Effects of Simulated Hail Events and Subsequent Fungicide Applications on Cranberry Fruit Rot Incidence and Yield

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Abstract

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Storms containing hail are a common occurrence in Wisconsin, with a few or many cranberry (*Vaccinium macrocarpon*) growers being affected every year. Growers usually apply fungicides immediately following hail events to prevent fruit rot, despite a lack of research to support this practice. We conducted field trials in 2010 and 2011 to address the question of whether applying fungicides to injured fruit reduces fruit rot incidence (% rotten fruit). Hail damage was simulated by forcibly projecting pea gravel into cranberry beds using a mist-blower sprayer modified for this purpose, and the fungicides azoxystrobin or copper hydroxide were applied to fruit immediately after applying gravel. Fruit rot incidence and yield were evaluated within 2 weeks prior to commercial harvest in late September and early October. Fruit rot incidence was greater ($P \leq 0.05$) and yield was lower ($P <$

0.05) in plots treated with gravel than in the nontreated control plots in six of seven trials. Fungicides did not reduce fruit rot incidence ($P \geq 0.05$) in gravel-treated plots compared to the nontreated control in six of seven trials. However, in a trial conducted on relatively immature berries, fruit rot incidence in gravel-treated plots treated with azoxystrobin was less ($P = 0.0103$) than fruit rot incidence in gravel-treated plots receiving no fungicide treatment. In that same trial, fruit rot incidence was not reduced ($P = 0.1243$) in gravel-treated plots treated with copper hydroxide compared to gravel-treated plots that were not treated with fungicide. Results suggest that under most circumstances, if cranberries are damaged by hail, it is unlikely that an application of fungicide will reduce the amount of fruit rot at the time of harvest.

Crop losses due to hail damage in the United States averaged \$581 million annually in the 1949 to 2006 period (4). For this reason, American farmers have referred to hail as the “white plague” (9). The majority of hail events occur during the months of May through September (4), which correlates with the growing and harvesting seasons of many crops in the United States, including the large American cranberry (*Vaccinium macrocarpon* Aiton).

Cranberry is the most important fruit crop in Wisconsin, with more than 7,284 hectares in production, and farm gate values of approximately \$166 million, \$172 million, and \$193 million per year in 2009, 2010, and 2011, respectively (24). Storms containing hail are a common occurrence in Wisconsin and occasionally affect growers in other cranberry-growing regions of the United States and Canada. The occurrence of a hail event during the growing season, and especially after fruit set, causes significant economic losses for cranberry growers.

While the concern with hail in many crops is damage to and consequent loss of foliage and photosynthetic capabilities (1,3), the major burden for cranberry growers involves physical damage to the fruit, which often results in rotten, unmarketable berries. In an effort to prevent fruit rot caused by a complex of fungi (12), cranberry growers usually apply fungicides, often copper-based fungicides, immediately following hail events, despite a lack of research to support the efficacy of this practice. Copper-based fungicides have been favored for this purpose because historically they have been less expensive than synthetic fungicides, and being exempt from preharvest intervals, their use is allowed late in the season. Some fungicides, such as Headline (pyraclostrobin; BASF Corp., Research Triangle Park, NC), have labels that state a benefit of “better tolerance to hail” in corn, barley, rye, and wheat, which has

contributed to an increased use of these fungicides in field crops (2,3). There are currently no fungicides approved for use in cranberry that have labels that state benefits when applied after the occurrence of hail damage. However, with fruit rot increasing in incidence and severity in Wisconsin over the past decade (P. S. McManus, *personal communication*), growers are becoming more reliant on fungicides to protect their investment, especially following hail events. Despite a presumed relationship between hail injury and disease development on a wide variety of crops (5,7,8,14–19,21,22), we are aware of just one study (3) in which the effects of applying fungicides following hail simulation were reported. In the current study, we describe a novel, inexpensive method to simulate hail injury in cranberry plantings, which easily could be applied for research on other crops. The specific objectives of this research were to determine: (i) the efficacy in controlling cranberry fruit rot and effect on yield of applying fungicides to fruit following hail simulation; and (ii) the relationship between the amount of hail simulation applied to berries and fruit scarring or rot at the time of harvest.

Materials and Methods

Field sites. Trials were conducted in 2010 and 2011 at two commercial cranberry marshes near Tomah and Necedah, in the major cranberry growing region of central Wisconsin. At both sites, fruit were grown for processing. At Tomah, experiments were conducted in a mature bed (i.e., >7 years) of ‘Grygleski Hybrid 2’ (GH2) in 2010 and a mature bed of ‘Grygleski Hybrid 1’ (GH1) in 2011. During bloom in 2010 and 2011, the grower made two and three applications of broad-spectrum protectant fungicides, respectively. In 2010, an application of mancozeb (Penncozeb, United Phosphorous, Inc., King of Prussia, PA, at 4,203 g a.i. ha⁻¹) was followed by an application of chlorothalonil (Bravo Ultrex, Syngenta Crop Protection, LLC, Greensboro, NC, at 5,086 g a.i. ha⁻¹), and in 2011 an application of chlorothalonil (Bravo Ultrex at 5,086 g a.i. ha⁻¹) was followed by two applications of mancozeb (Penncozeb at 4,203 g a.i. ha⁻¹). At Necedah, experiments were conducted in a mature bed of ‘Stevens’ in both years. For several years leading up to our study and during 2010 and 2011, no fungicides were applied by the grower at Necedah. Growers at both

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marshes applied fertilizers, herbicides, insecticides, and water as needed to manage the crop.

Effects of fungicides on fruit treated with simulated hail. In 2010, trials were conducted on 28 July and 4 August at Tomah and 18 August at Necedah. In 2011, trials were conducted on 30 July and 29 August at Tomah, and 10 August and 7 September at Necedah. The experimental design was a two-by-three factorial (simulated hail by fungicide) arranged in a randomized complete block design with four replicated blocks. There were two levels of simulated hail (with or without) and three fungicide treatments (azoxystrobin [Abound, Syngenta Crop Protection, LLC] at 280 g a.i. ha⁻¹; copper hydroxide [Champ Formula 2 Flowable, Nufarm Agricultural Products, Burr Ridge, IL] at 3,441 g a.i. ha⁻¹; or no fungicide). This resulted in six treatments: (i) simulated hail + Abound; (ii) simulated hail + Champ Formula 2; (iii) simulated hail + no fungicide; (iv) no simulated hail + Abound; (v) no simulated hail + Champ Formula 2; and (vi) no simulated hail + no fungicide. These six treatments were applied in all seven trials

Fig. 1. Effect of gravel and fungicide applications on fruit rot incidence from field trials in 2010. Treatments: azoxystrobin (Abound, Syngenta Crop Protection, Greensboro, NC; 280 g a.i. ha⁻¹); copper hydroxide (Champ Formula 2 Flowable, Nufarm Agricultural Products, Burr Ridge, IL; 3,441 g a.i. ha⁻¹); or no fungicide. For each treatment, $n = 4$. Bars represent $\pm$ one standard error of the mean.

except the 28 July 2010 trial at Tomah, in which Champ Formula 2 treatments were omitted. In all trials, treatments were applied to 0.37 m² plots with 0.3-m-wide nontreated borders between plots. As a measure of crop development stage, berry diameter and weight at the time of treatment were determined for berry samples at each treatment date. A SOLO backpack mist blower (SOLO 450, Newport News, VA) was modified so that all-purpose pea gravel (approximately 1 cm in diameter) could be introduced into the airstream. The spray tank was empty while gravel was applied. In 2010, 200 ml (approximately 310 g) of gravel was forcibly projected into each plot; in 2011, the amount of pea gravel was increased to 300 ml (approximately 470 g) with the goal of damaging a greater percentage of berries. At these doses, the number of gravel stones applied ranged from 630 to 860 in 2010 and from 935 to 1,011 in 2011. To estimate the percentage of berries damaged, additional plots beyond those used in the fungicide trials were treated with pea gravel and then berries were harvested immediately and inspected for damage within 1 day. In 2010 and 2011, 31 to 50% and 37 to 72% of fruit were injured by pea gravel, respectively. Immediately following simulated hail, fungicides were applied at the highest rates recommended on product labels, as listed above, in a volume of 2,800 liters of water/ha using a SOLO handheld sprayer powered by a piston pump (SOLO 420, Newport News, VA). Applications were performed in low-wind conditions and using shields to minimize drift between plots. For all trials, the ground and crop canopy was dry at the time of treatment. Rainfall data were collected from University of Wisconsin-Extension weather stations located 10 and 19 km from the Tomah and Necedah sites, respectively.

Berries from a 0.09 m² area from the middle of each of the 0.37 m² plots were harvested by hand on 11 October 2010 and 10 October 2011 at Tomah and 27 September 2010 and 1 October 2011 at Necedah, dates that were less than 2 weeks prior to commercial harvest. For each treatment, fruit were sorted into three categories: sound, marketable berries with no apparent injury; soft, rotten berries; or sound berries showing signs of damage from simulated hail. Berries were counted to determine fruit rot incidence (% rotten berries) and weighed to determine yield. Across all trials, an average of 270 berries was harvested from each 0.09 m² area.

Dose response. In 2011, trials were conducted on 16 August at Tomah and 25 August at Necedah in the beds described previously to estimate the amount of fruit rot (response) that resulted from bombardment with different volumes of pea gravel (dose). Five treatments (50, 150, 250, 350, or 500 ml pea gravel) were applied as described previously to 0.37 m² plots in a randomized complete block design with four replicate blocks. Berries were harvested from a 0.09 m² area from the middle of each of the 0.37 m² plots on 10 October 2011 at Tomah and on 1 October 2011 at Necedah, and then sorted into categories as described previously.

Statistical analyses. Disease incidence (i.e., percentage of berries with rot symptoms), incidence of visible injury from simulated hail, and yield (i.e., fresh weight of fruit) were subjected to analysis of variance using the mixed procedure (PROC MIXED) in SAS statistical software (version 9, SAS Institute, Cary, NC). Block was considered a random effect, whereas simulated hail and fungicide treatments were considered fixed effects in the model. Means separation was performed according to Tukey's honestly significantly different test, after appropriate transformations to correct for unequal variances ($\alpha = 0.05$).

Results

Effect of fungicides on fruit rot and yield in fruit treated with simulated hail. Fruit rot incidence was greater ($P < 0.05$) in fruit treated with gravel than in the nontreated control in six of seven trials (Figs. 1 and 2). Gravel-treated berries had average rot levels of 4 to 38%, whereas berries not treated with gravel had average rot levels of <1 to 7% over both years and all treatments. Effect of fungicide and the fungicide $\times$ gravel interactions were not significant ($P > 0.05$) in six of the seven trials (Figs. 1 and 2). However, in the 30 July 2011 trial at Tomah, both the effect of

fungicide and fungicide $\times$ gravel interaction were significant ($P = 0.0165$ and $P = 0.0494$, respectively; Fig. 2). In that trial, fruit rot incidence was lower ($P = 0.0103$) in gravel-treated plots sprayed with azoxystrobin than in gravel-treated, nonsprayed plots, but fruit rot incidence was not lower ($P = 0.1243$) in gravel-treated plots treated with copper hydroxide compared to gravel-treated, non-sprayed plots.

Average yield (weight of sound berries) was lower ($P < 0.05$) in plots treated with gravel (1.5 to 4.9 kg m⁻²) than in plots not treated with gravel (3.3 to 5.6 kg m⁻²) in six of seven trials (data not shown). In the trial at Tomah on 28 July 2010, yield was numerically but not significantly lower ($P = 0.1367$) in plots treated with gravel (3.1 kg m⁻²) compared to plots not treated with gravel (3.8 kg m⁻²). The fungicide $\times$ gravel interactions were not significant ($P > 0.05$) for yield in six of the seven trials (data not shown). However, in the 18 August 2010 trial at Necedah, the fungicide $\times$ gravel interaction was significant ($P = 0.0018$) for yield.

The damage caused by gravel closely resembled natural hail injury. In Wisconsin, natural hailstorms can range in severity from causing minor injury to dislodging fruit from vines. As such, our hail simulation is representative of a moderate hailstorm. According to the Tornado and Storm Research Organisation (TORRO), maximum hailstone size is the most important trait determining structural damage (23). Based on size, our pea gravel would correspond to a hailstorm intensity rating of H1 to H2, which is typically associated with slight to significant damage to fruit, crops, and vegetation (23).

Dose response. Damage to fruit increased as increasing volumes of pea gravel were applied. Average percent firm but scarred fruit ranged from 13 to 26% at Tomah and 13 to 34% at

Necedah (Fig. 3). Fruit rot incidence also increased with increasing volumes of pea gravel at both sites in 2011. Average percent rotten fruit ranged from 15 to 42% at Tomah and 12 to 46% at Necedah (Fig. 3).

Discussion

The results suggest that in most cases, application of azoxystrobin or copper hydroxide fungicides following hail events will not reduce cranberry fruit rot incidence or increase yield. Regardless of fungicide treatment, fruit rot incidence was greater and yield was lower in plots treated with gravel to simulate hail than in plots not receiving the simulated hail treatment. When cranberry fruit is struck by hail, damage arises from the direct impact of hailstones. For numerous crops infected by a wide range of fungal and bacterial pathogens, damage also arises from the creation of an infection court when fruit and/or foliage are struck by hailstones (5,7,8,14–19,21,22). However, the creation of an infection court may be relatively unimportant for cranberries and the fruit rot pathogens. While the precise life cycle of each fruit rot pathogen is not known, inoculum is believed to be available over several weeks during the growing season, and infection takes place during bloom and early fruit set (12,20). Thus, fungicides are effective in controlling cranberry fruit rot pathogens when applied during this time (11,12). However, in our study, fungicides failed to protect gravel-treated fruit from rot in six of seven trials, possibly because cranberries were infected prior to the occurrence of simulated hail events. In many cases, the epidermis of rotten fruit from plots treated with gravel appeared intact, suggesting that bruising without rupturing the epidermis was sufficient to trigger rot. In such cases, the physiological stress of the injury, latent pathogens that

Fig. 2. Effect of gravel and fungicide applications on fruit rot incidence from field trials in 2011. Treatments: azoxystrobin (Abound, Syngenta Crop Protection, Greensboro, NC; 280 g a.i. ha⁻¹); copper hydroxide (Champ Formula 2 Flowable, Nufarm Agricultural Products, Burr Ridge, IL; 3,441 g a.i. ha⁻¹); or no fungicide. Percent rotten fruit means marked with different letters are significantly different and were separated by Tukey-adjusted multiple pairwise-comparisons ($\alpha = 0.05$). For each treatment, $n = 4$. Bars represent $\pm$ one standard error of the mean.

infected during bloom and early fruit set (10), or both of these factors might have resulted in rot that could not be prevented by application of fungicides to fruit following hail simulation.

In 2011, fungi were isolated from soft, rotten berries that were treated with gravel but not fungicides, and from rotten berries treated with neither gravel nor fungicides, in an attempt to determine which pathogens might proliferate in injured fruit (data not shown). Cranberry fruit rot pathogens such as *Phylospora vaccinii*, *Phomopsis vaccinii*, *Coleophoma empetri*, and *Colletotrichum acutatum* were recovered, as were saprophytes such as species of *Alternaria*, *Penicillium*, and *Trichoderma*. However, high variability among trials and replicates within a trial made it impossible to discern patterns in the array of fungi isolated from injured versus intact berries.

Results from our trials suggest that fungicide physical mode of action (i.e., systemic versus protectant), as well as stage of berry maturity, might affect the efficacy of fungicides in reducing fruit rot incidence following hail damage. Many fungicides currently labeled for cranberry fruit rot control are protectant fungicides (e.g., chlorothalonil, mancozeb, and copper hydroxide) that lack systemic activity. To be effective, protectant fungicides must be applied prior to fungal infection (i.e., during bloom and early fruit set for cranberries). On the other hand, the strobilurin fungicide, azoxystrobin, has both protectant and limited systemic activity, and therefore might be expected to inhibit fungi after infection has occurred but before extensive colonization by the fungus. We hypothesize that the uptake of a systemic fungicide would be greater in immature cranberry fruits because they have relatively thin cuticles compared to the well-developed cuticles of mature fruit (6). In fact, the one trial in which applying azoxystrobin following hail simulation benefited fruit was the trial in which fruit were least mature (30 July 2011), based on berry weight. Further investigation is needed to clarify the effect of cranberry fruit developmental stage in the control of fruit rot with systemic fungicides. Regardless, copper hydroxide did not reduce the incidence of fruit rot

when applied following injury of berries at a range of maturity stages.

We applied fungicides less than an hour after the simulated hail event to reproduce the efforts of many growers who attempt to protect fruit as soon as possible after natural hail events. We acknowledge, however, that the conditions under which our experiments were conducted are very different from natural storms. High winds, lower temperatures, and rain are associated with hail events, and wind in particular is often responsible for crop damage resulting from these storms (4). While our trials were not conducted under such conditions, the damage inflicted upon the cranberry fruit as a result of pea gravel impact was very similar in appearance to cranberry fruit damaged by natural hailstones. While infection of cranberry fruit by fruit rot pathogens during bloom and early fruit set is believed most important for disease development (12,20), inoculum may be available later in the growing season as well. Thus, it is possible that wind- or rain splash-borne inoculum available at the time of the hail event would contribute to higher disease pressure than observed in our trials. In 2010, rain occurred within 6 days of hail simulation for all trials (data not shown). In 2011, rain occurred within 3 days of hail simulation for all trials except the 7 September trial at Necedah, where rain was not recorded until 11 days following hail simulation (data not shown). Because of inherent differences among trials (e.g., cultivar, berry size, gravel dose), we cannot discern the role of rain or other weather factors in causing fruit rot. However, regardless of weather and other differences among trials, the effects of hail simulation and fungicide treatment were similar.

In many crops, the severity of the damage incurred from hail depends on the duration of the storm, size of hailstones, and growth stage of the plants at the time of the storm. These factors, along with environmental conditions following the storm, contribute to the ability of the plants to recover from injury. In the case of cranberry, more than 95% of the crop is grown for the processing market, and superficial blemishes are acceptable on berries destined for processing. Thus, in our trials, not all fruit that was injured during hail simulation was unmarketable. Some damaged fruit matured with only surface scarring and minor malformations visible at the time of harvest. This sort of injury is commonly seen in other fruit crops affected by hail (7,13,14), although our study is the first to quantify the relationship between extent of hail exposure during the growing season and fruit injury and/or rot at the time of harvest. At Tomah, a greater number of berries rotted than healed with minor scarring across all doses of simulated hail, with fruit rot incidence leveling off at high (i.e., 350 and 500 ml) doses. At Necedah, the amounts of rotten and of sound but scarred berries were approximately equal at doses up to 350 ml gravel, suggesting that berries at this site were better able to heal following injury. What accounted for the difference between sites is unclear, but differences in cultivar, canopy density, berry size, and berry maturity stage at the time of the simulated hail treatment each could have a role.

In summary, results from field trials conducted over two years at two sites suggest that except when hail injures very immature fruit, the application of fungicides following hail is not likely to prevent fruit rot or improve yield. We believe this is because factors other than fungal infection during or shortly after hail events are the primary cause of rot in injured fruit. However, our findings are limited by the fact that rain, wind, and other conditions common during natural hailstorms might facilitate infection by pathogens, which in turn would enhance the role of pathogens in causing rot. The simple modification of a backpack mist blower sprayer to forcibly eject standard pea gravel provides an inexpensive method for conducting controlled, replicated hail simulation and should be applicable to many crop systems.

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Fig. 3. Effect of application of different volumes (doses) of pea gravel during the growing season on fruit rot incidence and firm but scarred fruit (responses) at the time of harvest. For each dose treatment, $n = 4$. Bars represent $\pm$ one standard error of the mean.

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