Managing Phytophthora Crown and Root Rot in Bell Pepper Using Fungicides and Host Resistance

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ABSTRACT

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A resistant pepper cultivar and nine fungicides were tested in both the field and greenhouse and their ability to limit Phytophthora crown and root rot was demonstrated. In both settings, the resistant pepper 'Paladin' and the susceptible pepper 'Red Knight' were inoculated with prepared millet seed infested with *Phytophthora capsici*. Foliar sprays were applied to the pepper plants on a 7-day interval in the field, and foliar sprays or drenches were applied at 7- or 14-day intervals in the greenhouse. Cv. Paladin had significantly less plant death than Red Knight. In the field, plants treated with fluopicolide or mandipropamid had significantly less plant death than the untreated control plants and, in the greenhouse, all fixed effects, including cultivar, fungicide treatment, application method, and application interval, were significant. The interactions among fungicide-cultivar, application method-cultivar, application method-fungicide, and fungicide-cultivar-application method were also significant in the greenhouse. Treatments applied as drenches provided greater control of *P. capsici* than those applied foliarly. Combining a resistant cultivar with a fungicide applied as a drench may help reduce the incidence of crown and root rot in pepper.

Michigan producers grow both hot and bell pepper types for fresh and processing markets with a farm gate value of \$12 million (1). *Phytophthora capsici* Leonian is a major pathogen of pepper that causes root, crown, and fruit rot as well as stem and leaf blight (11,18). Raised plant beds with drip irrigation covered with black plastic mulch (18) are used to control *P. capsici* in production of pepper for the fresh market; the mulch is a physical barrier that reduces rain splash of infested soil onto susceptible plants, and drip irrigation reduces rain splash and soil saturation (3,4,17,20,25). Pepper plants for the processing market are grown on flat plant beds without drip irrigation to reduce costs. Field epidemics often occur on flat-bed systems because aerial plant tissues are not protected from infested soil and soil may become saturated readily, which exacerbates crown and root rot (8). *P. capsici* can overwinter for lengthy periods in the soil (>10 years) (8), limiting the usefulness of crop rotation as a management strategy (10).

Several commercial bell pepper cultivars are fully or partially resistant to some isolates of *P. capsici*. Physiological races have

been reported in the *P. capsici*-pepper system, and resistance may be race specific (6,14,22). This observation was recently reported by Sy et al. (22), who created 26 recombinant inbred lines (RILs) by crossing the resistant CM334 with the susceptible 'Early Jalapeno' and screened them against isolates from New Mexico, California, and the Netherlands. They found that 13 root rot races differentiated out of the 17 isolates screened, and concluded that the level of resistance observed for the RILs varied by *P. capsici* isolate or race (22).

Root rot and foliar blight resistance are controlled by two different dominant genes (23). Sy et al. (21) demonstrated that resistance in pepper to Phytophthora stem blight, root rot, and foliar blight are controlled by separate genetic systems. Hence, cultivars resistant to root rot may not be resistant to foliar blight and foliar fungicide applications may be necessary for cultivars with root rot resistance in order to control foliar symptoms. McGrath and Davey (13) applied foliar fungicides to the root-rot-resistant 'Aristotle' and the susceptible 'Red Knight.' All foliar fungicides reduced incidence of Phytophthora fruit and crown rot in both cultivars compared with the untreated control (13). In Michigan, crown and root rot occurs more frequently in pepper than fruit rot or stem and leaf blight (8). The efficacy of fungicides applied as a drench for controlling Phytophthora root rot of pepper has been tested (2,7,12,13). Matheron and Porchas (12) found that drench applications of

fungicides provided excellent control of *P. capsici* in Aristotle and extended the life-span of the plant compared with untreated control plants under greenhouse conditions. With the exception of metalaxyl, mefenoxam, mono- and dibasic sodium, potassium, and ammonium phosphites, fungicides registered for controlling Phytophthora on pepper are specified to be applied to the foliage. Considering that some pepper isolates demonstrate higher virulence relative to other isolates (5), a combination of control measures is needed to limit disease and includes raised plant beds, resistant cultivars, and fungicides.

The objective of our research was to compare the effects of select fungicides when applied as a drench or foliar treatment on susceptible and resistant bell pepper cultivars to control Phytophthora root and crown rot caused by *P. capsici*.

MATERIALS AND METHODS

Inoculum preparation. Cultures of *P. capsici* isolate 12889 (mating type A1, insensitive to the fungicide mefenoxam, isolated from a pepper fruit, and more virulent on pepper than other Michigan isolates previously tested; 5) were obtained from agar plugs from long-term stock cultures (stored at 20°C in sterile microcentrifuge tubes with 1 ml of sterile water and a sterile hemp seed) in the laboratory of Dr. Mary Hausbeck (Michigan State University [MSU]). Agar plugs were transferred from the stock cultures onto unclarified V8 agar (UCV8; 16 g of agar, 3 g of CaCO₃, 160 ml of unfiltered V8 juice, and 840 ml of distilled water) and maintained under constant fluorescent light at room temperature (21 ± 2°C) for 7 days. Millet seed inoculum was prepared according to the methods of Quesada et al. (16).

Field experiment. Field trials were established at two sites: the Muck Soils Research Farm (MSRF) in Clinton County, MI on clay loam soil and the Southwest Michigan Research and Extension Center (SWMREC) in Berrien County, MI on loamy fine sand. Flats (128-cell) of *P. capsici*-resistant 'Paladin' and *P. capsici*-susceptible Red Knight bell pepper transplants were obtained from Keitzer Farms (Hartford, MI). Pepper transplants were 9 weeks old with three true leaves and were placed outside for 3 days prior to transplanting to acclimate the seedlings to the outdoors. Seedlings were transplanted into raised plant beds (0.6 m wide and 15.24

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cm high) covered with black plastic mulch (1.25-mil thickness). Plant beds were spaced 1.5 m apart on center with drip irrigation. Each treatment plot was 12.2 m long and contained a row of each cultivar spaced 0.3 m apart, using staggered planting. Plants were placed 0.3 m apart within their row, resulting in 80 pepper plants per treatment plot. The plots were arranged in a randomized complete block design, with blocks replicated four times.

Fourteen days after transplanting, 1 g of millet seed inoculum was inserted 2.5 cm into the soil directly beside the transplant plug. Weeds surrounding the plants within the planting beds were removed by hand; weeds between planting beds at the MSRF were controlled with clomazone (Command 3ME; FMC Corporation, Philadelphia) at 0.12 kg a.i./ha and S-metolachlor (Dual Magnum; Syngenta Crop Protection, Inc., Greensboro, NC) at 0.66 kg a.i./ha prior to transplanting. At SWMREC, weeds were controlled between the planting beds with halosulfuron-methyl (Sandea; Gowan Company, Yuma, AZ) at 0.01 kg a.i./ha and S-metolachlor at 0.66 kg a.i./ha after transplanting. Insects were controlled at both locations with two applications of imidacloprid (Admire Pro; Bayer CropScience, Greensboro, NC) at 0.11 kg a.i./ha applied through drip-irrigation emitters calibrated to deliver 473 liters/ha. Four days after planting (9 June), maneb (Maneb 75DF; Cerexagri-Nisso, King of Prussia, PA) at 0.51 kg a.i./ha and copper hydroxide (Champ Formula 2; Nufarm Americas Inc., Burr Ridge, IL) at 0.33 kg a.i./ha were applied to the pepper foliage at SWMREC. No fungicides were applied thereafter aside from experimental treatments. Both sites were fertilized once a week with Mora-Leaf 20-20-20 soluble fertilizer at 5.7 kg/ha via the drip system (Wilbur Ellis, Fresno, CA) for the first 4 weeks after planting and twice weekly for

the remainder of the experiment. At 4 and 8 weeks after transplanting, plots were fertilized with calcium at 1.2 liter/ha.

Drench treatments (Table 1) were applied to the transplant tray prior to removing the seedlings for planting using a 7.6-liter watering can at 945 liter/ha. Foliar treatments (Table 1) commenced at planting and were reapplied every 7 days using a backpack sprayer and a three-nozzle boom with 50-mesh screens and 8003XR nozzles, calibrated to deliver 473 liter/ha. The outer two nozzles were aligned at a 45° angle toward the pepper crown, with the middle nozzle positioned directly over the canopy.

The number of plants per row of each cultivar exhibiting symptoms of infection, including wilting, stem lesions, and plant death, were counted weekly. Phytotoxic effects of fungicides on pepper plants were evaluated on a 1-to-5 scale per plot (1 = no phytotoxicity, 2 = slight stunting or chlorosis, 3 = moderate stunting or chlorosis, 4 = major stunting or chlorosis, 5 = plant death due to phytotoxicity). The area under the disease progress curve (AUDPC) was calculated according to the methods of Shaner and Finney (19) to describe the cumulative plant infection incidence (%) throughout the growing period. Marketable-sized fruit (≥ 7.5 cm in width and ≥ 9.0 cm in length) were harvested from the entire length of row per plot and weighed.

Greenhouse experiments. Pepper seed of Paladin and Red Knight, obtained from Seedway (Hall, NY), were sown in 128-cell flats containing soilless potting media (BACCTO Professional Planting Mix; Michigan Peat Company, Houston) and placed in a greenhouse with a 14-h photoperiod. When seedlings developed three to four true leaves, they were transplanted into 1.5-liter pots filled with soilless potting media (BACCTO Professional Planting Mix) and arranged in a completely

randomized design in a greenhouse with a 14-h photoperiod at the MSU Horticulture Teaching and Research Center, East Lansing. Pots were irrigated individually using a hose and a breaker every 1 to 2 days and fertilized three times a week with Peters 20-20-20 (Scott's Company, Marysville, OH) at 200 ppm. Irrigation water was amended with phosphoric acid at 132 ppm twice weekly to maintain the media pH at approximately 6.0 to 6.5. The pH was checked monthly by collecting random media samples and using a pH meter (Hanna Instruments, Woonsocket, RI).

Each pot was inoculated with 1 g of millet seed inoculum (as previously described) 24 h after transplanting, except for 24 pots of each cultivar that were untreated and uninoculated. Fungicides and application rates were identical to the field experiment but included mefenoxam (Ridomil Gold 4SL; Syngenta Crop Protection) at 0.56 kg a.i./ha as an additional treatment. Twenty-four pots of each cultivar were untreated and inoculated with *P. capsici*. Fungicide treatments were applied immediately following inoculation. Foliar applications were made using a backpack sprayer as previously described. Drench applications were made by hand, applying enough fungicide solution to each pot at a rate equivalent to 945 liter/ha (approximately 80 ml). Each fungicide treatment, application method, and treatment interval combination was replicated six times; the trial was conducted twice. The experiment was arranged with treatments in a completely randomized design.

Disease was assessed using a 1-to-5 scale (1 = healthy, 2 = minor wilting, 3 = moderate wilting, 4 = severe wilting, and 5 = plant death) modified from Glosier et al. (6) every 2 days following the first symptom of plant wilting and continued for 14 days after the final fungicide application. The AUDPC was calculated according to

Table 1. Fungicide treatment, rate, and application schedules applied weekly to pepper plants inoculated with *Phytophthora capsici*

Treatment	Rate (kg a.i./ha)	Product information
Untreated uninoculated	...	...
Untreated inoculated	...	...
Mandipropamid ^w	0.15	Revus 2.08SC (Syngenta Crop Protection, Greensboro, NC)
+ Nonionic surfactant ^w	0.15	Activator 90 8.33EC (Loveland Products Inc., Greeley, CO)
Fluopicolide ^w	0.10	Presidio 4FL (Valent U.S.A. Corporation, Walnut Creek, CA)
Dimethomorph ^w	0.22	Acrobat 50WP (BASF Corporation, Greensboro, NC)
Potassium phosphite ^x	2.47	Prophyt 4.2EC (Helena Chemical Company, Collierville, TN)
Potassium phosphite ^y	3.71	Prophyt 4.2EC
Fenamidone ^w	0.19	Reason 500SC (Bayer CropScience, Greensboro, NC)
Dimethomorph ^w	0.22	Forum 4.16SC (BASF Corporation)
Famoxadone/cymoxanil ^w	0.28	Tanos 50WG (E.I. du Pont Corporation, Wilmington, DE)
Copper hydroxide ^w	1.21	Kocide 2000 54DF (E.I. du Pont Corporation)
Program treatment		
Potassium phosphite ^x	2.47	Prophyt 4.2EC
Fluopicolide ^z	0.10	Presidio 4FL
Dimethomorph ^z	0.22	Acrobat 50WP
Potassium phosphite ^z	3.71	Prophyt 4.2EC

^w Foliar treatments were applied with a backpack sprayer and three-nozzle hand-boom (473 liter/ha) and continued every 7 days for 12 weeks.

^x Drench treatments were applied directly to the transplant tray (945 liter/ha) at planting.

^y Foliar treatments commenced 14 days after planting and continued every 7 days for 12 weeks.

^z Foliar treatments commenced 7 days after planting. Products were applied alone and alternated every 7 days for 12 weeks.

the methods of Shaner and Finney (19) to demonstrate the cumulative plant infection (%) throughout the growing period.

Pathogen confirmation. Approximately 10% of the symptomatic plants from both the field and greenhouse experiments were returned to the laboratory to isolate the pathogen. The plants were rinsed with deionized water and the roots and crowns were surface sterilized with a 70% ethanol solution. Three sections of root and crown tissue were excised and plated onto UCV8 plates amended with benomyl at 25 ppm, ampicillin at 100 ppm, rifampicin at 30 ppm, and pentachloronitrobenzene at 100 ppm. Plates were incubated at room temperature ($21 \pm 2^\circ\text{C}$) under continual fluorescent light for 7 days and observed microscopically at $\times 200$ using a compound microscope to confirm *P. capsici* morphological characteristics according to the *Phytophthora* spp. key by Waterhouse (24).

Weather monitoring. Hourly measurements of air temperature, relative humidity, and rainfall were recorded using a Watchdog data recorder (Model 450; Spectrum Technologies, Inc., Plainfield, IL) and tipping-bucket rain collector (Spectrum Technologies, Inc.) in the field. In the greenhouse, air temperature and relative humidity were recorded using a Watchdog data recorder. Total rainfall was 442.2 and 480.6 mm at the MSRF and SWMREC, respectively (Table 2). Mean air temperatures at MSRF and SWMREC were 18.7 and 20.2°C , respectively. The average temperature recorded during the greenhouse experiments was 16.0°C (minimum 1°C , maximum 38.4°C). The average relative humidity was 65.7% (minimum 20.7%, maximum 93.1%).

Statistical analysis. AUDPC values, plant death (%), and yield data from both the field and greenhouse experiments were subjected to analysis of variance (ANOVA) using the PROC MIXED of SAS (v. 9.1; SAS Institute Inc., Cary, NC). Fisher's protected least significant difference (LSD) was used for separation of means when effects were found to be statistically significant in ANOVA analysis ($P \leq 0.05$). Greenhouse AUDPC data were log transformed prior to LSD analysis to satisfy

assumptions of normality. To characterize significant interactions ($P \leq 0.05$), effects were sliced into single factors or factor combinations. Significant interactions were separated with Fisher's protected LSD. Data from noninoculated control plants were removed from the data set prior to statistical analysis.

RESULTS

Field experiment. Symptoms of disease, including wilting and stem lesions, were observed 7 days postinoculation (dpi) at both sites for the inoculated control plants. When untreated, plant death at the final evaluation was 8.6 and 84.1% for Paladin and Red Knight, respectively (Fig. 1). Significant differences were detected for plant death incidence and AUDPC values calculated for the cultivars ($P < 0.0001$ and 0.0001 , respectively) and fungicides ($P = 0.0010$ and 0.0192 , respectively) (Table 3). Treatment with the fungicides fluopicolide, mandipropamid, and the program treatment (potassium phosphite, fluopicolide, and dimethomorph

50WP) resulted in significantly less plant death (%) than the inoculated untreated control (Table 3). Applications of the fungicides fluopicolide, mandipropamid, dimethomorph 50WP, potassium phosphite, and the program treatment fungicides had AUDPC values that were significantly lower than the inoculated, untreated control. Marketable yields differed significantly for cultivars ($P < 0.0001$) but not for the fungicide treatments. The interaction between cultivar and fungicide was not significant for either plant death ($P = 0.6256$), AUDPC ($P = 0.4754$), or yield ($P = 0.0869$). Applications of potassium phosphite, alone and in the program treatment, appeared to cause phytotoxicity on Paladin but not Red Knight (*data not shown*). Phytotoxicity, including plant stunting, browning, and curling of leaf margins and brown speckling on the leaves, occurred only at MSRF.

Greenhouse experiment. Pepper plants in the first and second repetitions began showing symptoms of infection, including wilt and lesions at the base of the stem, at

Fig. 1. Disease progress curve of bell pepper cvs. Paladin and Red Knight in untreated field plots at two sites in Michigan inoculated with an isolate of *Phytophthora capsici* in 2008.

Table 2. Precipitation (Precip.) and soil and air temperature (average, minimum, and maximum) at the Muck Soil Research Farm (MSRF) and Southwest Michigan Research and Extension Center (SWMREC) in Michigan, 2008

Field, month	Air temperature (°C)			Soil temperature (°C)			Precip. (total mm)
	Average	Minimum	Maximum	Average	Minimum	Maximum	
MSRF							
June	19.6	4.5	32.6	19.9	11.1	30.4	91.1
July	20.7	3.6	31.4	21.7	13.0	29.8	93.7
August	18.8	2.3	30.6	21.5	12.2	32.9	39.6
September	15.6	1.0	32.6	18.2	9.7	30.4	217.8
SWMREC							
June	20.2	8.2	31.0	21.9	14.4	30.3	59.1
July	21.9	9.3	31.9	24.9	17.8	32.2	92.2
August	20.6	10.3	31.4	24.5	17.9	32.6	36.3
September	17.9	7.6	32.9	20.6	14.7	31.9	293.0

7 and 20 dpi, respectively. The untreated, noninoculated control plants remained asymptomatic for the duration of the experiment. The ANOVA for fixed effects was significant for the AUDPC values of cultivar ($P < 0.0001$), fungicide treatment ($P < 0.0001$), treatment interval ($P = 0.0090$), and application method ($P < 0.0001$) (Table 4). Fungicides applied at 7-day intervals (36.3% plant death) had statistically lower AUDPC values than those applied at 14-day intervals (41.9% plant death). Drench applications (21.8% plant death) of fungicides had a significantly lower mean AUDPC value than foliar applications (56.5% plant death). Paladin (14.4% plant death) had a significantly lower mean AUDPC value than Red Knight (67.9% plant death). All fungicide treatments, except copper hydroxide, had lower AUDPC values than the untreated inoculated control plants (Table 5).

The P value for interactions among the effects fungicide–cultivar ($P = 0.0001$), application method–cultivar ($P < 0.0001$), and application method–fungicide ($P < 0.0001$) were also significant. Regardless of fungicide treatment, Paladin had statistically lower AUDPC values than Red Knight (Table 5). However, the differences between the cultivars' AUDPC were not of the same magnitude. Plants treated with potassium phosphite, for example, had a greater difference in mean AUDPC values between Paladin and Red Knight than plants treated with famoxadone or cymoxanil. Differences in magnitude were also observed between application method and cultivar (*data not shown*). All combinations of Paladin and Red Knight with drench and foliar applications were statistically different but it appears as though drench applications had a greater effect on

Red Knight than on Paladin. The interaction between application method and fungicide differed in magnitude, and drench applications always had statistically lower AUDPC values than foliar applications for all fungicides except copper hydroxide (Table 6).

A three-way interaction among application method–cultivar–fungicide was significant and differed in magnitude ($P = 0.0470$) (Table 7). The effects of drench treatments of famoxadone or cymoxanil, fluopicolide, mandipropamid, fenamidone, dimethomorph 50WP, and dimethomorph 4.16SC were statistically similar for Paladin and Red Knight. Foliar applications of all fungicides on Paladin resulted in statistically lower AUDPC values than the same fungicide applied to Red Knight. Treatments applied to Paladin had statistically similar AUDPC values when applied as either a drench or foliar application. The application method had a greater effect on Red Knight, because all drench applications had lower AUDPC values than when the same product was applied to foliage. In general, fungicides applied to the foliage of Red Knight resulted in statistically higher AUDPC values than foliar applications made to Paladin and drench applications made to both cultivars. Also, drench applications made to Paladin had lower AUDPC values than foliar applications or drench applications made to Red Knight, although this trend was not always statistically significant.

Repeated drench and foliar applications of mefenoxam resulted in phytotoxicity. Phytotoxicity first appeared as chlorotic areas on the leaves with leaf margins subsequently turning white and resulted in defoliation, leaving an apparently healthy green stem. Repeated drench applications

of fenamidone also resulted in phytotoxicity. Small yellow to brown spots appeared on the leaves, causing eventual plant wilt without death.

DISCUSSION

Host resistance coupled with fungicide applications and cultural control are important in managing *Phytophthora* crown and root rot (8,18). Several pepper lines resistant to *P. capsici* are available but few have demonstrated resistance to a wide range of isolates (5,6,22). In this study, Paladin was significantly more tolerant to the Michigan pepper isolate 12889 than Red Knight. Others have noted the importance of screening cultivars with local isolates (6,22). Glosier et al. identified 14 distinct virulence groups out of 34 isolates from California, New Mexico, and the Netherlands (6). A significant interaction was observed between isolate and cultivar; some cultivars were resistant to certain

Table 4. Area under the disease progress curve (AUDPC) and plant death (%) for treatment interval, application method, and cultivar of bell pepper inoculated with *Phytophthora capsici* in the greenhouse

Effect	AUDPC ^z	Plant death (%)
Interval		
7-day	79 a	36.3
14-day	84 b	41.9
Method		
Drench	60 a	21.8
Foliar	103 b	56.5
Cultivar		
Paladin	58 a	14.4
Red Knight	105 b	67.9

^z AUDPC means within the same effect that are followed by the same letter are not statistically different according to Fisher's least significant difference ($P = 0.05$).

Table 3. Plant death (%), area under the disease progress curve (AUDPC), and marketable yield of bell pepper cvs. Red Knight (RK) and Paladin (Pal) treated with fungicides in the field^u

Treatment, rate (kg a.i./ha) ^v	Plant death (%)			AUDPC			Marketable yield (kg/12.2 m of row)		
	Both	Pal	RK	Both	Pal	RK	Both	Pal	RK
Untreated inoculated	57.8 c	20.0	92.8	3,228 c	963	5,494 b–d	14.7	26.8	2.5
Fluopicolide, 0.15 ^w	43.9 a	3.8	84.1	2,518 a	198	4,838 ab	14.9	28.0	1.8
Mandipropamid, 0.10 ^w	47.3 ab	3.8	90.9	2,632 ab	202	5,062 a–c	14.3	26.5	2.1
Program treatment									
Potassium phosphite, 2.47 ^x	...	...	...	...	...	...	...	...	...
Fluopicolide, 0.10 ^y	...	...	...	...	...	...	...	...	...
Dimethomorph 50WP, 0.22 ^y	...	...	...	...	...	...	...	...	...
Potassium phosphite, 3.71 ^y	47.8 ab	8.8	86.9	2,883 a	291	4,632 a	9.7	14.4	5.0
Dimethomorph 50WP, 0.22 ^w	51.4 a–c	10.9	91.9	2,848 ab	478	5,217 a–c	12.7	23.6	1.7
Potassium phosphite, 2.47 ^x	...	...	...	...	...	...	...	...	...
Potassium phosphite, 3.71 ^z	51.6 bc	8.4	94.7	2,883 ab	291	5,474 b–d	10.0	17.7	5.3
Copper hydroxide, 1.21 ^w	52.5 bc	10.9	94.1	3,103 bc	619	5,587 cd	16.1	31.0	1.1
Dimethomorph, 4.18SC 0.22 ^w	52.7 bc	8.4	96.9	3,053 bc	408	5,699 cd	13.2	24.6	1.8
Fenamidone, 0.19 ^w	52.8 bc	11.6	95.9	3,197 c	674	5,719 cd	13.9	26.5	1.4
Famoxadone/cymoxanil, 0.28 ^w	55.8 c	15.9	95.6	3,383 c	819	5,947 d	14.8	28.5	1.2

^u Data are the single effect of the fungicides on plant death (%), AUDPC, and marketable yield. Column means with a letter in common or with no letter are not significantly different (Fisher's Method; $P = 0.05$).

^v Each plant was inoculated with 1 g of millet seed inoculum prepared with *Phytophthora capsici* isolate 12889 from Michigan.

^w Treatments were applied as foliar applications calibrated to deliver 473 liter/ha, weekly commencing at transplanting.

^x Treatments were applied as a drench application directly to the transplant tray.

^y Treatments were alternated every 7 days, commencing 7 days after transplanting.

^z Treatment was applied as foliar applications calibrated to deliver 473 liter/ha, weekly commencing 14 days after transplanting.

isolates but susceptible to others. Hence, cultivars with proven resistance to *P. capsici* isolates in one region may have little or no resistance to the isolates in other regions.

In Michigan, a management strategy should be tailored to crown and root rot, which is the most common disease symptom of *Phytophthora* spp. on pepper. In this study, a drench application of fungicides provided greater control than a foliar application. Because fungicides are expensive, it is important that the fungicides chosen effectively control *P. capsici*, provide adequate coverage of the targeted plant parts, and are applied in the most effective manner.

The fungicide mefenoxam has historically been used to control *P. capsici* on pepper. However, resistance of *P. capsici* to mefenoxam has been documented in the United States (15) and in Michigan (9), which has necessitated the use of other fungicides. Although directing foliar fungicide applications to the base of susceptible pepper cultivars growing in the field limited crown and root rot compared with the untreated control in our study, the level of control was not satisfactory. Plants treated with fluopicolide and mandipropamid had statistically less plant death than the untreated control but >40% plant death was still observed. Producers often experience large-scale epidemics, especially in low-lying areas of the field (8,17,18) where disease pressure can be high but where this level of fungicide performance might be too low (8,13). McGrath and Davey (13) evaluated the efficacy of six different fungicides, including mefenoxam, for control of *Phytophthora* blight. All fungicide applications resulted in a statistically lower percentage of plant death than the untreated control but the most effective treatment for Red Knight still resulted in 25% plant death. When fungicides were used in combination with the resistant bell pepper Aristotle, plant death (%) in the most effective treatment was limited to 7%. In the present study, when resistant bell pepper plants were used in combina-

tion with fungicides, plant death decreased significantly in both the field and greenhouse.

In greenhouse experiments, products had statistically lower AUDPC values when applied at 7-day versus 14-day inter-

vals. Also, products applied as drenches were more effective than when applied as foliar treatments. There was no interaction between treatment interval and application method, implying that both foliar and drench applications were most effective at

Table 6. Interaction in area under the disease progress curve (AUDPC) between application method (drench and foliar) and fungicide treatment in the greenhouse

Treatment and AUDPC ^z			
Drench		Foliar	
Famoxadone/cymoxanil	48.6 a	Famoxadone/cymoxanil	74.9 cd
Fluopicolide	48.8 a	Fluopicolide	98.1 e
Mandipropamid	50.3 a	Dimethomorph 4.18SC	102.3 ef
Dimethomorph 50DF	53.8 ab	Copper hydroxide	105.6 ef
Dimethomorph 4.18SC	57.5 ab	Fenamidone	106.5 f
Mefenoxam	59.2 a–c	Dimethomorph 50DF	107.3 f
Fenamidone	66.7 bc	Mandipropamid	107.7 f
Potassium phosphite	75.5 bd	Mefenoxam	109.6 f
Copper hydroxide	85.5 de	Potassium phosphite	110.8 f

^z Each plant was inoculated with 1 g of *Phytophthora capsici*-infested millet seed. Mean AUDPC values with letters in common are not statistically different according to Fisher's least significant difference ($P = 0.05$).

Table 7. Interaction in area under the disease progress curve (AUDPC) between cvs. Red Knight and Paladin, application method (drench versus foliar), and fungicide treatment in the greenhouse

Cultivar, treatment, and AUDPC ^z			
Paladin		Red Knight	
Drench			
Famoxadone/cymoxanil	49 a	Famoxadone/cymoxanil	49 a
Dimethomorph 4.18SC	49 a	Fluopicolide	49 a
Fluopicolide	49 a	Mandipropamid	52 ab
Mandipropamid	49 a	Dimethomorph 50WP	59 a–d
Dimethomorph 50WP	49 a	Dimethomorph 4.18SC	66 a–d
Mefenoxam	49 a	Mefenoxam	69 b–d
Potassium phosphite	59 a–d	Fenamidone	72 cd
Fenamidone	62 a–d	Potassium phosphite	92 ef
Copper hydroxide	64 a–d	Copper hydroxide	106 f
Foliar			
Famoxadone/cymoxanil	49 a	Famoxadone/cymoxanil	101 f
Dimethomorph 4.18SC	55 a–c	Fluopicolide	136 g
Fluopicolide	61 a–d	Fenamidone	137 g
Mandipropamid	63 a–d	Copper hydroxide	145 gh
Potassium phosphite	64 a–d	Dimethomorph 50WP	149 gh
Dimethomorph 50WP	66 a–d	Dimethomorph 4.18SC	150 gh
Copper hydroxide	66 a–d	Mandipropamid	152 gh
Mefenoxam	67 a–d	Mefenoxam	152 gh
Fenamidone	76 de	Potassium phosphite	158 h

^z Each plant was inoculated with 1 g of *Phytophthora capsici* infested millet seed. Mean AUDPC values with letters in common are not statistically different according to Fisher's least significant difference ($P = 0.05$).

Table 5. Mean area under the disease progress curve (AUDPC) and plant death (%), caused by *Phytophthora capsici*, calculated over 8 weeks in the greenhouse^y

Treatment, rate (kg a.i./ha) ^z	Mean AUDPC			Plant death (%)		
	Both cvs.	'Paladin'	'Red Knight'	Both cvs.	'Paladin'	'Red Knight'
Untreated inoculated	103 f	64 b–d	141 j	59.4	18.7	100.0
Famoxadone/cymoxanil, 0.28	62 a	49 a	75 de	19.8	2.1	35.4
Fluopicolide, 0.15	74 b	55 a–c	92 ef	26.0	8.3	43.8
Mandipropamid, 0.10	79 bc	56 a–c	102 fg	32.3	10.4	54.2
Dimethomorph 4.18SC, 0.22	80 bc	52 ab	108 gh	34.4	2.1	66.7
Dimethomorph 50WP, 0.22	81 bc	57 a–c	104 fg	35.4	12.5	56.3
Mefenoxam, 0.56	84 cd	58 a–c	111 g–i	47.9	8.3	85.4
Fenamidone, 0.19	87 c–e	69 cd	104 fg	56.3	18.8	68.8
Potassium phosphite, 2.47, 3.71	93 de	61 a–d	125 hi	44.8	12.5	77.1
Copper hydroxide, 1.21	96 ef	65 b–d	126 i	57.3	25.0	91.7

^y Mean AUDPCs within a column followed by the same letter or with no letter are not statistically different according to Fisher's least significant difference ($P = 0.05$).

^z Treatments were applied for 6 weeks on a 7- or 14-day schedule as drenches or foliar applications.

7-day intervals. Matheron and Porchas (12) found that drench applications provided greater control of *P. capsici* compared with the untreated control, yet no direct comparison between drench and foliar applications were made. In our experiment, additional *P. capsici* inoculum was not introduced into the pots after the initial inoculation, which may not adequately reflect field conditions where the soil may be reinfested following each rainfall or mechanical cultivation (8). Results from both our study and Matheron and Porchas (12) clearly indicate that fungicides applied as drenches to the crowns and roots of pepper plants will significantly reduce Phytophthora root and crown rot compared with foliar applications. Babadoost (2) also made soil drench applications at transplanting with fluopicolide and mandipropamid, and found that both fungicides lessened *P. capsici* symptoms when compared with the untreated control.

The efficacy of currently registered fungicides applied as preplant soil applications via drip irrigation or as transplant-tray dips is relatively unknown and should be further investigated. Also, the compatibility of registered fungicides with irrigation equipment is unknown. If drenches applied through drip irrigation were to require less fungicide than a standard 7-day application program, they may be the most effective and economical. However, the most effective rate of registered fungicides when applied as a drench via irrigation equipment has not been studied. The application rates of drenches through drip irrigation used in combination with foliar applications were evaluated by Hausbeck and Cortright (7). In that study, drenches of fluopicolide or propamocarb applied directly to the planting bed at two application rates and continued treatment 16 days later with a 7-day foliar application program resulted in the lower rate being as effective for controlling *P. capsici* as the higher rate.

In summary, when fungicides are used in combination with host resistance, Phytophthora crown and root rot caused by *P. capsici* may be reduced. Fungicides applied as a drench may provide greater control of *P. capsici* but further research is warranted to investigate different applica-

tion methods and treatment rates in the field.

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