M. xenoplax* populations and enhanced tree survival on a PTSL site. Six years after orchard establishment, tree survival was aided by the solar-wheat treatment equally as well as by MBr fumigation. Solarization had a more suppressive effect on *M. xenoplax* than did the repeated applications of a *Pseudomonas* spp. cocktail. Economically, soil solarization alone (approximately \$500/ha) appears to be cost-effective when compared with strip-applied MBr-chloropicrin fumigation (approximately \$2,500/ha) and comparable with Telone II fumigation (approximately \$350/ha) (P. Fuller, TriEst Ag Group, Inc., *personal communication*). The results of this study support further examination of preplant soil solarization, followed by postplant peach tree intercropping with wheat, as a useful alternative for managing PTSL.

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