Crop Protection 29 (2010) 349–353

Contents lists available at ScienceDirect

Crop Protection

journal homepage: www.elsevier.com/locate/cropro

A comparative evaluation of post-infection efficacy of mefenoxam and potassium phosphite with protectant efficacy of azoxystrobin and potassium phosphite for controlling leather rot of strawberry caused by *Phytophthora cactorum*

A. Rebollar-Alviter [a,*], L.L. Wilson [b], L.V. Madden [b], M.A. Ellis [b]

[a] *Centro Regional Morelia, Universidad Autónoma Chapingo, Periférico Paseo de la República No. 1000 Morelia, Michoacán, México 58170*
[b] *Department of Plant Pathology, The Ohio State University/OARDC, Wooster, OH 44691, USA*

ARTICLE INFO

Article history:
Received 10 May 2009
Received in revised form
8 December 2009
Accepted 11 December 2009

keywords:
Azoxystrobin
Phenylamides
QoI
Phosphonates
Strawberry diseases
Leather rot

ABSTRACT

Leather rot, caused by *Phytophthora cactorum*, is one of the most important fruit-rotting diseases of strawberry worldwide. Efficacy of mefenoxam and potassium phosphite against leather rot, when applied in a post-infection fungicide program, made in response to rain events was evaluated over 3 years of testing. Post-infection treatments of potassium phosphite and mefenoxam were compared with calendar-based treatments of azoxystrobin or potassium phosphite sprayed weekly, starting at late bloom (fruit set). In order to obtain high-risk conditions for infection (splash dispersal of the pathogen and subsequent infection periods), plots were flooded until standing water was observed between the rows. Post-infection applications were made within 36 h after the initiation of a flooding event. Leather rot incidence in the untreated controls ranged from 15 to 66% over the 3 years. All fungicide treatments had significantly ($P < 0.001$) less leather rot incidence than in the untreated control. There were no significant differences in leather rot incidence between the different fungicide treatments. Percent control (the percentage reduction in incidence relative to the check) was as high as 100% with all fungicide treatments. Mefenoxam and potassium phosphite post-infection (after flooding) provided control equal to that obtained with a calendar-based spray program, but with from 1 to 3 fewer fungicide applications.

1. Introduction

Leather rot of strawberry, caused by *Phytophthora cactorum* (Lebert and Cohn) Scröt, is a common disease of strawberry (*Fragaria* × *ananassa*) in which fruits can become infected at all stages of development. On green fruits, dark brown areas covering the entire fruit may appear. Fruits appear leathery and eventually will dry down and mummify. On mature diseased fruits, symptoms may not be easy to recognize, and infected fruits can be inadvertently picked along with healthy fruits. Farmers have experienced complaints from "pick your own" costumers because of the characteristic bad taste and foul odor of infected fruits. The off-odor of diseased fruits is caused by compounds derived from phenolic acids, such as 4-ethyl-phenol and 4-ethyl-2-metoxy-phenol (Jelen et al., 2005). Losses due to leather rot can reach 50% under favorable conditions (Ellis and Grove, 1983).

Leather rot is favored by periods of heavy rainfall and saturated soils. Splashing of infective propagules by rainfall and wetness periods as short as 2 h are important components for the development of leather rot epidemics (Grove et al., 1985; Madden et al., 1991). Cultural practices such as avoiding saturated soils through proper site selection, improving soil drainage, and applying straw mulch between the rows are beneficial to disease control. Straw mulch prevents fruits from touching the soil and standing water, and reduces the splashing of water droplets containing sporangia and zoospores (Madden et al., 1991). However, under high disease pressure, cultural control may not be sufficient to provide satisfactory disease control. Fungicides have been reported to be highly effective for controlling leather rot (Ellis et al., 1998; Rebollar-Alviter et al., 2005). Protectant fungicides such as captan and thiram have been used for many years against leather rot; however, under high disease pressure they provide poor disease control

* Corresponding author.
E-mail address: rebollaralviter@gmail.com (A. Rebollar-Alviter).

0261-2194/$ – see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.cropro.2009.12.009

(Wedge et al., 2007). The introduction of systemic and more efficacious fungicides has greatly improved chemical control of leather rot. Currently, azoxystrobin (Abound 22.9F, manufactured by Syngenta Crop Protection, P.O. box 18300, Greensboro, NC 27419, USA), potassium phosphite (AgriFos 45.8%, manufactured by Agrichem/ Liquid Fertiliser Pty. Ltd., 4–10 Chetwynd St., Loganholme, Queensland 4129, Australia) and mefenoxam (Ridomil Gold 4 EC, manufactured by Syngenta Crop Protection, Inc.) are registered in the USA for controlling leather rot of strawberry. According to the label, mefenoxam (the R-enantiomer of metalaxyl) is recommended for applications during pre-bloom and 30 days before harvest. A third application is recommended for supplemental control during the harvest season. Previous experiments with metalaxyl have shown that one application during bloom may provide sufficient protection for the entire season against leather rot in matted-row production systems (Ellis et al., 1998). Applications of azoxystrobin and phosphorous acid-based compounds are initiated at 10% bloom and with repeated applications at 7–10 day intervals as needed.

Several studies have been conducted on the physical mode of action of the QoI (strobilurin) fungicide azoxystrobin. Wong and Wilcox (2001) working with grapevine downy mildew (*Plasmopara viticola*), reported that azoxystrobin provided 100% control when applied 1–5 days before inoculation, but post-infection applications did not provide a satisfactory reduction of downy mildew incidence. Azoxystrobin provided excellent activity against leather rot under very high disease pressure in the field (Rebollar-Alviter et al., 2005). Rebollar-Alviter reported that azoxystrobin provided protectant activity against leather rot for up to 7 days before inoculation, but only slight curative activity when applied at 13 h after inoculation (Rebollar-Alviter et al., 2007). The strobilurin fungicides represent an important addition to currently used fungicides for control of leather rot. In addition to providing excellent protectant activity against *P. cactorum*, they are also in a different class of chemistry than mefenoxam and the phosphite fungicides. If used in alternating spray programs with mefenoxam and the phosphite fungicides, they should be useful in preventing or delaying the development of fungicide resistance in *P. cactorum*.

Mefenoxam is systemic and can be taken up by roots and leaves, and translocated via xylem following the transpiration stream (Gisi, 2002). Mefenoxam exhibits strong preventive and curative activity against several foliar, soil-borne and seed infecting oomycete pathogens (Gisi, 2002). For example, post-infection applications of metalaxyl to grapes have provided control of grape downy mildew for up to 48 h after inoculation and a substantial reduction in disease development for up to 5 days after inoculation (Kennelly et al., 2007; Wong and Wilcox, 2001).

Phosphite fungicides, on the other hand, are the only truly systemic fungicides that move through phloem from source to sink, and through xylem following the transpiration stream (Gisi, 2002). The mode of action of phosphite fungicides is not known but various reports suggest that phosphite fungicides act by interfering with several enzymes and with phosphorous metabolism (McDonald et al., 2001; Niere et al., 1990; Stehmann and Grant, 2000). In addition, phosphite fungicides have been associated with the stimulation of plant defense responses (Gisi, 2002; Guest and Grant, 1991; Jackson et al., 2000).

Mefenoxam and phosphorous acid are commonly used fungicides for post-infection control of oomycete pathogens on different crops. For instance, both fungicides provided protectant activity for up 12 days against *P. viticola*. Mefenoxam applied post-infection against the same pathogen provided up to 4 days of curative activity; whilst, fosetyl-al only provided 2 days of curative activity (Gisi, 2002; Wicks et al., 1991). Post-infection applications of phosphorous acid or mefenoxam against cankers caused by *P. cactorum* in almond reduced canker development between 36 and 88% (Browne and Viveros, 2004).

The curative activity of mefenoxam and phosphorous acid makes them potentially useful in post-infection fungicide programs where fungicides are applied in response to recorded or predicted infection periods. A disease forecasting system for leather rot has been developed by Reynolds et al. (1987). The influence of weather variables on sporulation, infection and dispersal of *P. cactorum*, and on disease progress, was previously investigated (Grove et al., 1985; Madden et al., 1991; Reynolds et al., 1988). Based on this information, Reynolds et al. (1987) developed a prototype forecasting system for leather rot using discriminant analysis; this forecaster classified weather conditions into categories corresponding to low, medium and high disease risk. From this analysis, the authors concluded that it was possible to predict disease hazards associated with individual rain events with a high degree of reliability, based on the amount of rainfall, an estimation of previous disease incidence, an index of sporulation and an inoculum-dispersal index. Because *P. cactorum* requires very short wetness periods over a wide range of temperatures to cause fruit infection (assuming that propagules are in contact with fruit), determining the occurrence of infection periods (independent of dispersal and high-sporulation events) would not be sufficient for accurately predicting infection periods used to schedule post-infection applications of fungicide. Rather, high risk (or hazard), as determined by individual rain storms and the amount of rainfall during critical periods, is a better indicator of the need to apply a fungicide, because this takes into account the dissemination of propagules to susceptible fruits (a requirement for infection to occur). However, fruit infection would have already occurred (or started) if fungicides were applied only after the high-risk periods, given the very short time needed for fruit infection during wet conditions (Grove et al., 1985). Therefore, fungicides used in this manner would need to have good post-infection or curative activity.

In Ohio, chemical control of leather rot is currently based on calendar-based spray program where prophylactic applications of fungicide are made on a 5–7 day protectant schedule with no regard to infection events. Previous experiments in the greenhouse to investigate the physical mode of action of mefenoxam and phosphorous acid showed that both fungicides provide excellent protectant activity against leather rot for at least 7 days as well as excellent post-infection (curative) activity for up to 36 h after inoculation with *P. cactorum* (Rebollar-Alviter et al., 2007). Since rainfall is a major component that drives the epidemic in this pathosystem, by favoring splash dispersal of primary and secondary inoculum (Madden et al., 1991), scheduling fungicide applications only after the occurrence of moderate to heavy rain events (Reynolds et al., 1987, 1988) could reduce fungicide applications in a leather rot management program. The objective of this research was to evaluate and compare the post-infection activity of mefenoxam and phosphorous acid and the protectant activity of azoxystrobin and phosphorous acid for control of strawberry leather rot in the field.

2. Materials and methods

2.1. Field trials and experimental conditions

Three field trials were established during spring of 2005, 2006 and 2007 in a commercial strawberry planting near Wooster, Ohio, where leather rot is a major problem. The land in all plantings was broadcast fumigated with TERR-O-GAS 67 (methyl bromide (67%) and chloropichrin (33%)), Manufactured by Great Lakes Chemical Corp., P.O. Box 2200, West Lafayette, IN 47996, USA. Fumigation was performed in the fall before the planting was established the following spring. Fumigant was injected into the soil at a rate of 390 Kg/ha. At the time of fumigant injection, soil was simultaneously covered with 1-mil black plastic and left covered for 30 days. The 2005 trial was conducted in a 4-year-old planting (third bearing year) of the cultivar Honeoye. Plants were grown in a matted-row perennial system, with rows approximately 30-cm wide grown on 90-cm centers. Individual plots consisted of three rows each 3-m long. The trial in 2006 was conducted on the same commercial farm in a 2-year-old planting (first bearing year) of the cultivar Honeoye. The same plot was used to conduct the 2007 trial. The planting was 3-years old (second bearing year). Plots were established as described for the 2005 trial. In each year of testing, straw was removed from between the rows from May 9–12 of each year, leaving bare soil to enhance leather rot development. In addition, to further promote disease development, plots were flooded for a period of at least 3 h using overhead irrigation delivering approximately 120 mm of water on various dates from May 20 to June 15 of each year until standing water was observed between the rows (Table 1). Dates for flooding events were selected to insure a specific number of days (hours) between flooding and curative sprays. Temperature and rainfall were recorded with a 21X Campbell data logger (Campbell Scientific, Inc., Logan, UT, USA) every 5 min and averaged.

2.2. Treatments and experimental design

Treatments were arranged in a completely randomized block design, with four replications (blocks). Tested fungicides included azoxystrobin (Abound, 22.9 F 1.1 L/ha, 22.9% AI), potassium phosphite (AgriFos, 4.6 L/ha, 45.8% Mono-and di-potassium salts of Phosphorous acid) and mefenoxam (Ridomil 4 EC, 1 L/ha, 47.6% AI). In 2005, four treatments and a control were evaluated. Two treatments were applied on a protectant, calendar-based program with applications every 7–10 days, and two treatments were applied in a post-infection, curative program in response to flooding events (infection periods). Treatments and application dates are provided in Table 1. In all years of testing, applications were initiated at late bloom (fruit set) and were continued through harvest. Curative treatments were always applied within 36 h after the initiation of a flooding event. Flooding events that occurred within 7 days of a curative application were ignored because we assumed we had 7 days of protectant activity following a curative treatment. In 2006 and 2007, only three fungicide treatments and a control were evaluated. One treatment was applied on a protectant, calendar-based program (of azoxystrobin [two applications] alternated with potassium phosphite [two applications]), and two treatments (mefenoxam and potassium phosphite) were applied in a curative program made in response to flooding events (Table 1). In 2006 and 2007, calendar-based treatments were applied according to current recommendations for management of fungicide resistance development to QoI fungicides (Fungicide Resistance Action Committee, FRAC). All fungicides were applied to run-off in an equivalent of 935 L of water per hectare to the center row of each plot using a CO_2 back pack sprayer at 275.8 kPa. All ripe and diseased fruits were harvested two or three times during each of the 3 years of testing. In perennial matted-row production systems, the harvest period is approximately 2 weeks. With a 5-day interval between harvests, the majority of marketable fruit in all plots was harvested. Remaining fruit at the end of the harvest season are generally small and are left in the field. The percentage of fruit with leather rot was determined based on visual symptoms for each harvest. The incidence of grey mold (caused by *Botrytis cinerea*) and anthracnose (caused by *Colletotrichum acutatum*) was also determined, based on symptoms, when either of these diseases developed.

Table 1
Summary of treatments, timings, dates of fungicide applications and flooding events applied during the course of experiments conducted on 2005, 2006 and 2007 at Wooster, OH.

Treatments[a]	Timing[b]	Date of treatment application	Date of flooding events
2005			
1. Pp–Pp–Pp–Pp	Pre-I	May 19, 26; June 6, 10	May 20, 21; June 3, 4, 7, 8, 10
2. Az–Az–Pp–Pp	Pre-I	May 19, 26; June 6, 10	
3. Mf–Mf	Post-I	May 22; June 12	
4. Pp–Pp–Pp	Post-I	May 22; June 5,12	
5. Control	–	–	
2006			
1. Az–Az–Pp–Pp	Pre-I	May 24, 31; June 7, 14	May 25; June 1, 2, 8, 9, 12
2. Mf	Post-I	May 27	
3. Pp–Pp	Post-I	May 27; June 3, 13	
4. Control	–	–	
2007			
1. Pp–Pp–Az–Az	Pre-I	May 15, 22, 29; June 5	May 21, 29
2. Mf	Post-I	May 22	
3. Pp–Pp	Post-I	May 22, May 30	
4. Control	–	–	

[a] Pp = Potassium phosphite, Az = azoxystrobin, Mf = Mefenoxam.
[b] Pre-I: Protectant or calendar-based ("pre-infection") application; Post-I: post-Infection application; in 2005 season, calendar-based applications correspond to treatments 1 and 2; 2006 and 2007, calendar-based treatment correspond to treatment 1.

2.3. Data analysis

For each year of testing, disease incidence data from different harvest dates were pooled before analysis to construct an overall incidence value for each replicate of each treatment. The angular transformation (Schabenberger and Pierce, 2002) of incidence was calculated to obtain a response variable with an approximately constant variance. In order to determine the effect of treatment on disease, analysis of variance (ANOVA) was performed based on fitting a linear mixed model to the angular-transformed values using the MIXED procedure of SAS (SAS Institute, Inc. Cary, NC, USA). Treatment was considered a fixed effect and block a random effect.

The achieved significance level (P) for treatment was determined based on an F test. Significant differences of the estimated least-squares means were determined based on the least significant difference (LSD; critical significance level of $\alpha = 0.05$). The effect of treatment was considered significant, and mean comparisons were conducted, if P from the F test was less than α (17). For presentation purposes, least-squares means for the angular values were back-transformed to the actual disease incidence values on a percent scale.

The same analysis was also conducted to determine the effect of treatment on grey mold incidence, and when symptoms were present, anthracnose incidence. Percentage of healthy fruit (no symptoms of any disease) were similarly analyzed.

3. Results and discussion

In 2005, removing straw from between the rows and flooding test plots (Table 1) resulted in a mean leather rot disease incidence of 66% for plots that were not treated with fungicide (Table 2). There were significant ($P < 0.001$) differences in disease incidence among treatments. All fungicide treatments had significantly less leather rot incidence than the untreated control; furthermore, there were no significant differences in leather rot incidence among the different fungicide treatments. Azoxstrobin and potassium phosphite provided excellent leather rot control when applied in a four-spray, calendar-

Table 2
Effect of fungicides applied on a calendar-based protectant program or on a post-infection curative program for the control of leather rot of strawberry and other fruit-rot diseases, 2005.

Treatment[a]	Leather rot (%)	Anthracnose (%)	Grey mold (%)	Healthy fruits (%)
1. Potassium phosphite	4.3 a[b]	9.3 ab	3.0 b	79 ab
2 Azoxystrobin-P. phosphite	1.7 a	2.0 a	1.4 bc	92 a
3. Mefenoxam	2.0 a	21.0 b	2.8 ab	71 b
4. P. phosphite	1.6 a	7.7 a	2.3 ab	83 ab
5. Control	66.0 b	1.3 a	0.5 c	33 c

[a] Treatments 1 an 2 were applied as protectant (calendar-based) applications; treatments 3 and 4 applied as post-infection curative applications. Harvest dates were 10, 14, and 17 June 2005.
[b] Means followed by the same letter are not significantly different according a least significant difference (LSD) of means at the 5% significance level ($\alpha = 0.05$). Data analysis was conducted based on fitting a linear mixed model to angular-transformed incidence data, and then back-transforming least-squares means after analysis.

based protectant program. Mefenoxam and potassium phosphite both provided good control of leather rot when applied as curative treatments in response to flooding events. Both fungicides applied in curative treatments provided leather rot control equal to that of the four-spray calendar-based, protectant treatments with two and one fewer applications, respectively (Table 1).

Anthracnose fruit rot, caused by the fungus *C. acutatum*, developed in the trial in 2005. Although anthracnose did not develop in 2006 and 2007, results in 2005 suggested that neither mefenoxam nor potassium phoshite had any activity against anthracnose. In fact, the untreated control had significantly less anthracnose incidence than the mefenoxam curative treatment (Table 2).

Leather rot incidence in untreated plots was much lower in 2006 than in 2005 (Table 3). Removing straw from between the rows and flooding test plots resulted in a mean disease incidence of 15% in untreated control plots (Table 3). In 2005, the strawberry planting used for this trial was in its third and final year of bearing, and was destroyed after harvest. In 2006, the experiment was conducted in a new planting during its first fruit-bearing year, and the planting was established on fumigated soil. Thus, disease pressure was much higher in 2005 than in 2006 and 2007. However, there were still significant ($P < 0.001$) differences among treatments. In 2006, no diseased fruit were found in any of the fungicide-treated plots, resulting in 100% disease control. All treatments also had a significantly ($P < 0.001$) higher percentage of healthy fruit than the untreated control (Table 3). There were no significant differences in leather rot incidence (or healthy fruit) between any of the fungicide treatments. The curative programs with mefenoxam and potassium phosphite provided an equal level of disease control as the four-spray calendar-based protectant program of azoxystrobin and potassium phosphite (Table 3), with three and one fewer sprays, respectively (Table 1).

A fairly high level of Botrytis fruit rot (grey mold), caused by the fungus *B. cinerea*, developed in the trial of 2006, with nearly 10% incidence in the untreated control. None of the treatments appeared to provide satisfactory control of *B. cinerea* in 2006, and the curative treatment with mefenoxam had significantly more Botrytis fruit rot than all other treatments (Table 3).

In 2007, removing straw from between the rows and flooding the plots resulted in a mean leather rot disease incidence of 30% in the untreated control (Table 4). Thus, there appeared to be a build-up of inoculum in the planting between 2006 and 2007. There were significant ($P < 0.001$) differences in disease incidence among treatments. Mean incidence was less than 1% in all the fungicide treatments, indicating that the treatments provided nearly 100% disease control. The percentage of healthy fruit was also significantly ($P < 0.001$) higher for all fungicide treatments compared with the untreated control (Table 4). There were no significant differences between any of the fungicide treatments in percentage disease control or percentage healthy fruit. The curative programs with mefenoxam and potassium phosphite provided a similar level of disease control as the four-spray, calendar-based protectant program of potassium phosphite and azoxystrobin (Table 4), with three and two fewer sprays, respectively (Table 1). The results in 2007 were very similar to those in 2005 and 2006. Only trace levels of other fruit rot diseases developed in 2007.

In 2006 and 2007, only one post-infection application of mefenoxam was made compared with two in 2005. This change was made in order to conform to current label recommendations for strawberries in established plantings. The current recommendations state "apply up to three times per crop. Make first application in the spring after ground thaws and before first bloom. Make a second application after harvest in the fall." These two applications are directed at control of red stele root rot, caused by the oomycete *Phytophthora fragarie*. For leather rot control, the label further states "For control of leather rot, make a supplemental application during the growing season at fruit set." In these studies, the supplemental application was made in response to the first flooding event (infection period). It is interesting to note that the single application of mefenoxam not only provided at least 48 h of curative activity, but also provided excellent protectant activity throughout the entire harvest period. This agrees with a previous report that a single application of metalaxyl at late bloom (fruit set) provided excellent control of leather rot through harvest (Ellis et al., 1998).

All fungicide programs evaluated during 3 years of testing provided excellent control of strawberry leather rot under conditions of moderate to extremely high disease pressure. By removing straw mulch and creating multiple high-risk periods for disease development

Table 3
Effect of fungicides applied on a calendar-based protectant program or on a post-infection curative program for the control of leather rot of strawberry and also grey mold, 2006.

Treatment[a]	Leather rot (%)	Grey mold (%)[b]	Healthy fruits (%)
1.Azoxystrobin-P. phosphite	0.00 b[b]	7.00 b	87 a
2. Mefenoxam	0.00 b	15.45 a	76 a
3. P. phosphite	0.00 b	12.12 b	80 a
4. Control	15.16 a	9.80 b	64 b

[a] Treatment 1 was applied protectant (calendar-based) application; Treatments 2 and 3 were applied as curative post-infection applications. Harvest dates were 16 and 21 June 2006.
[b] Means followed by the same letter are not significantly different according to a least significant difference (LSD) of means at the 5% significance level ($\alpha = 0.05$). Data analysis was conducted based on fitting a linear mixed model to angular-transformed data incidence data, and then back-transforming least-squares means after analysis.

Table 4
Effect of fungicides applied on a calendar-based protectant program or on a post-infection curative program for the control of leather rot of strawberry and grey mold, 2007.

Treatment[a]	Leather rot (%)	Grey mold[b] (%)	Healthy fruits (%)
1. P. phosphite-Azoxistrobin	0.41 b	0.57 b	97 a
2. Mefenoxam	0.69 b	1.00 b	97 a
3. P. phosphite	0.41 b	0.62 b	98 a
4. Control	30.36 a	3.91 a	64 b

[a] Treatment 1 was applied as protectant (pre-infection) treatment; Treatments 2 and 3 were applied as curative post-infection treatments. Harvest dates were 6 and 11 June 2007.
[b] Means followed by the same letter are not significantly different according to a least significant difference (LSD) of means at the 5% significance level ($\alpha = 0.05$). Data analysis was conducted based on fitting a linear mixed model to angular-transformed data and then back-transforming least-squares means after analysis.

(through frequent flooding), 15–66% leather rot incidence developed in the untreated control. In 3 years of testing, calendar-based, protectant treatments based on potassium phosphite and the QoI fungicide azoxystrobin provided excellent control of leather rot. Moreover, the disease was effectively controlled with post-infection, curative applications of mefenoxan and potassium phosphite applied in response to flooding events (infection periods following splash-dispersal events). The results of this study agrees with previous reports that both phosphite and mefenoxam provide strong post-infection activity against leather rot when applied up to 36 h after inoculation and moderate post-infection activity when applied up to 48 h after inoculation (Rebollar-Alviter et al., 2007). Both mefenoxam and potassium phosphite have been reported to have excellent protectant activity against leather rot as well (Rebollar-Alviter et al., 2007). Our results support previous observations (Ellis et al., 1998) that mefenoxam provides protectant activity for greater than 7 days. In 2006 and 2007, one application of mefenoxam in response to the first flooding event provided effective control of leather rot through harvest. This indicates mefenoxam provided effective protectant activity for 25 and 20 days in 2006 and 2007, respectively.

Results from this study indicate that a curative spray program for leather rot was equally as effective as a calendar-based protectant spray program and resulted in from 1 to 3 fewer applications per season. Reynolds et al. (1987) operationally defined a rain (and, hence, splash-dispersal) event as any 1-h period in which at least 1 mm of rainfall was recorded. Two or more rain events were considered to belong to a single rain period if the time between the end of one event and the start of the next was less that 12 h and fruit surfaces were recorded as being continuously wet in the interim. A rain period (and hence, splash-dispersal event) was considered terminated if a rain event in the period was followed by either a time interval greater than 12 h during which no rain fell and fruit surfaces were dry. In our experiments, we simulated rain events by irrigating until standing water was observed between the rows (at least 120 mm) in order to produce infection events necessitating post-infection applications of fungicides. In the Reynolds et al. model, disease risk is a nonlinear function of rain amount. With the amount of irrigation provided in these studies, each flooding event corresponded to the highest risk defined by Reynolds et al. (1987, 1988). Knowing that *P. cactorum* sporangia and zoospores require as little as 2 h of wetness (with temperatures between 17 and 25 °C) to infect fruits, it is reasonable to assume that fruit infections occurred during these flooding events (Grove et al., 1985; Madden et al., 1991; Reynolds et al., 1987). Thus, based on previous work demonstrating post-infection activity of mefenoxam and phosphite, we believe that the fungicide applications applied in response to flooding events in these studies were providing curative activity against leather rot. In addition to strong curative activity, all of the fungicides tested in these studies also provide strong protectant activity; therefore, we were able to ignore flooding events (infection periods) that occurred within at least 7 days of a curative application. The combination of strong curative and protectant activity should make a curative program for strawberry leather rot more practical and easily adaptable by perennial matted-row strawberry growers in the Midwest and Northeast USA

In summary, calendar-based spray programs, involving QoI fungicides such as azoxystrobin, alternated with potassium phosphite, and post-infection spray programs, consisting of mefenoxam or potassium phosphite, provided excellent control of leather rot under conditions of extremely high disease pressure. Our results showed that when applying mefenoxan and potassium phosphite within approximately 36 h of the occurrence of a flooding event, it is possible to control leather rot of strawberry as well as with a more intensive calendar-based approach. This approach to disease management conforms to current IPM strategies of obtaining acceptable disease control with the fewest number of fungicide applications. The curative activity of these fungicides could also be of benefit even for growers who prefer to follow a calendar-based protectant fungicide program for leather rot control. For example, if heavy or prolonged rainfall occurred, especially around the time of late bloom through harvest, it may not be possible to apply a protectant fungicide in a timely manner. In such situations, it may be beneficial to apply a fungicide with strong curative activity, especially if the application could be made 36 h (or possibly 48 h) after the initiation of the rainfall event. Whereas mefenoxam and potassium phosphite provided excellent control of leather rot in these studies, under field conditions of prolonged wetness that are highly conducive to disease development, their use should be supplemented (tank-mixed) with fungicides that have activity against Botrytis and anthracnose fruit rot. Regardless of the spray program used, it is important to note that each of the fungicides used in the study have different fungicide chemistry (modes of action). Growers should alternate the use of these materials in their spray program to prevent or delay the development of fungicide resistance in *P. cactorum*.

References

Browne, G.T., Viveros, M.A., 2004. Effects of phosphonate and mefenoxam treatments on development of perennial cankers caused by two *Phytophthora* spp. on almond. Plant Dis. 89, 241–249.

Ellis, M.A., Grove, G.G., 1983. Leather rot in Ohio strawberries. Plant Dis. 67, 549.

Ellis, M.A., Wilcox, W.F., Madden, L.V., 1998. Efficacy of metalaxyl, fosetyl-aluminum, and straw mulch for control of strawberry leather rot caused by *Phytophthora cactorum*. Plant Dis 82, 329–332.

Gisi, U., 2002. Chemical control of downy mildews. In: Spencer-Phyllips, N.T.E., Gisi, U., Lebeda, A. (Eds.), Advances in Downy Mildew Research. Academic Press, pp. 119–159.

Grove, G.G., Madden, L.V., Ellis, M.A., 1985. Influence of temperature and wetness duration on sporulation of *Phytophthora cactorum* on infected strawberry fruit. Phytopathology 75, 700–703.

Guest, D., Grant, B.R., 1991. The complex action of phosphonates as antifungal agents. Biol. Rev. 66, 159–187.

Jackson, T.J., Burgess, T., Colquhoun, I., Hardy, G.E.St.J., 2000. Action of the fungicide phosphite on the *Eucalyptus marginata* inoculated with *Phytophthora cinnamomi*. Plant Pathol. 49, 147–154.

Jelen, H.H., Krawczyk, J., Larsen, T.O., Jarosz, A., Golebniak, B., 2005. Main compounds responsible for off-odor of strawberries infected by *Phytophthora cactorum*. Lett. Appl. Microbiol. 40, 255–259.

Kennelly, M.M., Goudury, D.M., Wilcox, F.W., Seem, R.C., 2007. Vapor activity and systemic movement of mefenoxam control grape downy mildew. Plant Dis. 91, 1260–1264.

Madden, L.V., Ellis, M.A., Grove, G.G., Reynolds, K.M., Wilson, L.L., 1991. Epidemiology and control of leather rot of strawberries. Plant Dis. 75, 439–445.

McDonald, A.E., Grant, B.R., Plaxton, W.C., 2001. Phosphite (phosphorous acid): its relevance in the environment and agriculture and influence on plant phosphate starvation response. J. Plant Nutr. 24, 1505–1519.

Niere, J.O., Griffith, J.M., Grant, B.R., 1990. ^{31}P NMR studies on the effect of phosphite on *Phytophthora palmivora*. J. Gen. Microbiol. 136, 147–156.

Rebollar-Alviter, A., Madden, L. V., Ellis, M. A., 2005. Efficacy of azoxystrobin, pyraclostrobin, potassium phosphite, and mefenoxam for control of strawberry leather rot caused by Phytophthora cactorum. *Plant Health Progress*. doi:10.1094/PHP-2005-0107-01-RS.

Rebollar-Alviter, A., Madden, L.V., Ellis, M.A., 2007. Pre- and Post-infection activity of azoxystrobin, pyraclostrobin, mefenoxam and phosphite against leather rot of strawberry, caused by *Phytophthora cactorum*. Plant Dis. 91, 559–564.

Reynolds, K.M., Ellis, M.A., Madden, L.V., 1987. Progress in development of a strawberry leather rot forecasting system. Adv. Strawberry Prod. 6, 18–22.

Reynolds, K.M., Madden, L.V., Ellis, M.A., 1988. Effect of weather variables on strawberry leather rot epidemics. Phytopathology 78, 822–827.

Schabenberger, O., Pierce, F.J., 2002. Contemporary Statistical Models for the Plant and Soil Sciences. CRC Press, Boca Raton, FL.

Stehmann, C., Grant, B., 2000. Inhibition of enzymes of the glycolytic pathway and hexose monophosphate bypass by phosphonate. Pestic. Biochem. Physiol. 67, 13–24.

Wedge, D.E., Smith, B.J., Quebedeaux, J.P., Constantin, R.J., 2007. Fungicide management strategies for control of strawberry fruit rot diseases in Louisiana and Mississippi. Crop Prot. 26, 1449–1458.

Wicks, T.J., Magarey, P.A., Wachtel, M.F., Frensham, A.B., 1991. Effect of postinfection applications of phosphorous (phosphonic) acid on the incidence and esporulation of *Plasmopara viticola* on grapevine. Plant Dis. 75, 40–43.

Wong, P.F., Wilcox, F.W., 2001. Comparative physical modes of action of azoxystrobin, mancozeb, and metalaxyl against *Plasmopara viticola* (Grapevine downy mildew). Plant Dis. 85, 649–656.