Activity of Fungicides Against *Monilinia vaccinii-corymbosi* in Blueberry Flowers Treated at Different Phenological Stages

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ABSTRACT

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The activity of fenbuconazole and azoxystrobin applied to blueberry flowers at different phenological stages against subsequent gynoecial infection by the mummy berry fungus *Monilinia vaccinii-corymbosi* was evaluated. In the greenhouse, potted blueberry plants having flower clusters at five distinct stages (from bud scale separation to anthesis) were treated with the two fungicides. One day after anthesis (between 1 and 15 days after fungicide treatment), individual flowers were detached and inoculated with conidia of *M. vaccinii-corymbosi* in the laboratory. Four days after inoculation, hyphal ingress into the style was determined microscopically as a measure of fungicide efficacy. Results revealed a significant flower stage effect ($P < 0.0001$), whereby only fungicide application at anthesis but not at the four preanthesis stages reduced subsequent fungal ingress into the style. There was no significant difference between the two fungicides ($P > 0.50$) nor was there a significant fungicide-flower stage interaction ($P > 0.30$). In the field during 2 years, mature blueberry plants were treated with the two fungicides and exposed to natural pathogen inoculum. At the time of application, flower clusters at anthesis and at three preanthesis stages were selected and tagged. Mummy berry incidence in fruit developing from the tagged clusters was assessed to determine treatment effects. Whereas fenbuconazole lowered disease incidence for all preanthesis stages, azoxystrobin was effective only at the latest preanthesis stage. The discrepancy between these results and those of the greenhouse study (where there was no preanthesis activity of either fungicide) indirectly suggests post-infection fungicidal activity in the ovary, the base of which was exposed to the fungicide spray at the time of treatment for all flower phenology stages. Thus, although there appears to be insufficient translocation of the two fungicides in flowers treated at preanthesis stages to prevent stylar ingress by the pathogen, fungicidal activity in the ovary may be sufficient to halt subsequent fungal colonization, especially for fenbuconazole. To prescribe the most effective management program for flower-infecting fungi, translocation and post-infection activity of fungicides in floral tissues must be better understood.

Additional keywords: demethylation inhibitor, quinone outside inhibitor, rabbiteye blueberry, *Vaccinium virgatum*

During the past 25 years, blueberry (*Vaccinium* section *Cyanococcus*) has emerged as an important crop in Georgia, surpassing peach as the fruit crop with the highest utilized value of production in 2005 and 2006 (1). In part due to the recent recognition of the health benefits associated with blueberry fruit consumption (12,29), the production area of blueberry statewide has risen from <500 ha in the 1980s to >3,600 ha in 2005 (4,20).

Mummy berry disease, caused by the fungus *Monilinia vaccinii-corymbosi*, is a major disease confronting blueberry growers in North America (3,7,10). In a survey

published in 2001, >75% of Georgia blueberry producers reported mummy berry as a major or moderate disease problem (21). Most losses associated with the disease are due to the rejection or downgrading of commercial blueberry shipments that contain mummified fruit (19).

Fruit mummification by *M. vaccinii-corymbosi* is the result of conidial infection of open flowers through the stigma and style, whereby fungal hyphae grow through the gynoecial pathway into the ovary to colonize the developing fruit internally (14,23). As the fruit develop, the locules of the ovaries are filled with dense mycelial growth. The hyphae migrate into the mesocarp, in which a pseudosclerotium (mummy) forms during the fruit maturation process. Mummified fruit fall to the ground where they overwinter and overwinter, serving as the source of primary inoculum in the following spring (3,13). Ascospores, produced in apothecia formed on overwintered mummies, incite primary

infection in late winter or early spring, blighting emerging leaves and shoots (primary infection). Conidia produced on blighted tissue subsequently serve as the source of inoculum for infection of open flowers during bloom (secondary infection).

Management of mummy berry disease requires repeated applications of fungicide from vegetative bud break through the end of bloom in order to mitigate both shoot blight and flower infection. To minimize the number of sprays needed for disease control, host phenology-based application schedules have been developed (6,22,25-27). Since the 1990s, the demethylation inhibitor (DMI) fenbuconazole (Indar) has become the standard for managing primary and secondary infection by *M. vaccinii-corymbosi* (22,25-27). In Georgia, two to three bloom applications of fenbuconazole proved effective in controlling mummy berry disease (22). Other active ingredients currently labeled against the disease include the quinone outside inhibitors (QoIs) azoxystrobin (Abound) and pyraclostrobin + boscalid (Pristine).

An important problem with timing bloom sprays against mummy berry disease is the high degree of variability in bloom progression among blueberry cultivars and years. During favorable weather, numerous new infection courts (stigmatic surfaces) can become exposed to inoculum within a few days. Conversely, less favorable environmental conditions can lead to a highly protracted bloom period. It is unknown to what degree the pistils of flowers treated before anthesis (when the pistil is still enclosed by the corolla) are protected from infection after the flowers open. Any preanthesis activity of fungicides in flowers should be related to (i) the ability of the applied active ingredient to translocate into the style from the base of the ovary, the only part of the pistil exposed during spray application to unopened flowers; and (ii) the post-infection activity of the fungicide in the ovary, where it may prevent colonization after successful pathogen ingress through stigma and style. In general, DMIs have more pronounced systemic properties (8,28) and post-infection activity (5,9,17) than QoI fungicides, whose translocation often is limited to translaminar movement (2). However, there is no specific information on mobility and activity of different fungicidal compounds in flowers. In the

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field, fenbuconazole is consistently effective in controlling secondary infection by *M. vaccinii-corymbosi*, whereas azoxystrobin generally exhibits lower or more variable levels of control for the same number of applications (22,25,27). This difference in efficacy may be due, in part, to different degrees of mobility of the two compounds in the floral tissues through which the pathogen infects.

This study sought to determine the duration of control afforded by fenbuconazole and azoxystrobin against *M. vaccinii-*

corymbosi in blueberry flowers treated at different phenological stages. Experiments were carried out (i) in controlled conditions by assessing hyphal ingress of *M. vaccinii-corymbosi* into the styles of artificially inoculated flowers taken from greenhouse-grown plants previously treated with the two fungicides and (ii) in the field in the presence of natural inoculum by comparing the incidence of fruit infection in plants treated with the fungicides when a range of distinct flower phenology stages was present.

MATERIALS AND METHODS

Greenhouse experiments. Four- to five-year-old rabbiteye blueberry plants (*Vaccinium virgatum* cv. Climax) were maintained in 11.4-liter pots in a cold room (5 to 6°C) during the winter. At intervals from early January to early May, groups of plants were moved to a greenhouse maintained at 24 to 28°C to obtain subsets of plants with staggered bloom periods. Each individual run of the experiment was carried out when a sufficient number of flower clusters at the designated phenological stages (see below) was available. The experiment was carried out five times over two growing seasons, and the individual experimental runs were considered replicates (blocks) in the analysis.

The experimental design was a split-plot with fungicide (three levels) as the main plot and flower phenology stage (five levels) as the subplot. Each main plot consisted of a single plant having all five flower stages present simultaneously. Numerical flower stages (24) at the time of fungicide treatment were 3 = bud scales separated, apices of flowers visible; 4 = individual flowers distinguishable, bud scales abscised; early 5 = individual flowers distinctly separated and corollas short, unexpanded, and closed; late 5 = individual flowers distinctly separated and corollas longer and somewhat expanded, but still closed; and early 6 = anthesis (i.e., corollas completely expanded, flowers open). On the day of fungicide treatment, six flower clusters per stage were tagged on each plant using colored embroidery thread.

Fungicide treatments consisted of a single application of fenbuconazole (Indar 75WSP; 0.3 g of formulated product per liter; Dow AgroSciences, Indianapolis, IN), azoxystrobin (Abound SC; 1.9 ml formulated product per liter; Syngenta Crop Protection, Greensboro, NC), or a water control. Each plant was treated with 0.3 liters of fungicide suspension or water using a 7.6-liter handheld sprayer.

Individual flowers at stage 6 (newly open at the time of fungicide application) were detached 1 day after treatment, positioned in microtiter plate wells in the laboratory, and inoculated with conidia of *M. vaccinii-corymbosi* as described by Ngugi et al. (16), except that oat bran agar was used for fungal culture instead of oatmeal agar. Oat bran agar was prepared by boiling 20 g of oat bran in 600 ml of deionized water, simmering for 40 min with frequent stirring, filtering the suspension through cheesecloth, and bringing the total volume to 750 ml with deionized water prior to adding 10 g of agar and autoclaving. Detached flowers were used for inoculation because they allowed for precise application of conidia under a stereomicroscope. Previous work in our laboratory documented a highly significant linear correlation between hyphal growth rates in de-

Fig. 1. Hyphal ingress of *Monilinia vaccinii-corymbosi* into flower styles of greenhouse-grown Climax rabbiteye blueberry in relation to fungicide active ingredient and flower stage at the time of fungicide application. **A**, Number of hyphae that penetrated at least 20% of the length of the style. **B**, Average hyphal growth rate per style. Flowers were treated with fungicide at the stages indicated, detached, inoculated with conidia of *M. vaccinii-corymbosi* 1 day after anthesis, and fixed for microscopic assessment 4 days later. Values are means and standard errors of five replicate experiments, each with eight styles per treatment combination.

tached flowers and fruit mummification incidence on attached flowers across a range of treatments (16).

Flowers treated with fungicide at earlier phenology stages were monitored daily, detached 1 day after reaching anthesis, and inoculated similarly. Thus, flowers at all five stages were treated with fungicide at the same time in a given experimental run, but inoculations occurred at staggered times (between 1 and 15 days after fungicide application) depending on when flowers of each stage opened. Four days after inoculation, corollas and ovaries from a sample of eight inoculated flowers per fungicide-flower stage combination were removed, and the styles were fixed and stained with decolorized aniline blue for fluorescence microscopy (16). They were cut longitudinally with a scalpel, and hyphal ingress by *M. vaccinii-corymbosi* was measured microscopically using an ocular micrometer. As in Ngugi et al. (16), the number of hyphae penetrating at least one-fifth the length of the style was counted. In addition, the lengths of the eight longest hyphae per style, regardless of depth of penetration, were measured to determine hyphal growth rates; fewer hyphae were measured if <8 hyphae penetrated into the stylar canal. Means and standard errors of the two variables were calculated across all flowers for each fungicide-flower stage combination. Data on number of hyphae per style and hyphal growth rate were subjected to analysis of variance for a split-plot design (11) using SAS (v. 8.02; SAS Institute, Cary, NC). All data were expressed as a percentage of the water control prior to the analysis. This was done to (i) standardize disease values across experimental runs and (ii) emphasize the comparison between the two fungicide active ingredients rather than that between the two fungicides and the water control.

Field experiments. A field study to determine the effect of fenbuconazole and azoxystrobin applied to plants having flowers at a range of phenological stages was carried out in a commercial rabbiteye blueberry planting near Social Circle, GA,

in 2005 and 2006 in rows of mature bushes of cv. Tifblue. The experimental design was a split-plot with four blocks (replicates), fungicide (three levels: fenbuconazole, azoxystrobin, and water control) in the main plot, and flower phenology stage (four levels: stages 4, early 5, late 5, and 6) in the subplot. Each main plot consisted of a single blueberry bush surrounded by untreated buffer plants.

On each bush, 12 flower clusters at each designated stage were tagged with colored embroidery thread just prior to fungicide application. Fungicides (at the rates described for the greenhouse study above) were applied once at early bloom when all designated flower stages were present. No artificial inoculations were carried out. Treated clusters were harvested when green berries reached a diameter of 7 to 10 mm. Berries were bisected to determine the incidence of infection by *M. vaccinii-corymbosi* as evidenced by visible mycelial strands, a mycelial matrix in the locules, or the presence of an immature or mature pseudosclerotium. Analysis of variance for a split-plot design was performed using incidence data expressed as a percentage of the water control.

RESULTS

Greenhouse experiments. For both fungicides, pathogen ingress into the style for flowers treated at preanthesis stages 3 through late 5 was not significantly different from the water control, as shown by the overlapping standard errors in Figure 1. Only flowers treated at anthesis (stage 6) showed reduced pathogen ingress for both fungicides. In those flowers, an average of 2.7 and 1.6 hyphae penetrated at least one-fifth of the length of styles treated with fenbuconazole and azoxystrobin, respectively, compared with 10.9 hyphae in water-treated styles (Fig. 1A). Similarly, growth rates in styles treated with fenbuconazole or azoxystrobin at anthesis were 0.24 and 0.13 mm day⁻¹, respectively, compared with 1.40 mm day⁻¹ for hyphae in the water control styles (Fig. 1B). Conidia inoculated on flowers treated with

fenbuconazole at anthesis often showed some germination but no penetration, whereas those inoculated on flowers treated with azoxystrobin rarely showed any signs of germination (*data not shown*).

When both response variables (number of hyphae per style and hyphal growth rates) were expressed as percentages of the water control, analysis of variance indicated a highly significant effect of flower stage at the time of application, whereas fungicide (fenbuconazole versus azoxystrobin) and the fungicide-flower stage interaction were not significant (Table 1).

Field experiments. Because of low disease incidence levels (<10% in the water control in both years), data from the 2 years were combined to increase the power of the analysis. Inoculum pressure varied during the bloom period, as evidenced by the decline in the average incidence of fruit infection in the water control from 7.7% for flowers at stage 4 at the time of treatment to 2.2% for those at stage 6 at the time of treatment (Fig. 2). Whereas fenbuconazole applications resulted in significant disease suppression relative to the water control at all preanthesis stages, azoxystrobin was effective only at the late-5 stage, as shown by the overlapping standard errors in Figure 2 for all other stages. Disease incidence for flowers at stage 6 at the time of fungicide application were very low, regardless of the treatment. When data were expressed as a percentage of the water control, analysis of variance revealed a significant difference between the two fungicides ($P = 0.0436$), whereas there was no significant flower stage effect or fungicide-flower stage interaction (Table 2).

DISCUSSION

Repeated fungicide sprays during bloom can be an effective management strategy for mummy berry disease of blueberry (22,25–27). However, in the field, many flowers open between fungicide applications, and their stigmatic surfaces, which serve as the infection court for *M. vaccinii-corymbosi*, are not covered directly by fungicide spray. Thus, the preanthesis ac-

Table 1. Results of a split-plot analysis of variance to determine the effects of fungicide, flower stage at the time of fungicide application, and their interaction on penetration of *Monilinia vaccinii-corymbosi* into flower styles of greenhouse-grown Climax rabbiteye blueberry^a

Source	df	Number of hyphae per style			Average growth rate of hyphae		
		Mean square	F	P > F	Mean square	F	P > F
Replication ^b	4	1,298.2	2.12	0.2424	828.6	2.27	0.2232
Fungicide ^c	1	128.7	0.21	0.6704	132.3	0.36	0.5795
Main-plot error	4	612.5	...	...	364.8	...	...
Flower stage ^d	4	7,288.7	10.25	<0.0001	9,112.3	25.47	<0.0001
Fungicide-flower stage interaction	4	389.3	0.55	0.7021	434.4	1.21	0.3247
Subplot error	31	711.0	...	...	357.7	...	...

^a Flowers were treated with fungicide at the stages indicated below; detached, inoculated with conidia of *M. vaccinii-corymbosi* 1 day after anthesis, and fixed for microscopic assessment 4 days later. Analysis based on values expressed as a percentage of the water control.

^b Five separate experiments, each with eight styles per treatment combination.

^c Indar 75WSP (fenbuconazole) or Abound (azoxystrobin) applied as formulated product at 0.3 g/liter and 1.9 ml/liter, respectively.

^d Numerical flower stages (24) at the time of fungicide treatment were 3 = bud scales separated, apices of flowers visible; 4 = individual flowers distinguishable, bud scales abscised; early 5 = individual flowers distinctly separated and corollas short, unexpanded, and closed; late 5 = individual flowers distinctly separated and corollas longer and somewhat expanded, but still closed; and early 6 = anthesis (i.e., corollas completely expanded, flowers open).

tivity provided by fungicides is important in determining the application timing and frequency necessary to protect against infection by this pathogen. In recent field studies, fungicides have been applied according to bloom phenology rather than based on calendar days, resulting in considerably shorter application intervals than specified by the product labels in years when bloom progressed rapidly (25,26). Timing and frequency of applications could be improved if the preinfection ac-

tivity of fungicides applied prior to anthesis could be quantified. This was intended in the present study.

The greenhouse study showed that, for both fenbuconazole and azoxystrobin, only flowers treated at anthesis (stigmas exposed to direct fungicide coverage) were protected from stylar penetration by *M. vaccinii-corymbosi* following artificial inoculation. Flowers sprayed prior to anthesis showed no decrease in hyphal penetration when they were inoculated after

they opened 1 to 15 days after application, suggesting that neither fungicide was translocated from the ovary, the only exposed part of the pistil in preanthesis flowers, into the style or stigma in sufficient concentration to prevent hyphal ingress by the pathogen. A similar conclusion, albeit for a different pathosystem, was reached by Ryley et al. (18), who found that, in their spray timing trials against *Claviceps africana*, another fungus that infects through the stigma and style, systemic protection of sorghum panicles by DMI fungicides was limited. Although DMIs generally are more systemic than QoI fungicides, fenbuconazole appears to have translaminar rather than fully systemic activity (28). The lack of conidial germination in stage-6 flowers treated with azoxystrobin is consistent with the compound's activity as a spore germination inhibitor, whereas fenbuconazole, a triazole fungicide, does not inhibit spore germination and early germ tube growth (2,28).

In the field study, fenbuconazole showed considerable activity against infection by *M. vaccinii-corymbosi* when applied pre-anthesis, whereas there was no such activity in the greenhouse study. The discrepancy between the two studies indirectly suggests post-infection fungicidal activity of fenbuconazole in the ovary, the base of which is the only part of the pistil directly covered by fungicide in flowers sprayed before anthesis. Although fenbuconazole does not appear to move systemically from the ovary into the style (as indicated by the greenhouse study), it may translocate within the ovary and halt colonization by the pathogen after the hyphae have entered through the style. In leaf tissue, DMI fungicides show some post-infection activity when applied shortly after infection (5,9,17,28); such activity also could be present in flowers and could explain why some control has been noted in the field even when sprays are applied at early flower phenology stages or at longer intervals (6,25). Future studies which measure both hyphal ingress and ovary colonization are needed to clarify this aspect of the activity of fenbuconazole.

The preanthesis activity of azoxystrobin in the field was considerably weaker than that of fenbuconazole, being limited to late stage-5 flowers. This is consistent with previous reports (22,25) that azoxystrobin generally is less effective in managing the secondary infection phase of mummy berry disease. The compound acts mostly by inhibiting spore germination (2), requiring application before germination of conidia to be most effective. The lower efficacy of azoxystrobin in the field also could have been due to the fact that flower phenology could not be controlled as precisely in the field as in the greenhouse study. Previous laboratory work (16) showed a significant effect of flower age (time after anthesis) on infection success

Fig. 2. Incidence of fruit infection by *Monilinia vaccinii-corymbosi* on Tifblue rabbiteye blueberry in the field in relation to fungicide active ingredient and flower stage at the time of fungicide application. Flower clusters were treated with fungicide at the stages indicated, exposed to natural inoculum of *M. vaccinii-corymbosi*, and fruit developing from these clusters were harvested and assessed for disease incidence. Values are means and standard errors of eight replications (four replicate plots in each of 2 years), each with 12 flower clusters per treatment combination.

Table 2. Results of a split-plot analysis of variance to determine the effects of fungicide, flower stage at the time of fungicide application, and their interaction on the incidence of fruit infection by *Monilinia vaccinii-corymbosi* on Tifblue rabbiteye blueberry in the field^a

Source	df	Mean square	F	P > F
Replication ^b	7	3,484.5	2.86	0.0943
Fungicide (main plot) ^c	1	7,351.9	6.04	0.0436
Main plot error	7	1,217.1	...	...
Flower stage (subplot) ^d	3	2,531.1	2.22	0.0995
Fungicide-flower stage interaction	3	2,155.8	1.89	0.1453
Subplot error	42	1,138.2	...	...

^a Flower clusters were treated with fungicide at the stages indicated below and exposed to natural inoculum of *M. vaccinii-corymbosi*; fruit developing from these clusters were harvested and assessed for disease incidence. Analysis based on values expressed as a percentage of the water control.

^b Combined data from 2 years with four replications per year.

^c Indar 75WSP (fenbuconazole) or Abound (azoxystrobin) applied as formulated products at 0.3 g/liter and 1.9 ml/liter, respectively.

^d Numerical flower stages (24) at the time of fungicide treatment were 4 = individual flowers distinguishable, bud scales abscised; early 5 = individual flowers distinctly separated and corollas short, unexpanded, and closed; late 5 = individual flowers distinctly separated and corollas longer and somewhat expanded, but still closed; and early 6 = anthesis (i.e., corollas completely expanded, flowers open).

by *M. vaccinii-corymbosi*, whereby newly opened flowers were most receptive to infection and receptivity decreased rapidly with increasing flower age. In the present study, stage-6 flowers in the greenhouse were sprayed the day they opened and inoculated 1 day later, an age at which fungal ingress would have been expected to be near optimum. In contrast, in the field, it was not possible to determine how long stage-6 flowers had been open before fungicide application or how soon before or after application they were exposed to conidia of *M. vaccinii-corymbosi*. Thus, the flowers may have been infected already at the time of treatment, or they may have been infected after the azoxystrobin treatment was most effective.

In a broader context, this study highlights the need to determine mobility and activity of fungicidal active ingredients in floral tissues, because flowers are physiologically very different from leaves. Knowledge of a compound's activity in leaves cannot be extrapolated to flowers; hence, for the numerous pathosystems involving flowers (15), it is more difficult to prescribe chemical control measures. Further research investigating translocation and post-infection activity of different active ingredients against *M. vaccinii-corymbosi* would be useful, including documentation of the inhibition of mycelial colonization via residual activity in the ovary after successful penetration of the style has occurred.

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