Soil Solarization as a Component of an Integrated Program for Control of Raspberry Root Rot

J. N. Pinkerton, USDA-ARS, HCRL, Corvallis, OR 97330; P. R. Bristow and G. E. Windom, Washington State University, Puyallup Research and Extension Center, Puyallup, WA 98371; and T. W. Walters, WSU-Mount Vernon NWREC, Mt Vernon, WA 98273

ABSTRACT

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Field and growth chamber studies were conducted during 2000 to 2005 to determine the efficacy of soil solarization for the control of *Phytophthora* root rot of raspberry (PRR). The exposure time that was lethal to *Phytophthora rubi* cultures on V8 juice agar plates was evaluated at intervals up to 240 h and at a range of temperatures from 20 to 35°C. Colonies incubated at 20 and 25°C nearly covered the plates in 240 h, while radial growth slowed at 27°C and ceased at temperatures $\geq 29^\circ\text{C}$. The exposure times required to kill *P. rubi* were estimated to be 222 h at 29°C, 168 h at 31°C, 108 h at 33°C, and 52 h at 35°C. Previous exposure to shorter durations at temperature $\geq 29^\circ\text{C}$ slowed growth of colonies when they later were incubated at 20°C. Field trials were established in 2000 and 2003 at three locations in Washington State to evaluate soil solarization for the management of PRR. Cumulative hours with soil temperatures $>29^\circ\text{C}$ at 30 cm soil depth in solarized plots exceeded 200 h in each trial. In the 2000 trial, combinations of solarization, bed shape, and amendments of gypsum were evaluated. Over the 3 years after planting PRR-susceptible raspberry 'Malahat' and 'Willamette', primocane growth and survival were greater ($P < 0.05$) in raised bed plots that were solarized than in solarized and nonsolarized flat bed plots or hilled bed plots with gypsum. In 2003, trials were initiated to evaluate solarization in combination with applications of mefenoxam and fosetyl-Al. In 2004, solarization increased ($P < 0.05$) primocane growth of 'Malahat' and 'Qualicum' raspberries at both locations compared to application of fungicides alone and nontreated control plots. At both locations in 2005, density and growth of 'Qualicum' primocanes were greatest in solarized plots, while canes in solarized and fungicide only plots of 'Malahat' were similar. Incidence of diseased canes was lowest in plots that received fungicides. Primocane survival and fruit yields were very low at both locations in the third season because of favorable conditions for PRR and plant stress in late spring. These results indicate that soil solarization can be an effective component of integrated management of PRR in the Pacific Northwest, especially when combined with raised beds and gypsum amendments.

Raspberry root rot (PRR), caused by *Phytophthora* spp., can cause economic losses in cool, wet production areas (6,12,19,35,36). These pathogens reduce plant vigor, decrease yields, and can cause large areas in fields to die out in one or two seasons. PRR caused by *Phytophthora* spp. was first reported in the Pacific Northwest (PNW) in 1968 (6). The predominant species isolated from raspberry in the PNW is *Phytophthora rubi* (Basionym *Phytophthora fragariae* var. *rubi*).

Management of PRR is difficult because oospores of *P. fragariae* may persist in field soil for many years, limiting the efficacy of crop rotations for disease control (8,36). Soil fumigation with methyl bromide may delay the onset of root rot in red raspberry plantings by only 3 to 4 years (15). In addition, isolates of *P. fragariae* which are resistant to metalaxyl (Ridomil, Ciba, Greensboro, NC) have been found in strawberry plantings in the PNW (27). Disease control is markedly reduced in some Washington fields when raspberries are replanted into soil with a history of metalaxyl use (P. Bristow, unpublished data). Metalaxyl has been shown to be ineffective for controlling PRR under high disease pressure (38). These limitations leave the raspberry industries searching for alternative management tools for root rot control.

Alternative management tools include host resistance, hilling, and amendment

with gypsum (39). Another management tool, soil solarization, is a process that employs solar radiation to heat soil under a transparent plastic film to temperatures that are detrimental to soilborne pathogens (17). Solarization targets mesophyllic organisms, which include most plant pathogens and pests, without destroying thermotolerant fungi and *Bacillus* spp. (17). Changes in the microflora following solarization may account for enhanced plant growth and induced suppressiveness to plant pathogens (14,29). Solarization can enhance the effectiveness of other pest management approaches (4,30) and has the additional advantages of being a non-chemical alternative for pathogen control.

In Oregon and Washington, solarization has shown promise for the control of soilborne plant pathogenic fungi, bacteria, nematodes, and weeds affecting nursery and small fruit crops (21–23). Introduced populations of *Verticillium dahliae*, *Pratylenchus penetrans*, and *Agrobacterium tumefaciens* were significantly reduced in solarized plots, and *Phytophthora cinnamomi* was not recovered from the test soils following solarization (22). Soil solarization also showed promise for managing root diseases of raspberry and strawberry, including those caused by *P. fragariae* and *P. rubi* (23). An integrated program utilizing raised beds, gypsum amendments, and fungicide applications provided the best control of raspberry root rot in New York State (18). These management inputs are compatible with, and may be enhanced by, soil solarization. The objectives of this research were to determine the lethal thermal exposure for growth of *P. rubi* and to evaluate soil solarization as a component of an integrated program for reducing populations of root rot pathogens before planting raspberry.

MATERIALS AND METHODS

In vitro growth study. Colony growth rate and survival studies were conducted over a range of temperature doses, i.e., temperature $\times$ incubation duration. An isolate of *P. rubi* originally collected from red raspberry in Clark County near Vancouver, WA and described as *P. erythrosetica* (6) was transferred to petri dishes of

Corresponding author: J. N. Pinkerton
E-mail: Jack.Pinkerton@ARS.USDA.GOV

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V8 (6%) juice agar and incubated at 20 to 24°C. After 7 days, 5-mm-diameter cores were cut from the margin of the actively growing colonies with a sterile no. 3 cork borer and placed in the center of 100-mm-diameter petri dishes containing V8 juice agar (one core per dish). The petri dishes were placed in incubators set at 20, 25, 27, 29, 31, 33, or 35°C ($\pm 0.4^\circ\text{C}$) for 12, 24, 36, 48, 72, 96, 120, 144, 196, or 240 h. Temperature $\times$ exposure times were evaluated with three replicate dishes for each treatment combination, and the experiment was conducted twice. Diameters of colonies in the dishes (maximum 80 mm) were recorded at the end of each incubation period and again at 48-h intervals after plates were transferred to 20°C.

Field solarization studies. Field trials were conducted in three locations that represented the northern to southern (~ 400 km) distribution and climatic ranges of red raspberry production in western Washington. Sites were cropped previously with red raspberry and had histories of stand decline caused by PRR. In 2000, a trial was established at the WSU-Vancouver Research and Extension Unit in Clark County (Southwestern Washington, $45^\circ 40' \text{N}$, $122^\circ 39' \text{W}$) to evaluate an integrated management program utilizing solarization, bed architecture, and gypsum amendments. In 2003, identical trials were established at the WSU Puyallup Research and Extension Center in Pierce County (Western Washington, $47^\circ 11' \text{N}$, $122^\circ 13' \text{W}$) and in a commercial raspberry field in rural Whatcom County (Northwestern Washington, $48^\circ 54' \text{N}$, $122^\circ 19' \text{W}$) to evaluate solarization with and without fungicide applications to manage root rot. Symptomatic plants from all three locations tested positive for *P. rubi* by enzyme-linked immunosorbent assay (ELISA) and polymerase chain reaction (PCR) (C. MacConnell, *personal communication*).

Clark County solarization trial. The trial was situated on Hillsboro silt loam soil (fine silty, mixed, superactive, Mesic, Argixerolls; 3.2% organic matter, pH 5.7, and cation exchange capacity [CEC] 10 meq/100 g) which was naturally infested with *P. rubi* and had been used for numerous PRR field trials (3,31). The area was planted in grass for several years before it was plowed and disked in mid-July 2000. The experiment included six treatments: two bed types (raised or flat beds), two solarization treatments (solarized or nonsolarized), two amendment treatments (gypsum or no gypsum), and nontreated controls in a split block design across six rows and with four replicates. Gypsum amendments were not evaluated in the plots with flat beds. Plots were 10×3.9 m with 1.5-m borders between rows and 1 m between plots in rows. On 26 July, granular (prilled) agricultural gypsum was applied in a 2.4-m band in the center of raised bed plots with a Gandy drop spreader at 13,450

kg/ha and incorporated by rotovating to a depth of 20 cm. Raised beds 1 to 1.2 m wide by 30 cm high were formed with a tractor drawn bed shaper which drew soil from a 2.9-m width of the plots. Soil was irrigated with ca. 10 mm of irrigation via overhead sprinklers. On 27 July 2000, a 0.05-mm-thick clear polyethylene film (Tyco Nursery Supply, City of Industry, CA) was stretched across the soil surface of plots to be solarized and secured in place by burying the edges. The remaining plots in each replication were maintained in bare fallow as nonsolarized controls. Thermocouples were buried at 10 and 30 cm in one solarized and one nonsolarized plot. Hourly temperature data were recorded through 20 September with a datalogger (Campbell Scientific, Logan, UT).

Tarps were rolled back to leave a 1.5-m alleyway between the planting rows which was planted with tall fescue (*Festuca arundinacea*) on 5 October 2000. On 17 May 2001, the film was removed and the plots were rotovated to a depth of 10 cm with a garden rototiller. All solarized plots were tilled before nonsolarized plots to eliminate the movement of nonsolarized soil into solarized plots. Five plants of highly susceptible raspberry cultivars Malahat and Willamette (31) were planted on 60-cm spacing in opposite halves of the plots. Drip irrigation tubing and a trellis system were installed at this time. Plants were maintained with recommended fertilizer and management practices throughout the experiment (28). Weed density in plots was estimated on 7 July 2001 by rating weed groundcover on a scale of 0 to 5 (0 = no weed cover, 1 = 20%, up to 5 = 100% groundcover). After this weed evaluation through the end of the experiment, weeds were managed by hand weeding and applications of glyphosate (Roundup; Monsanto, St. Louis, MO).

Effects of treatments were evaluated for 3 years by annually counting canes, measuring cane lengths or weight, and collecting fruit yield data in the third year. On 15 October 2001, primocanes in each plot were cut to the ground, and total cane weight of each cultivar was recorded. In 2002, number of primocanes of each plant cultivar per hill, number canes per plot, and height of 50 canes per plot were recorded on 14 June, 12 August, and 18 October, respectively. During the final year, canes per plot were counted on 22 May and 6 November. Fruit was machine harvested 11 times between 28 June and 17 July 2003.

Pierce and Whatcom county trials. The Whatcom County trial was in a field cropped with red raspberries for the previous 20 years. Plants showed symptoms of root rot the last 5 years. The soil was a well-drained Orinda silt loam (coarse-silty, mixed superactive, nonacid, Mesic Fluvaquentic, Endoaquepts; 3.5% organic matter, pH 5.1, and CEC 10.2 meq/100 g). A

single 200-m row of raspberries in the plantings was removed, soil was tilled, and a 10-cm-high raised bed was formed by hand in early July 2003 in the center of this row. The Pierce County trial was established in a site that had been used for raspberry root rot research, but had been planted in grass for the 2 years prior to the solarization trial. The plot area was plowed to incorporate the sod and rotovated to form a flat bed in early July 2003. The soil type was a Sultan silt loam (fine-silty, isotic, Mesic, Aquardic Dystrochrepts; 3.1% organic matter, pH 5.9, and CEC 13.0 meq/100 g). The experimental design at both locations was a randomized complete block with four replicates. Treatments included solarized and nonsolarized plots, each with and without application of the fungicides mefenoxam (Ridomil Gold; Ciba, Greensboro, NC) and fosetyl-Al (Aliette; Bayer CropScience, Research Triangle Park, NC). Individual plots of 7.6×3 m (Pierce) and 9.2×3 m (Whatcom) were arranged along a single row. A 1.8-m border was left on either side of the plot row.

Plot areas were irrigated the day before laying the solarization film. Thermocouples were buried at 10 and 30 cm depths in one solarized and one nonsolarized plot, and hourly temperatures were recorded with mini-dataloggers (HOBO; Onset Computer Corp., Pocasset, MA). The film was laid on 22 and 23 July 2003 at Pierce and Whatcom county plots, respectively. Shallow trenches (10 cm) were dug at the perimeter of the plots to be solarized, the film was stretched over the plots, and the trenches were backfilled to secure the edges of the film.

Temperature recorders were removed from the plots in September. The film was removed in February 2004 at the Whatcom site and 27 April at the Pierce site. Plots were rotovated to a depth of 10 cm with a garden rototiller. All solarized plots were tilled before nonsolarized plots to eliminate the movement of nonsolarized soil into solarized plots. Two root rot susceptible raspberry cultivars (3,31) were planted on 13 May (Pierce) and 14 May (Whatcom): field grown 'Malahat' and tissue culture propagated 'Qualicum' plants (supplied by Sakuma Bros., Burlington, WA). Five (Pierce) or six (Whatcom) plants of each cultivar were planted along the centerline of the plots on 60-cm spacing at opposite ends of each plot. In plots that received fungicide treatments, mefenoxam (118.3 ml formulated mefenoxam in 3,785 liters of water per 304.8 m of row) was applied to the surface of the soil in a 0.9-m-wide band centered on the plant row during a period of rain in the spring and fall each year. Fosetyl-Al (5.7 formulated kg/ha in 190 liters of water) was sprayed on the leaves and canes twice at approximately 4-week intervals each spring and fall. Weeds were managed through the

study with hand-hoeing and applications of glyphosate. Trellis systems were installed and the canes thinned and trained in February 2006. Plants were maintained with recommended fertilizer and management practices (28) throughout the experiment.

Effects of treatments were evaluated for 3 years. The survival of hills and the num-

ber of canes per hill were recorded on 26 August 2004. Primocanes were cut to the ground on 2 December (Pierce) and 27 December 2004 (Whatcom), and the number of canes, cane lengths, and weight were recorded for canes in each surviving hill. The number of primocanes per hill was counted on 18 April 2005. The num-

ber of primocanes and the percentage of canes with symptoms of root rot were recorded on 16 August. On 13 December, the height of 50 primocanes in two 50-cm sections of the row in each plot was recorded. In 2006, the Whatcom County plots were machine harvested and fruit yield data were collected on three dates between 22 June and 18 July 2006. Because of poor plant survival at Pierce County, plots were not harvested, but fruit load was estimated once on 28 June (rated 1 = no fruit to 10 = typical commercial fruit load). The number and mean heights of primocanes >8 mm diameter was recorded on 7 July 2006 at both locations.

Statistical analysis. For each sample date in field trials, cane survival and growth and fruit yield data were analyzed by Multifactor ANOVA using GLM procedures, and means were separated using Fisher's protected LSD procedure (Statgraphics Plus version 5; Manugistics Inc., Rockville, MD). The duration of exposure at each temperature required to kill colonies in the *in vitro* study was estimated as the x-intercept of a linear regression model of the incubation time and the diameter of the colonies after additional periods of incubation at 20°C. Colony growth data from the two experiments were combined for analysis. Response surface figures of the relationship of thermal dose to colony growth were graphed using Sigma Plot software (version 10; Systat Software, Inc., San Jose, CA).

RESULTS

In vitro growth study. The growth patterns of the two replicates were not different ($P < 0.05$) over the range of temperature tested. The rate of colony growth was linear at 20, 25, and 27°C ($R^2 > 0.99$) with growth rates of 0.140, 0.144, and 0.05 mm h⁻¹, respectively (Fig. 1). Colonies nearly covered the surface of the medium after 240 h at 20 and 25°C. Colonies incubated at 29°C grew less than 1 mm in 240 h, and no growth was observed at 31 to 35°C. After incubation at each temperature, colony growth resumed when cultures were returned to 20°C and incubated for 240 h (Fig. 2). Exposure time had little effect on cultures incubated at 25 and 27°C, i.e., colonies reached 95 to 100% maximum growth after 240 h at 20°C. After exposure to test temperatures $\geq 29^\circ\text{C}$, colony growth was suppressed upon return of colonies to 20°C, and the degree of suppression increased with increasing duration of exposure to high temperature. Radial growth was reduced to 22, 11.6, 2, and 0.8 mm by exposure to 29°C for 96, 144, 192, and 240 h, respectively. The exposure times required to kill the fungi were estimated as 222 h at 29°C ($R^2 = 97$), 168 h at 31°C ($R^2 = 91$), 108 h at 33°C ($R^2 = 91$), and 52 h at 35°C ($R^2 = 83$). Radial growth of colonies was reduced by 90% (≤ 4 mm) after exposure to 29, 31, and 33°C for 199, 148, and

Fig. 1. Growth of colonies of *Phytophthora rubi* on V8 juice agar incubated for 0 to 240 h at 20 to 35°C. Maximum growth is 80 mm.

Fig. 2. Growth of colonies of *Phytophthora rubi* on V8 juice agar after exposure at temperatures from 25 to 35°C for 0 to 240 h and then incubation at 20°C for an additional 240 h. Maximum growth is 40 mm.

76 h, respectively, relative to the control maintained at 20°C.

Clark County solarization trial. Solarization increased maximum soil temperatures 4.1 to 11.7°C (Table 1). Mean hourly soil temperatures were >28.2°C at both 10 and 30 cm soil depth in solarized plots, while mean temperatures in nonsolarized plots did not exceed 23.1°C. Mean hourly temperature at 30 cm was 2°C greater in solarized, raised bed plots compared to solarized flat bed plots. Approximately 800 cumulative hours with temperature >29°C were recorded at both depths in solarized raised bed plots. Solarized flat bed plots had 655 and 519 cumulative hours >29°C at 10 and 30 cm, respectively. Temperatures exceeded 29°C for ca. 100 h at 10 cm in nonsolarized plots, but did not reach 29°C at 30 cm.

ANOVA of the Clark County data with bed treatments as plots and cultivars as subplots in a split-plot design indicated that bed treatment and cultivar effects were

significant for all variables in Table 2 except for 2002 primocane height (differences not significant for both treatment and cultivar) and 2003 yield (differences not significant for cultivar only). Because treatment × cultivar interaction terms were significant for 2001 primocane weight and for 2003 primocane number, the data for the two cultivars are presented separately in Table 2.

During the 3 years, plant survival, growth, and yield were significantly greater in solarized raised bed plots than in plots receiving other treatments, and ‘Willamette’ produced more primocanes than ‘Malahat’. At the end of 2001, primocane weights of both varieties were greatest ($P < 0.05$) in raised solarized plots with and without gypsum amendment and least in nonsolarized flat bed plots (Table 2). A similar pattern was observed in the number of canes per hill in June 2002, August 2002, and October 2003 (Table 2). By October 2003, few canes of either cultivar

survived in flat bed or nonsolarized raised bed plots compared to solarized raised bed plots. In addition, the number of canes per hill was greater in solarized raised bed plots that were amended with gypsum than those without gypsum. Mean cane height of ‘Malahat’ was greater in solarized raised beds with gypsum amendment than in nonsolarized flat beds without gypsum, but ‘Willamette’ cane height differences were not as notable. Berry yields in plots of ‘Malahat’ were 2,658 g and 405 g in solarized raised beds with and without gypsum amendment, respectively, but less than 100 g for other treatments. The pattern was similar for ‘Willamette’ berry yields, but differences were not statistically significant for this variety.

The effects of solarization on the growth of weeds in plots were evident through the first year after planting raspberries. Weed density rating values were lower ($P < 0.05$) in raised bed solarized plots (1.5 to 1.9) than in nonsolarized plots (3.1 to 3.4). In

Table 1. Soil temperatures in solarized and nonsolarized plots at Clark County in 2000 and at Pierce County and Whatcom County in 2002

Location	Bed shape	Solarized	Depth (cm)	Temperature ^z (°C)		Cumulative hours				
				Mean	Max	h > 27°C	h > 29°C	h > 31°C	h > 33°C	h > 35°C
Clark Co.	Flat	–	10	23.1	32.3	214	106	33	0	0
	Flat	–	30	22.1	28.0	1	0	0	0	0
	Raised	–	10	22.9	32.3	213	90	21	0	0
	Raised	–	30	23.2	26.1	0	0	0	0	0
	Flat	+	10	31.2	41.6	848	655	484	383	289
	Flat	+	30	28.2	32.1	940	519	92	0	0
Whatcom Co.	Raised	+	10	32.1	44.0	927	787	546	443	364
	Raised	+	30	30.3	35.3	926	793	501	188	18
	Flat	–	10	18.7	28.7	21	0	0	0	0
	Flat	–	30	18.7	26.7	0	0	0	0	0
	Flat	+	10	28.0	42.9	816	604	425	293	180
	Flat	+	30	25.7	31.9	532	206	37	0	0
Pierce Co.	Flat	–	10	21.7	29.2	40	3	0	0	0
	Flat	–	30	20.9	22.5	0	0	0	0	0
	Flat	+	10	30.7	41.5	639	434	313	231	131
	Flat	+	30	28.5	31.9	643	345	66	0	0

^z Temperatures were recorded hourly by dataloggers. Thermocouples were buried at each depth in one solarized and one nonsolarized plot at each location. Temperature data were collected from 27 July to 20 September 2000 at Clark County, from 23 July to 13 September 2003 at Whatcom County, and only from 22 July to 20 August 2003 at Pierce County because of equipment failure.

Table 2. Effects of soil solarization, bed shape, and amendments of gypsum on the survival, growth, and yield of two root rot susceptible red raspberry cultivars, ‘Malahat’ and ‘Willamette’, planted in soil infested with *Phytophthora rubi* at the Vancouver Research and Extension Center in Clark County, WA

Bed shape	Solarized ^x	Gypsum ^y	Primocane weight (g) October 2001	Primocanes per hill			Primocane height (cm)		Berry yield per plot (g) July 2003
				June 2002	August 2002	October 2003	October 2002	October 2003	
Malahat									
Flat	–	–	39.0 a ^z	1.3 a	0.5 a	0.4 a	70 a	25 a	0 a
Flat	+	–	81.4 a	6.9 ab	5.6 a	1.1 a	88 ab	206 bc	13 a
Raised	–	–	84.5 a	8.1 ab	5.1 a	0.3 a	109 b	50 a	83 a
Raised	–	+	67.0 a	13.6 b	7.7 a	0.8 a	104 ab	113 ab	48 a
Raised	+	–	282.0 b	27.9 c	30.6 b	10.0 b	109 b	219 bc	405 a
Raised	+	+	295.0 b	26.0 c	22.9 b	15.2 c	124 b	294 c	2,658 b
Willamette									
Flat	–	–	113.1 a	8.0 a	7.4 a	2.2 a	94	169	160
Flat	+	–	177.8 a	10.2 a	9.2 a	4.3 a	125	181	1,323
Raised	–	–	198.7 a	7.4 a	4.7 a	0.9 a	88	163	8
Raised	–	+	160.4 a	17.8 a	17.1 a	7.2 a	126	266	913
Raised	+	–	661.8 c	46.0 b	38.4 b	25.5 b	105	288	2,048
Raised	+	+	384.5 b	37.4 b	37.4 b	42.3 c	118	359	2,843

^x Plots were solarized from 27 July through September 2000. Polyethylene film was left on the soil surface until raspberries were planted in May 2001.

^y Granular (prilled) agricultural gypsum was applied at 13,450 kg/ha and incorporated by rotovating to a depth of 20 cm.

^z Mean values within columns followed by different letters were significantly different ($P < 0.05$) according to Fisher’s LSD procedure.

subsequent years, there were no differences in weed densities between treatments.

Pierce and Whatcom county trials. The effects of soil solarization were evident in August 2004, 3 months after planting. The number of primocanes per hill was greater ($P < 0.05$) in plots that were solarized than in nonsolarized plots, but the percentage of surviving hills did not differ between treatments (Table 3). Total length and weight of canes per hill (collected in December) were reduced >30% (Whatcom County) and >60% (Pierce County) in nonsolarized compared with solarized plots ($P < 0.05$) (Table 3). Applications of fungicides combined with solarization reduced cane lengths of 'Malahat' in Pierce County and 'Qualicum' in Whatcom County. Plant growth was not different between plots in which only fungicides were applied and the nontreated control plots.

In 2005, plant vigor and disease incidence among the treatments were similar at both locations, but disease severity was

greater at the Pierce County site. In April, the number of primocanes per hill at Pierce County in solarized 'Qualicum' plots was greater ($P < 0.05$) than in both nonsolarized treatments and in solarized 'Malahat' plots compared to the nontreated plots (Table 4). At Whatcom County, cane stands in solarized plots of 'Qualicum' were not different than those that received only fungicides. In August, the number of primocanes per hill was similar to that in April at both locations, with the greatest number in solarized plots, intermediate number in plot that received only fungicides, and fewest in number in nontreated control plots. More canes survived ($P < 0.05$) in solarized + fungicide plots of 'Qualicum' than in solarized or fungicide only treatments. The percentage of diseased canes was greater in nontreated plots than in plots that received fungicide applications, but only significantly greater ($P < 0.05$) at Pierce County. In December, differences in cane height between treatments were evident at Pierce County where primocanes of 'Qualicum' plants in solarized

plots were longer ($P < 0.05$) than those that received only fungicides, and at Whatcom County where canes of 'Malahat' plants in solarized + fungicide treatment were longer ($P < 0.05$) than canes in the other treatments.

In 2006, the final year of the experiment, the survival of plants was extremely low in all plots at both locations (Table 5), indicating that both solarization and fungicide treatments were not sufficient to sustain productivity with these root rot susceptible varieties at these locations. Although there were significant differences between treatments for some parameters, these differences provide little biological information. For example, primocane survival at Pierce County was ≤ 1.5 canes per hill, which indicates complete failure of all treatments. Primocane survival was better at Whatcom County than at Pierce County.

DISCUSSION

The effects of elevated temperature and solarization on *Phytophthora* spp. are well-

Table 3. Effects of soil solarization and application of mefenoxam and fosetyl-Al on survival and primocane growth of two root rot susceptible red raspberry cultivars, 'Malahat' and 'Qualicum', during 2004, the first season after planting in two fields infested with *Phytophthora rubi* in Washington State

Location	Treatment		Malahat				Qualicum			
	Solarized ^v	Fungicide ^w	% Hill survival ^x	Canes per hill	Cane length (cm) ^y	Cane weight (g) ^y	% Hill survival ^x	Canes per hill	Cane length (cm) ^y	Cane (g) ^y
Pierce Co.	—	—	85	2.3 a ^z	136 a	33 a	100	3.1 a	188 a	45 a
	—	+	85	4.1 a	123 a	51 a	100	4.0 ab	177 a	70 a
	+	—	90	7.5 b	642 c	222 b	100	5.2 bc	511 b	201 b
	+	+	90	5.2 b	475 b	156 b	100	6.0 c	500 b	197 b
Whatcom Co.	—	—	88	3.6	376 a	106 a	96	5.4 a	479 a	145 a
	—	+	83	4.4	372 a	100 a	100	4.3 a	360 a	108 a
	+	—	88	5.0	784 b	253 b	100	7.1 b	831 c	275 b
	+	+	88	4.4	736 b	226 b	100	7.2 b	697 b	233 b

^v Plots were solarized from 22 July (Pierce) and 23 July (Whatcom) through September 2003.

^w Mefenoxam was applied once and fosetyl-Al twice in the spring and fall each year.

^x Survival was based on the presence of one or more primocanes per hill.

^y Primocanes were cut to the ground in December 2004, and total cane length and weight were recorded.

^z Mean values within columns followed by different letters were significantly different ($P < 0.05$) according to Fisher's LSD procedure.

Table 4. Effects of soil solarization and application of mefenoxam and fosetyl-Al on primocane growth and disease incidence of two root rot susceptible red raspberry cultivars, 'Malahat' and 'Qualicum', during 2005, the 2 years after planting in two fields infested with *Phytophthora rubi* in Washington State

Location	Treatment		April 2005		August 2005		December 2005	
			Primocanes per hill ^u		Primocanes per hill ^u		% Diseased canes ^v	
	Solarized ^x	Fungicide ^y	Malahat	Qualicum	Malahat	Qualicum	Malahat	Qualicum
Pierce Co.	—	—	14.2 a ^z	11.7 a	6 a	2 a	14.8 c	27.5 b
	—	+	19.5 ab	15.6 a	19 ab	21 b	1.6 ab	2.5 a
	+	—	41.5 b	27.3 b	31 b	30 bc	13.3 bc	2.0 a
	+	+	35.6 b	31.5 b	33 b	35 c	0.1 a	1.5 a
Whatcom Co.	—	—	22.9	20.8 a	12	18 a	11.5 b	9.0
	—	+	28.9	25.0 ab	26	27 b	0.5 a	1.0
	+	—	29.0	34.7 b	26	35 bc	8.3 ab	4.3
	+	+	26.8	33.4 b	29	42 c	0.3 a	1.3

^u Survival was based on the presence of one or more primocanes per hill.

^v Percentage of canes with symptoms of raspberry root rot.

^w Height of 50 primocanes was measured in two 50-m lengths of the row of each cultivar in the plots.

^x Plots were solarized from 22 July (Pierce) and 23 July (Whatcom) through September 2003.

^y Mefenoxam was applied once and fosetyl-Al twice in spring and fall each year.

^z Mean values within columns followed by different letters were significantly different ($P < 0.05$) according to Fisher's LSD procedure.

documented (1,2,5,16,20,22,23). Wilcox reported that the optimal temperature for colony growth of a Chilean isolate of *P. rubi* on V8 juice agar was 22 to 25°C and no colony growth was observed after 9 days at 28°C (37). Pullman et al. (25) reported a logarithmic relationship between time and temperature (thermal dose) on the death of four soilborne plant pathogens. We observed no mycelial growth at 29°C after 240 h, but after incubation for shorter duration at 29°C, colonies resumed growth when transferred to the optimal temperature for growth. Exposure to sublethal thermal doses reduced greatly the radial growth of colonies incubated subsequently at 20°C. Freeman and Katan (13) reported that sublethal temperatures may adversely affect spore viability of *Fusarium* expressed as delayed germination and germ tube growth. They suggest that biological control activities of soil bacteria may be responsible for reduced viability of weakened propagules. Sublethal temperature treatment of microsclerotia of *Verticillium dahliae* reduced the rate of germination, production of melanized microsclerotia, and made microsclerotia more susceptible to the biocontrol fungus *Talaromyces flavus* (32). We do not know whether exposure to temperatures less than 29°C for 222 h, the lethal exposure in the in vitro study, will suppress *P. rubi* oospore germination and disease development in raspberry fields. The in vitro study supports our field data, but it is not by itself sufficient to predict field performance elsewhere. Temperatures in the in vitro study were continuous, whereas soil temperatures are variable, particularly in the upper 10 cm. Furthermore, our lethal exposure was based upon vegetative growth, and oospores may be more heat tolerant. However, Duncan reported the *P. fragariae* infectivity was lost rapidly at 30°C, and prolonged exposure to 30°C killed oospores (9,10). In our in vitro study, mycelia were killed by exposure to 35°C for 52 h.

Similarly, Duncan (7) reported that oospores were killed by exposure to 35°C for 24 h.

Previous experiments demonstrated that solarization can suppress several soilborne plant pathogens under conditions in Oregon and southwestern Washington (22,23). Root rot of strawberry and raspberry were significantly reduced in solarized plots where cumulative hours of temperature >30°C were 794 h at 20 cm depth and 221 h at 30 cm, respectively (23). In our current research, cumulative hour >29°C at 30 cm soil depth ranged from 206 to 793 h, thermal doses that exceed lethal level for *P. rubi* colonies in the laboratory study (Table 1). Nearly continuous periods of soil temperatures >29°C occurred at 30 cm in August and were only separated by very brief periods when temperatures ranged between 27 and 29°C (data not presented). Fluctuation of diurnal temperatures was more pronounced at the 10 cm soil depth, but temperature maximums were greatest at this depth, with recorded temperatures >35°C for 131 to 364 h (Table 1). These durations >35°C are much greater than those calculated to be lethal for vegetative growth in the in vitro study and much greater than those reported to be lethal to *P. fragariae* oospores (7). We recorded temperatures 2 to 3°C higher and an additional 274 h > 29°C at 30 cm in raised bed compared to flat beds, while temperatures at 30 cm did not reach 35°C in solarized flat beds and were >35°C for only 18 h in solarized raised beds. Chellemi et al. (4) observed a similar 2 to 4°C difference between solarized flat and raised beds and noted that raised beds eliminated the border effects associated with solarization. We believe that the additional temperature gain was due to morning and afternoon solar heating of the sides of the raised beds, which were orientated in north-south rows. The decline of raspberry stands in solarized plots in the third year may be a function of roots growing into soil depths

where thermal dose was insufficient to reduce inoculum density of *P. rubi*. The third year is also the first year of full crop production for florican-bearing varieties like 'Malahat' and 'Qualicum', so the collapse in this year could result from the stress of a full fruit load on plants with PRR-compromised root systems.

Climatic conditions can have a significant effect on the development of PRR of raspberry (18). In the Whatcom and Pierce experiments, plant stands in the solarization plots were denser and canes more vigorous in plots that were solarized compared to nonsolarized plots during the first 2 years after planting. In the third season, conditions were very conducive for the development of PRR (10,11). Precipitation was recorded on 90 days during the first 6 months of 2006 and the mean percent soil moisture was >24% during this period (AgWeatherNet, WSU, Prosser, WA). Mean soil temperature at 20 cm depth during the spring of 2006 was 12.2°C (6 to 16°C) and 12.5°C (7 to 19°C) at Pierce County and Whatcom County, respectively. During harvest in late June and early July, an unusual period of high temperatures (air temperature max. 34°C) and dry conditions stressed the plants, which wilted rapidly. These conditions resulted in very low survival of primocanes in the Pierce County plots where there was very high disease pressure. Substantial primocane mortality also was observed in the Whatcom County plots. Even PRR tolerant genotypes in the raspberry breeder's trial adjacent to the Pierce County plots showed PRR symptoms under the high disease pressure and stressful conditions (P. Moore, personal communication).

The management of PRR in raspberry requires a multifaceted approach. Wilcox et al. (38) reported that raised beds consistently improved raspberry yield compared to flat beds. Metalaxyl was least effective under high root rot pressure, initially improving yield of a susceptible variety, but

Table 5. Effects of soil solarization and application of mefenoxam and fosetyl-Al on primocane survival, growth, and fruit yield of two root rot susceptible red raspberry cultivars, 'Malahat' and 'Qualicum', in July 2006, 3 years after planting in *Phytophthora rubi* infested fields at two locations in Washington State

Location	Treatment		Berry yield ^v		Primocanes per hill ^w		Primocanes height (cm) ^w	
	Solarized ^x	Fungicide ^y	Malahat	Qualicum	Malahat	Qualicum	Malahat	Qualicum
Pierce Co.	–	–	1.0	1.0 a ^z	0.0 a	0.0 a	0.0	2.0 a
	–	+	1.3	4.5 b	0.8 b	1.5 b	0.0	56.0 b
	+	–	1.0	2.3 ab	0.1 a	0.3 a	0.0	14.0 ab
	+	+	1.3	3.8 ab	0.1 a	0.3 a	1.0	34.8 ab
Whatcom Co.	–	–	1,190	1,880	1.6	6.5	12.0	31.2 a
	–	+	1,410	3,660	3.1	10.7	21.9	54.9 b
	+	–	1,610	3,900	1.1	7.2	10.7	43.7 ab
	+	+	2,440	3,850	3.1	10.4	23.4	54.9 b

^v Whatcom plots were machine harvested on three dates between 22 June and 18 July 2006. Berry yield is total berry weight (g) from the three harvests. At Pierce Co., the fruit load was estimated on 28 June plots and rated 1 = no fruit to 10 = typical commercial fruit load.

^w Number and mean heights of primocanes >8 mm diameter was recorded on 7 July 2006 at both locations.

^x Plots were solarized from 22 July (Pierce) and 23 July (Whatcom) through September 2003.

^y Mefenoxam was applied once and fosetyl-Al twice in spring and fall each year.

^z Mean values within columns followed by different letters were significantly different ($P < 0.05$) according to Fisher's LSD procedure.

plants died the second year. They later reported gypsum amendments produced the best yield, better than metalaxyl, and that raised beds were not as effective with highly susceptible cultivars (18). They recommended an integrated program for managing raspberry root rot that included raised beds, gypsum amendments, fungicide applications, and planting more tolerant varieties. In the Clark County trial, we observed the greatest plant survival and fruit yield in plots with solarized raised beds in which soil was amended with gypsum. Hilling reduces waterlogging, making soil conditions less conducive for root rot. In addition, the calcium ions from gypsum can restrict the liberation and movement of zoospores and disease development (39). In our trials, soil solarization probably reduced the inoculum potential of *P. rubi*, thus complimenting the effects of raised beds and gypsum. The varieties that we planted were very susceptible to *P. rubi* (3,31) and the sites had high inoculum potential, so symptoms of root rot became evident in the third year, with PRR symptoms evident in all plots. Under such conditions, applications of mefenoxam and fosetyl-AI were ineffective in reducing PRR, as reported in New York (18).

Soil solarization has been reported to be as effective as methyl bromide fumigation (15) and metalaxyl (34) for control of *Phytophthora* root diseases. Our research demonstrated that solarization initially can suppress PRR, but solarization and chemical control were not sufficient to maintain productivity past the second year with susceptible varieties and high disease pressure. Other inputs are needed to maintain plant vigor and yield. An integrated program for management of PRR would combine solarization with root rot tolerant varieties, raised beds, gypsum amendments, and applications of fungicides. Solarization can be combined with fumigation (4), cultural practices (26,30), and biological control (24,32,33). Solarization is particularly attractive for small fruit production systems because the polyethylene tarp can be left on the soil surface after solar heating, followed by planting through this plastic mulch for extended weed control and increased soil temperature for early season root development.

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