Pathogenicity of *Phytophthora capsici* to Brassica Vegetable Crops and Biofumigation Cover Crops (*Brassica* spp.)

Charles S. Krasnow and Mary K. Hausbeck, Department of Plant, Soil, and Microbial Sciences, Michigan State University, East Lansing, 48824

Abstract

Krasnow, C. S., and Hausbeck, M. K. 2015. Pathogenicity of *Phytophthora capsici* to Brassica vegetable crops and biofumigation cover crops (*Brassica* spp.). Plant Dis. 99:1721-1726.

The soilborne oomycete *Phytophthora capsici* causes root, crown, and fruit rot of many vegetable crops in the Cucurbitaceae and Solanaceae families. *P. capsici* is a persistent problem in vegetable fields due to long-lived oospores that survive in soil and resist weathering and degradation. Vegetable crops in the Brassicaceae family have been considered nonhosts of *P. capsici* and are planted as rotational crops in infested fields. *Brassica* spp. are also grown as biofumigation cover crops to reduce inoculum levels of *P. capsici* and other soilborne pathogens, and this use has increased concurrent with restrictions on soil fumigation. Oriental mustard (*Brassica juncea*), oilseed rape (*B. napus*), and oilseed radish (*Raphanus sativus* var. *oleiferus*) contain high levels of glucosinolates and are widely recommended for biofumigation and as cover crops.

The objective of this study was to evaluate vegetables and biofumigation cover crops in the Brassicaceae family for susceptibility to *P. capsici*. *Brassica* spp. used as vegetable crops and for biofumigation were grown in *P. capsici*-infested potting soil in the greenhouse and disease incidence and severity were recorded. In greenhouse trials, infection by the pathogen reduced the fresh weight of all *Brassica* spp. tested and resulted in plant death of 44% of plants of *B. juncea* 'Pacific Gold'. *P. capsici* isolates exhibited differences in virulence ($P < 0.0001$), and were reisolated from the roots of all *Brassica* spp. included in the study. The biofumigation cover crop Pacific Gold mustard may not reduce populations of *P. capsici* in soil and, instead, may sustain or increase pathogen levels. Further research is necessary to test this possibility under field conditions.

The Brassicaceae family includes vegetables and cover crops considered important due to their diversity and adaptability to variable soil types and growing conditions (Nieuwhof 1969). In Michigan, over 2,500 ha of cabbage, turnip, radish, broccoli, and other *Brassica* vegetables are grown annually for the fresh and processing markets (Anonymous 2012). In addition to production as vegetable crops, *Brassica* spp. are widely planted as cover crops and for biofumigation in both horticultural and agronomic crop production (Kirkegaard and Sarwar 1998; Ngouajio and Mutch 2004; Snapp et al. 2006). Numerous studies have reported that *Brassica* biofumigation can reduce soilborne pathogens that are often an intractable problem in both conventional and organic vegetable production (Lewis and Papaviza 1971; Mattner et al. 2008; Mayton et al. 1996; Muehlchen et al. 1990). The use of *Brassica* spp. for this purpose has increased in recent years concurrent with the phase-out of the fumigant methyl bromide and an emphasis on sustainable disease management alternatives (Ackroyd 2010; Gardiner et al. 1999; Kirkegaard and Sarwar 1998; Lazzeri and Manici 2001). The ability of *Brassica* spp. to reduce pathogen inoculum density is attributed to glucosinolates, which are hydrophilic, thioglucoside compounds that are stored in the cell vacuoles of all *Brassica* spp. for use in sulfur assimilation and storage (Clossais-Besnard and Larher 1991; Larsen 1980; Marschner 1995). At vegetative maturity, *Brassica* cover crops are incorporated into the soil via flail mowing and disking, and the disruption of cellular content facilitates the hydrolysis of glucosinolates by the enzyme myrosinase (Fahn 1982; Marschner 1995; Morra and Kirkegaard 2002). Volatile isothiocyanates and other hydrolysis products that possess biocidal properties are produced during this process (Kirkegaard and Sarwar 1998; Larsen 1980; Smolinska et al. 1997) and come into

direct contact with pathogen propagules following soil incorporation (Lazzeri and Manici 2001; Lewis and Papaviza 1971; Snapp et al. 2006). Certain *Brassica* varieties have been developed and marketed specifically for the quantity and composition of glucosinolates produced by the plant (Anonymous 2014; Baysal and Miller 2009; Charron and Sams 1999; Morra and Kirkegaard 2002). Disease control recommendations using *Brassica* biofumigation have not been optimized, however, because glucosinolate production is environmentally and ontogenetically influenced (Greenhalgh and Mitchell 1976; He et al. 2003; McGregor 1988; Rosa et al. 1996; Sarwar and Kirkegaard 1998).

Phytophthora root and crown rot of *Brassica* crops caused by *Phytophthora drechsleri* and *P. megasperma* has been reported on cabbage, broccoli, cauliflower, and turnip, and occasionally causes major economic loss (Downes and Loughnane 1969; Geeson et al. 1990; Hamm and Koepsell 1984; Tompkins et al. 1936). Symptoms typical of *Phytophthora* root rot of *Brassica* crops include wilt, purple discoloration of the stem and older foliage, and eventual plant death (Downes and Loughnane 1969; Tompkins et al. 1936). *Phytophthora* spp. also cause postharvest rots during storage of cabbage, Chinese cabbage, and swede (Geeson 1976; Geeson et al. 1990; Hermansen and Hoftun 2005; Semb 1969). Management practices to control *Phytophthora* rots affecting *Brassica* spp. include planting into well-drained soil, fungicide application, and temperature control postharvest (Hermansen and Hoftun 2005; Kontaxis and Rubatzky 1983). *P. capsici* has been reported to be pathogenic to seedlings of cauliflower, radish, and turnip in studies conducted under controlled environmental conditions (Hartman and Huang 1993; Ji et al. 2012; Satour and Butler 1967; Tian and Babadoost 2004). In the same studies, *P. capsici* was nonpathogenic on cabbage, broccoli, mustard, rape, kale, and kohlrabi. Reports of *P. capsici* affecting traditional nonhost crops, including Fraser fir (Quesada-Ocampo et al. 2009), herbaceous ornamental plants (Enzenbacher 2011), snap bean (Geuens et al. 2008), and weed species such as *Portulaca oleracea* (French-Monar et al. 2006), highlight this pathogen's virulence and adaptability to diverse hosts. *P. capsici* is known to increase in virulence as a result of genetic exchange during oospore formation (Satour and Butler 1968), and the frequent occurrence of both mating types in vegetable fields (Lamour and Hausbeck 2000) heightens the importance of control methods to reduce inoculum pressure and

Corresponding author: M. K. Hausbeck; E-mail: hausbec1@msu.edu

Accepted for publication 24 May 2015.

<http://dx.doi.org/10.1094/PDIS-03-15-0271-RE>

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pathogen spread. *Brassica* vegetables such as cabbage, broccoli, and radish, and *Brassica* spp. used for biofumigation, are often planted into fields infested with *P. capsici* with the assumption that these crops are not affected by the pathogen and will reduce inoculum levels (M. K. Hausbeck, personal communication). The potential for *P. capsici* to cause disease on *Brassica* spp. or to survive and reproduce in debris remaining in the field postharvest would negatively affect growers facing limited crop rotation, fumigation, and fungicide control options (Hausbeck and Lamour 2004). The objective of this study was to evaluate select vegetables and biofumigation cover crops in the Brassicaceae family for susceptibility to *P. capsici*.

Materials and Methods

Isolate selection and inoculum preparation. *P. capsici* isolates originally collected from cucurbitaceous, solanaceous, and fabaceous hosts were selected from the culture collection of Dr. M. K. Hausbeck. The isolates were previously characterized for mating type (MT) and mefenoxam sensitivity (Lamour and Hausbeck 2000). Isolate 12889 (A1 MT) is mefenoxam insensitive and 10193 (A1 MT) and 14110 (A2 MT) are mefenoxam sensitive. The cultures were maintained on V8 agar media (143 ml of V8 juice, 3 g of CaCO₃, 16 g of agar, and 850 ml of distilled water). Prior to the study, the isolates were inoculated onto pepper fruit and subsequently recovered from the diseased fruit to ensure virulence of the isolates (Quesada-Ocampo and Hausbeck 2010). Millet inoculum (Quesada-Ocampo and Hausbeck 2010) was prepared by autoclaving millet seed (100 g), distilled water (72 ml), and L-asparagine (0.08 mg) in mushroom bags (RJG Sales, Port Richey, FL) twice consecutively, and adding seven 7-mm agar plugs colonized by a single *P. capsici* isolate. Infested millet seed was grown under constant fluorescent light for 3 to 4 weeks and mixed weekly prior to use as inoculum.

Pathogenicity testing of *P. capsici* on *Brassica* spp. *Brassica* vegetables and cover crops (Table 1) were sown into 288-cell flats in the Plant Science Research Greenhouses at Michigan State University, East Lansing. Millet (3 g) infested with a single isolate and prepared as described previously was deposited into each transplant hole in 10-cm pots containing autoclaved peat potting mixture (Suremix Michigan Grower Products Inc., Galesburg, MI) and gently

mixed to incorporate with the soil. Eight-day-old seedlings were used for the study and were transplanted into the infested peat potting mixture. Control pots received 3 g of millet prepared with sterile V8 agar plugs. The quantity of inoculum was selected based on previous studies (Quesada-Ocampo et al. 2009) and preliminary inoculum-density experiments with 'Bronco' cabbage (data not shown). A single plant was grown in each pot and was considered an experimental unit, with six pots per isolate for each cultivar. All plants in the experiment were inoculated on the same day. Plants were watered to maintain adequate soil moisture, and plant height from the soil-line to the tallest expanded foliage and width at the widest point were measured weekly during the experiment. Visual disease severity was rated on a 0-to-4 scale adapted from Glosier et al. (2008), where 0 = healthy; 1 = minor wilting, chlorosis, or stunting; 2 = moderate wilting, chlorosis, and stunting; 3 = severe wilting, chlorosis, and stunting; and 4 = plant death. Plants of 'Pacific Gold' and 'Florida Broad Leaf' mustard and 'Rover' and 'Groundhog' radish were harvested 3 weeks after inoculation, and all other crops were harvested 4 weeks after inoculation. Aboveground fresh weights were recorded at harvest for all crops. Root weights of Groundhog and Rover radish and 'Purple Top White Globe' turnip were also recorded. At the completion of the experiment, roots were rinsed in tap water to remove adhering potting mix and approximately 50% of the plants of each cultivar and isolate were arbitrarily selected for pathogen reisolation. Necrotic or water-soaked root tissue was rinsed in sterile distilled water and surface sterilized in 70% ethanol for 5 s prior to plating onto V8 agar amended with benomyl at 50 ppm, pentachloronitrobenzene at 100 ppm, ampicillin at 100 ppm, and rifampicin at 30 ppm. Isolated colonies were transferred to V8 agar and confirmed as *P. capsici* by pathogen morphology (Waterhouse 1963). Temperature and relative humidity were measured using a WatchDog data logger (Spectrum Technologies Inc., Plainfield, IL). The experiment was organized in a completely randomized design and was conducted twice.

Statistical analysis. Data were analyzed using SAS (version 9.4; SAS Institute, Cary, NC). Response variables were analyzed by analysis of variance (ANOVA) using the Proc Mixed procedure. *P. capsici* isolate and cultivar were considered fixed variables and trials were considered random variables. Interactions were sliced when found to be significant at $P = 0.05$ in an ANOVA to analyze simple main effects. The response variables fresh weight, root weight, plant height, and plant width were analyzed separately for each cultivar. Fisher's protected least significant difference was used to separate treatment differences using the SAS pdmix800 macro (Saxton 1998). Residuals were plotted against predicted values using Proc Gplot and checked for normality and equal variance to ensure that statistical assumptions were met. Data from noninoculated control plants were not included in the analysis because disease symptoms were not observed and root isolations did not yield *P. capsici*. Pearson's correlation coefficients between incidence of disease and the independent variables plant height, width, and aboveground weight were analyzed using Proc Corr to determine the degree of association between disease incidence and plant size. The likelihood of disease incidence due to specific isolates was analyzed using logistic regression.

Results

Disease symptoms observed for inoculated *Brassica* plants included stunting, wilting, chlorosis, and plant death (Fig. 1). Severely affected cauliflower and broccoli plants also exhibited purple discoloration of the foliage. Initial symptoms of wilting and chlorosis were typically evident within 3 days postinoculation. Discolored roots and constriction of the stem at the soil line were apparent upon harvest of symptomatic plants. The results were similar between the two trials and data were pooled for analysis because a significant trial-treatment interaction was accounted for by magnitude of plant growth, not rank. Differences in temperature and relative humidity were observed between the two experiments, with a mean temperature and relative humidity of 26.6°C and 19% in trial 1 and 29.4°C and 41% in trial 2.

Disease symptoms were noted on all inoculated *Brassica* cultivars included in this study (Table 2). There was a negative correlation

Table 1. *Brassica* spp. used as vegetables and biofumigation cover crops evaluated in *Phytophthora capsici* pathogenicity experiments

<i>Brassica</i> spp.	Cultivar	Intended use	Days to maturity
<i>Brassica juncea</i> L.			
Mustard	Florida Broad Leaf ^a	Fresh market	40
Indian mustard	Pacific Gold ^b	Biofumigation	65–80
<i>B. napus</i>			
Rape	Dwarf Essex ^b	Biofumigation ^d	60–80
<i>B. oleracea</i> var. <i>botrytis</i>			
Cauliflower	Snow Crown ^c	Fresh market	50
<i>B. oleracea</i> var. <i>capitata</i>			
Green cabbage	Bronco ^c	Fresh market	78
Red cabbage	Buscaro ^c	Fresh market/ processing	100
<i>B. oleracea</i> var. <i>italica</i>			
Broccoli	Emerald Crown ^c	Fresh market	60
<i>B. rapa</i>			
Turnip	Purple Top White Globe ^a	Fresh market	58
<i>Raphanus sativus</i>			
Radish	Rover ^c	Fresh market	25
<i>R. sativus</i> var. <i>oleiferus</i>			
Oilseed radish	Groundhog ^c	Biofumigation ^d	60–90

^a Rispens Seeds, Illinois.

^b Johnny's Selected Seeds, Maine.

^c Seedway, Pennsylvania.

^d Oilseed radish and rape are also used as traditional cover crops without mowing and incorporation of green tissue that is frequently practiced with biofumigation.

between fresh weight and disease incidence for all cultivars ($R^2 = -0.391$, $P < 0.0001$) and a similar correlation with height and width measurements was observed (data not shown). Using logistic regression, the probability of disease incidence was highest in Pacific Gold ($P < 0.0001$) and lowest in 'Dwarf Essex' ($P = 0.79$). Dwarf Essex displayed the lowest disease severity when compared with the other *Brassica* spp. (Table 2). The *Brassica* spp. used for biofumigation tended to exhibit a more drastic decrease in fresh weight than the vegetable crops (Table 3); for example, Pacific Gold and Groundhog displayed a 78 and 24% reduction, respectively, in fresh weight compared with the control ($P < 0.001$). The reduction in fresh weight for the *Brassica* spp. used as vegetable crops was significant for Bronco ($P < 0.01$) and 'Buscaro' ($P < 0.05$) cabbage, and was not significant for the remaining cultivars (Table 3). *P. capsici* also reduced root weight of the three *Brassica* spp. grown for their large root size ($P = 0.1$), most notably with Purple Top White Globe (Fig. 2).

The three *P. capsici* isolates selected for this study caused varying degrees of disease severity on the *Brassica* spp. tested. Differences in the cumulative disease severity values between isolates 14110 and 10193 for Rover and Pacific Gold and between isolates 14110 and 12889 for Purple Top White Globe were significant ($P < 0.05$, data not shown). However, at the final disease severity rating, differences among isolates were not significant ($P = 0.159$, Table 2). Isolate 14110 was the most virulent isolate tested based on disease incidence ($P < 0.001$, data not shown), as determined by binary logistic regression. All *P. capsici* isolates tested reduced the height of Pacific Gold plants ($P < 0.001$, Fig. 3) whereas significant differences among *P. capsici* isolates and the control were not observed with Florida Broad Leaf ($P = 0.213$). The differences in mean disease severity among *Brassica juncea* cultivars were larger than differences observed among other crops of the same species (Table 2). *P. capsici* was successfully reisolated from the roots of all *Brassica* cultivars tested (Table 2). Each of the three isolates included in the study were successfully recovered from at least one infected plant in both trials (data not shown).

Discussion

Cover crops are often grown in annual vegetable production systems primarily to improve soil drainage, suppress weeds, increase soil organic matter, capture nutrients, and reduce erosion (Hartwig

and Ammon 2002). *Brassica* spp. developed for biofumigation are planted in vegetable production systems when an additional goal is to decrease populations of soilborne pathogens (Ackroyd 2010; Charron and Sams 1999; Ngouajio and Mutch 2004; Snapp et al. 2006). The cover crops are usually seeded, grown to vegetative maturity, and incorporated prior to planting an economically important vegetable crop, or planted postharvest and killed by freezing temperatures (Snapp et al. 2006; Sundermeier 2008). Our greenhouse study indicates that *P. capsici* can colonize the roots of diverse *Brassica* spp. and can cause plant death of Pacific Gold mustard (*B. juncea*) and Groundhog radish (*Raphanus sativus* var. *oleiferus*) used specifically for biofumigation. There have been conflicting studies about the ability of *Brassica* cover crops to suppress oomycete plant pathogens (Larkin and Griffin 2007; Mattner et al. 2008; Wiggins and Kinkel 2005). Wiggins and Kinkel (2005) did not find a significant difference in Phytophthora root rot of alfalfa planted into pots of infested field soil that had been cropped to and amended with chopped canola (*B. napus*) tissue 20 days prior or left fallow. Similarly, a commercial biofumigation cover crop mixture of *B. napus* and *B. rapa* that was mowed and incorporated at anthesis into field soil did not decrease the viability of *P. cactorum* that was buried in the soil for 3 days following *Brassica* incorporation. Growth of the isolates on selective media after recovery from the soil, however, was reduced by 20% compared with *P. cactorum* buried and recovered from fallowed soils (Mattner et al. 2008). Control of pathogenic *Pythium* and *Aphanomyces* spp. with *Brassica* tissue and associated glucosinolate compounds has been more consistent than with *Phytophthora* spp. (Charron and Sams 1999; Lazzeri and Manici 2001; Lewis and Papaviza 1971; Muehlchen et al. 1990; Smolinska et al. 1997), although lack of suppression of *Pythium* spp. has been noted in studies on apple replant disease (Mazzola et al. 2007, 2009). Studies on the biofumigation potential of *Brassica* spp. to *P. capsici* have reported decreases in pathogen populations or disease severity upon incorporation of fresh or dry *Brassica* residues into soil, potting mix, or other media (Cohen et al. 2008; Demirci and Dolar 2006; Fan et al. 2008; Ji et al. 2012; Ludwig et al. 2004; McGrath and Menasha 2013; Ppoyil 2011; Sanogo and Schaub 2012; Wang et al. 2014). In a greenhouse study, the proportion of 'Dickenson' pumpkin plants infected by *P. capsici* crown rot was limited by adding macerated *Brassica* tissue to the soil around the crown of inoculated seedlings (Ppoyil 2011). McGrath and Menasha (2013) and Ji et al. (2012) found that mustard cultivars used for biofumigation were able to reduce the incidence of Phytophthora blight of pumpkin and squash, respectively,

Table 2. Disease severity of select *Brassica* spp. used as vegetables and biofumigation cover crops when inoculated with *Phytophthora capsici* in greenhouse trials and frequency of pathogen recovery from diseased roots

Cultivar	Disease severity ^a			Recovery ^b
	10193	12889	14110	
Bronco	0.25	0.33	0.50	+++
Buscaro	0.42	0.25	0.58	+++
Emerald Crown	0.33	0.50	0.33	+
Dwarf Essex	0.25	0.17	0.08	++
Florida Broad Leaf	0.67	0.25	0.50	++
Groundhog	0.80	0.40	0.56	+
Pacific Gold	2.25	3.00	3.25	++
Purple Top White Globe	0.33	0.25	0.75	++
Rover	0.0	0.08	0.33	+
Snow Crown	0.58	0.33	0.42	+
Mean	0.59	0.56	0.73	...

^a Disease severity values for each *P. capsici* isolate represent final visual rating of inoculated plants using a 0-to-4 scale, where 0 = healthy; 1 = minor wilting, chlorosis, or stunting; 2 = moderate wilting, chlorosis, and stunting; 3 = severe wilting, chlorosis, and stunting; and 4 = plant death. Values represent the mean of two trials, with six replications per trial. Disease was not observed on nor was *P. capsici* recovered from control plants, which were not included in the analysis. *P. capsici* isolates originally were recovered from three different host families. Isolate designation from the culture collection of Dr. M. K. Hausbeck.

^b Frequency of *P. capsici* recovery from roots of diseased *Brassica* spp.: + = <33%, ++ = 33 to 66%, and +++ = >66% recovery. Percentage of recovery represents the mean of two trials with six replications per trial.

Table 3. Effect of *Phytophthora capsici* isolate on aboveground fresh weight of select *Brassica* spp. used as vegetables and biofumigation cover crops in greenhouse pathogenicity trials

Cultivar	Reduction in fresh weight (%) ^a			
	10193	12889	14110	Mean ^b
Bronco	16	24	22	21**
Buscaro	13	22	29	21*
Emerald Crown	11	17	15	14
Dwarf Essex	6	0	0	2
Florida Broad Leaf	19	4	10	11
Groundhog	37	11	23	24**
Pacific Gold	66	78	90	78**
Purple Top White Globe	17	3	19	13
Rover	0	13	2	5
Snow Crown	9	11	19	13

^a Decrease in aboveground fresh weight (%) for each *P. capsici* isolate compared with control plants. Fresh weight (grams) was measured at the conclusion of each trial. Values represent the mean of two trials, with six replications per trial. *P. capsici* isolates originally were recovered from three different host families. Isolate designation from the culture collection of Dr. M. K. Hausbeck.

^b Asterisks * and ** indicate significant treatment differences at $P < 0.05$ and 0.01, respectively, according to Fisher's protected least significant difference test.

in field trials where the mustard cover crops were incorporated prior to planting. Additionally, pepper seeded into *P. capsici*-infested soil amended with *B. juncea* seed meal had a 46% germination rate as opposed to 6.7% in the infested control (Cohen et al. 2008). The sensitivity of *P. capsici* to *Brassica* tissue observed in previous studies may be related to the use of isolated volatile compounds, extracts, seed meal produced from Brassicaceous tissues, and macerated plant material (Charron and Sams 1999; Demirci and Dolar 2006; Mazzola et al. 2009; Morales-Rodriguez et al. 2014; Ppoyil 2011; Smolinska et al. 1997) to decrease pathogen levels. Differences exist among *Brassica* spp. between aboveground tissue and roots in quantity and composition of glucosinolates, with root tissue and seedlings usually containing higher quantities than shoots (Gardiner et al. 1999; Kirkegaard and Sarwar 1998; Muehlchen et al. 1990; Rosa

1997). However, higher concentrations of glucosinolates in shoot tissue have been noted with *Sinapis alba* and *B. juncea* (Anonymous 2014). *B. juncea* cultivars, including Pacific Gold used in this study, contain the highest concentration of glucosinolate compounds among

Fig. 1. Symptoms of disease caused by *Phytophthora capsici* on *Brassica* spp., including **A**, wilting of Groundhog radish; **B**, stunting of Groundhog radish; and **C**, plant death of Pacific Gold mustard.

Fig. 2. Effect of *Phytophthora capsici* isolate on root weight of three *Brassica* cultivars grown for their large root size. Each column represents the mean of two trials, with six replicate plants per isolate per trial. Columns with a letter in common are not significantly different within each cultivar based on Fisher's protected least significant difference ($P < 0.05$). Error bars represent the standard error of the mean.

Fig. 3. Differences in height of **A**, Pacific Gold and **B**, Florida Broad Leaf at 9 and 18 days postinoculation (DPI) with three *Phytophthora capsici* isolates. Each column represents the mean of two trials, with six replicate plants per isolate per trial. Error bars represent the standard error of the mean.

Brassica spp. used for biofumigation (Anonymous 2014; Charron and Sams 1999; Larkin and Griffin 2007; Smolinska and Horbowicz 1999; Snapp et al. 2006), and concentrations of glucosinolates are highest during the seedling stage (Fahey et al. 2001; He et al. 2003). Because *Brassica* spp. used for biofumigation and as cover crops are direct or broadcast seeded into vegetable production fields (Ngouajio and Mutch 2004; Sundermeier 2008), colonization of roots by *P. capsici* may increase pathogen populations in soil, nullifying the ability of glucosinolate compounds to significantly decrease pathogen levels. Additionally, *P. capsici* caused lesions on the foliage of seedlings and mature plants of cabbage, mustard, and other *Brassica* spp. when inoculated in the laboratory and greenhouse with zoospores or mycelia and incubated under high relative humidity (data not shown). The ability of the pathogen to infect diverse tissue types raises the possibility that the residues of *Brassica* spp. incorporated into the soil may sustain or increase *P. capsici* population densities in the field instead of reducing inoculum levels. *P. capsici* does not appear to be affected by glucosinolate compounds in *Brassica* tissue, and the disease reduction noted in previous studies using incorporated *Brassica* plant tissue to reduce *P. capsici* (Coelho et al. 1999; Cohen et al. 2008; Demirci and Dolar 2006; Ji et al. 2012; Ludwig et al. 2004; McGrath and Menasha 2013; Ppoyil 2011) may have been due to increases in antagonistic soil microorganisms (Mazzola et al. 2007; Wiggins and Kinkel 2005) or variations in *P. capsici* isolate sensitivity to the *Brassica* tissue and related volatile compounds (Morales-Rodriguez et al. 2014; Ppoyil 2011).

The difference in susceptibility of *B. juncea* Pacific Gold and Florida Broad Leaf suggests that tolerance to *P. capsici* may exist among *Brassica* spp. Field tolerance to *P. capsici* has been observed with other hosts such as *Cucurbita pepo* (Meyer and Hausbeck 2013) and *Capsicum annuum* (Foster and Hausbeck 2010), and host resistance is often considered an optimal disease management strategy (Granke et al. 2012; Ristaino and Johnston 1999). Using fungicides to keep biofumigant cover crops healthy is not desirable; therefore, screening *Brassica* cover crops for resistance to *P. capsici* isolates from diverse geographic locations is important. A similar screening has been successful in identifying tolerance in cauliflower to *Phytophthora* blight caused by *P. megasperma* (Hamm and Koepsell 1984; Kontaxis and Rubatzky 1983). *Phytophthora* spp. that affect *Brassica* vegetables have been observed during wet years or when fields with heavy soils that are prone to waterlogging are utilized (Tompkins et al. 1936). *P. drechsleri* and *P. megasperma* caused significant losses to *Brassica* crops both in the field (Hamm and Koepsell 1984; Thompson and Phillips 1988; Tompkins et al. 1936) and in storage (Geeson 1976; Geeson et al. 1990; Hermansen and Hoftun 2005), often after periods of soil saturation and wet conditions during harvest. The similarity of the reported symptoms of *Phytophthora* blight of *Brassica* vegetables to those observed in this study stresses the need for accurate identification of diseased plants. Fungicide recommendations have been made for controlling *Phytophthora* spp. on *Brassica* vegetables and include the systemic fungicide metalaxyl (Anonymous 1996; Kontaxis and Rubatzky 1983). However, widespread resistance to this fungicide and its racemic isomer, mefenoxam, have been reported for *P. capsici* (Hausbeck and Lamour 2004). Soil-directed fungicide applications of newer systemic fungicides are effective in controlling *P. capsici* root rots (Foster and Hausbeck 2010; Meyer and Hausbeck 2013) and trials are in progress to test the effectiveness of fungicides for management of *P. capsici* root rot of *Brassica* vegetables.

P. capsici has the potential to infect and cause significant losses on over 30,000 ha of susceptible vegetables grown annually in Michigan (Anonymous 2012), and uninfested land used for vegetable production that is available for rotation is becoming increasingly scarce (Hausbeck and Lamour 2004). The widespread utilization of *Brassica* spp. as vegetable crops and for biofumigation in vegetable production (Larsen 1980; Ngouajio and Mutch 2004; Snapp et al. 2006) and the prevalence of *P. capsici* in vegetable fields (Hausbeck and Lamour 2004) highlight the importance of conducting further studies into the etiology of this pathogen on *Brassica* spp. Even though severe disease was not observed on some of the vegetable crops tested

in this study, roots infected at the subclinical level may enable survival of *P. capsici* in soil (Shishkoff 2007) and result in significant reductions in yield (Stanghellini and Kronland 1986). The identification of *P. capsici* as a potential pathogen of *Brassica* spp. and the ability to cause severe disease on the biofumigation cover crop Pacific Gold means that these crops should be monitored for *Phytophthora* root rot when planted into fields with a history of *P. capsici*. In addition, recommendations for *Phytophthora* blight prevention and management (Hausbeck and Lamour 2004) should be strongly adhered to when considering planting *Brassica* vegetables into infested fields.

Acknowledgments

We thank the Michigan Department of Agriculture and Rural Development Specialty Crop Block Grant Number 791N4300114, administered by the Michigan Vegetable Council, for the funding provided; and S. Linderman for technical assistance in editing tables and figures during the preparation of this manuscript.

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