MANAGING CARROT FOLIAR DISEASES IN COMMERCIAL PRODUCTION FIELDS IN MICHIGAN

By

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A THESIS

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

Plant Pathology – Master of Science

2017

ABSTRACT

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Fungal foliar diseases caused by *Alternaria dauci* and *Cercospora carotae* occur annually on carrots. Our goal was to update the disease management tactics by: 1) Testing OMRI-approved and conventional fungicides and 2) Evaluating TOM-CAST. Trials were conducted in 2015 and 2016. Disease severity was visually assessed weekly using the Horsfall-Barratt scale and a petiole health scale; the area under the disease progress curve (AUDPC) was calculated for these parameters. Root yield was determined at harvest. Based on AUDPC results obtained in 2015 and 2016, the copper-based fungicides (copper hydroxide and copper hydroxide + copper oxychloride) were the only OMRI-approved products that significantly and consistently limited foliar blight. On the final assessment dates in both years, all conventional fungicides limited foliar and petiole blighting compared to the control with one exception; the propiconazole treatment in 2016 was similar to the control for petiole health. Yields differed significantly among the conventional treatments in 2016 but not in 2015. All treatments yielded significantly higher than the control except for iprodione. Treatments of pyraclostrobin + boscalid, fluxapyroxad + pyraclostrobin, and boscalid had statistically higher yields than penthiopyrad, iprodione, and propiconazole. TOM-CAST 15 and 25 DSV fungicide application schedules effectively reduced foliar blighting in 2015 under relatively light disease pressure. However, the TOM-CAST 25 DSV schedule did not adequately limit disease in 2016 when disease pressure was increased. Recently registered fungicides such as penthiopyrad and fluxapyroxad + pyraclostrobin and using TOM-CAST at the more conservative spray threshold of 15 DSV can help growers limit fungal foliar blight in years with higher disease pressure.

This manuscript is dedicated to Mary and Thomas Donne, who supported me and made education possible throughout my life.

ACKNOWLEDGEMENTS

This research was partially supported by funding from the Michigan Carrot Committee, the Michigan Vegetable Council, and by a State Specialty Crop Block Grant administered by the Michigan Carrot Committee.

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LITERATURE REVIEW

Introduction. Carrots are an important vegetable crop in the U.S.; they rank seventh in U.S. fresh vegetable consumption (Naeve 2015) and sixth in tonnage among vegetable crops produced in the U.S. (USDA, NASS 2017). Carrot production increased in the 1980s with the popularization of baby-cut carrots, sold in packages at supermarkets (Naeve 2015). Michigan is the fourth largest United States producer of carrots; California is the top producer. In 2016, Michigan produced approximately 70,920 metric tons of carrots total, while CA produced approximately 1,112,571 metric tons (USDA, NASS 2017).

Carrot, *Daucus carota* L. subsp. Sativus (Hoffm.) Arcang., is a member of the family Apiaceae, also known as Umbelliferae. Other important food and spice crops in the Apiaceae family include celery, parsley, cilantro, and cumin; carrot is the most extensively produced vegetable in this family. Pigmented carrot roots contain a relatively large amount of carotene, which is important for humans as a source of vitamin A. Carrots have been selectively bred to have different forms and colors. Orange carrots are preferred in the U.S. market compared to those that are yellow, red, or white. Cultivars suitable for growing in the temperate region are biennials producing a thick tap root and a whorl of leaves the first year with flowers and seeds following the second year (Rubastzky 2002).

Carrots are produced for the fresh market or the processing market (USDA, NSF... 1999; USDA, NASS 2016); varieties are often developed for their specific use. For use in processing, carrot production ranked sixth in the U.S. in 2015 at 294,000 tons harvested and sold (USDA, NASS 2017). Michigan was among the top five U.S. processing vegetable producers in 2015 for tonnage and crop value, based on eight selected vegetables, including carrots and pickling cucumbers (USDA, NASS 2016). Michigan produces carrots for the processing and fresh markets. In 2008, Michigan ranked third in state processing output (USDA, ERS 2011) and in

2012, Michigan harvested the fourth largest area of carrots for the processing industry, at approximately 1,144 hectares (USDA, NASS 2012).

Carrots are planted by direct seeding (Naeve 2015). When planted for use in the fresh market, plant stands may be 80 to 100 plants per m^2 or even more dense for smaller-rooted varieties. Larger-rooted carrots used for processing produce around 40 to 70 roots per m^2 (Rubastzky 2002). Commercial carrot production in Michigan generally requires the use of insecticides, herbicides and fungicides (Hausbeck 2008). Sometimes a cover crop such as rye is seeded with young carrots to protect the seedlings (USDA, NSF… 1999). Carrots in Michigan are harvested mechanically. Thus, the foliage must be protected from leaf blighting throughout the season, so that at harvest the machinery can grasp the foliage and pull the root out of the ground (Hausbeck 2008). Carrots used in processing are typically harvested late in the growing season, October through November in Michigan (USDA, NSF… 1999). Foliage weakened by foliar pathogens snaps off and reduces yield by leaving carrots in the ground. Damaged foliage can also reduce carrot taproot mass by reducing the photosynthetic area of the plant. One cause of necrotic foliage in Michigan's commercial carrot fields is fungal disease incited by *Alternaria dauci* and *Cercospora carotae* (Hausbeck 2008).

Alternaria dauci. *Alternaria dauci* was first described by J.G. Kühn in the 19th century and given the name *Sporidesmium exitiosum* var. *dauci* (Groves and Skolko 1944; IMA 2016a). The current pathogen designation is *Alternaria dauci* (J.G. Kühn) J.W. Groves and Skolko, as it was described by Groves and Skolko in the Canadian Journal of Research in 1944 (Groves and Skolko 1944; IMA 2016a). Disease caused by this pathogen has been reported in all of the main carrot production regions and causes necrotic foliar lesions that reduce photosynthetic capacity of the plant, negatively impacting yield (Farrar et al. 2004; Pryor and Strandberg 2002). Diseased foliage and petioles become weakened and die making it difficult to harvest carrots with a mechanical harvester (Pryor and Strandberg 2002). *A. dauci* typically infects mature carrot foliage, causing lesions that initially appear water-soaked but then become necrotic, sometimes with a chlorotic halo (Delahaut and Stevenson 2004). Lesions often start at the margins of the leaves, expand, and coalesce. Lesions also occur on petioles and may become elongated (Pryor and Strandberg 2002).

A. dauci belongs in the kingdom Fungi, phylum Ascomycota, class Dothideomycetes, order Pleosporales, family Pleosporaceae, and genus *Alternaria* (IMA 2016a). Conidia are obclavate or ellipsoid with a long, septate beak (Pryor and Strandberg 2002); a sexual stage is not known (Farrar et al. 2004). The conidium is segmented with multiple transepta and one or more longisepta (Pryor and Strandberg 2002). Conidia are usually released during the day (Strandberg 1977). The fungus may survive for up to a year as conidia or mycelium associated with carrot debris (Pryor et al. 2002). Conidia may also survive on volunteers or weeds, such as the wild carrot plant, Queen Anne's Lace (Pryor et al. 2002; Delahaut and Stevenson 2004). *A. dauci* may be seedborne (Strandberg 1983). Infested seeds may lead to damping off in the field; conidia germinate prolifically on the dead and dying seedlings (Pryor and Strandberg 2002).

Conidial germination and infection are favored by warm temperatures and prolonged leaf wetness (Pryor and Strandberg 2002).

In commercial carrot production, fungicide sprays are recommended once trace levels of disease are detected (Pryor and Strandberg 2002; Bounds et al. 2007). Burying infected foliar debris at the end of the season may be a helpful cultural technique for reducing inoculum by increasing the speed of carrot residue decomposition, thus decreasing the energy source for the pathogen (Delahaut and Stevenson 2004; Pryor et al. 2002). However, it is important to note that residue decomposition and pathogen survival likely depend on the soil moisture conditions (Pryor et al. 2002). Pryor et al. (2002) found evidence that *A. dauci* survival on crop residue decreased with increasing soil moisture.

Cercospora carotae. *Cercospora carotae* incites foliar blight and impacts carrots in various production regions, such as Michigan, New York, Wisconsin, and Quebec and Ontario in Canada (Carisse and Kushalappa 1992; Gugino et al. 2007; Hausbeck and Donne 2016; Raid 2002; Rogers and Stevenson 2006). This pathogen is more important in Canada than *A. dauci* (Raid 2002; Carisse et al. 1993). Young foliage may become infected and thus the pathogen can be distinguished from *A. dauci* (Raid 2002). *C. carotae* causes circular leaf lesions with a dark margin and a light tan center and lesions may coalesce. Petiole lesions are similar in appearance to leaf lesions, but appear more elongated (Raid 2002; Delahaut and Stevenson 2004). When conidiophores and conidia begin to develop, the center of the lesions may appear gray. Severe *C. carotae* infection in carrot fields can greatly weaken petioles and leaves, resulting in carrots that cannot be extracted from the soil by the mechanical harvester in large production fields. *C. carotae* is often managed with applications of fungicides (Carisse and Kushalappa 1990).

The conidia are filiform and cylindrical, have single or multiple septa, and may be lightly colored or hyaline (Raid 2002; Thomas 1943). This fungus is in the kingdom Fungi, phylum Ascomycota, class Dothideomycetes, order Capnodiales, family Mycosphaerellaceae, and genus *Cercospora* (IMA 2016b). The pathogen can overwinter on carrot debris, and survive on carrot seed and wild *Daucus* plants (Raid 2002; Thomas 1943). The pathogen grows optimally between 19 to 28^{o}C (Raid 2002); high temperature (32^{o}C) limits development (Carisse and Kushalappa 1990). Leaf wetness (>12 hours) is required for infection; conidia are readily produced following an initial extended period of leaf wetness followed by extended high relative humidity (Carisse et al. 1993).

Fungicides. Michigan growers apply foliar fungicides to limit disease caused by *A. dauci* and *C. carotae*. Chlorothalonil, a contact fungicide, is commonly used (Dorman et al. 2009; FRAC 2016; Hausbeck 2008) but is classified as a B2 carcinogen. Azoxystrobin is a reduced-risk fungicide used by Michigan growers to limit *A. dauci* and *C. carotae* (Dorman et al. 2009; Hausbeck 2008). Alternating sprays of chlorothalonil and azoxystrobin has been the industry standard for the protection of carrots in Michigan (Hausbeck 2014).

General disease management. Cultural disease controls include crop rotation, irrigation management, clean seed, resistant or tolerant varieties, and reduction or elimination of inoculum (Delahaut and Stevenson 2004; Hausbeck 2014). A two- to three-year crop rotation is recommended with crops outside of the Apiaceae family (Delahaut and Stevenson 2004; Egel et al. eds. 2017; Hausbeck 2014); *A. dauci* may survive up to twelve months in the soil (Pryor et al. 2002). *Alternaria* can be transferred to seed from infected parent plants (Strandberg 1983). Crop residue can harbor the fungus as well (Pryor and Strandberg 2002). Burying residue, or flooding fields that contain residue, can help to more quickly kill off surviving fungi (Pryor et al. 2002).

Removing volunteer carrot plants or related weed hosts such as wild carrot, also helps reduce potential sources of inoculum (Delahaut and Stevenson 2004; Pryor et al. 2002). Incorporating all of these cultural control methods into the farm disease management plan is ideal, but the addition of chemical management is necessary for maximum productivity on many commercial carrot farms (Carrisse and Kushalappa 1990; Farrar et al. 2004; Hausbeck 2014).

Fungicide chemistries. Some fungicides work as contact fungicides or "protectants" whereas other fungicides work systemically, entering the plant locally or moving through the vascular system (Schuman and D'Arcy 2010). Fungicides may disrupt certain enzyme pathways (Schuman and D'Arcy 2010). A number of these types of reactions have been classified by the Fungicide Resistance Action Committee (FRAC). Registered fungicides are grouped accordingly and assigned a FRAC code based on their specific mode of action (Schuman and D'Arcy 2010). Chlorothalonil and azoxystrobin are in the FRAC groups M 05 and 11, respectively. Fungicides in the 'M' group are considered to have multi-site contact activity. Fungicides in group 11 impact the cyt b gene, Qo site, particularly targeting cytochrome bc1 (aka ubiquinol oxidase). Group 11 is known as **Q**uinone **o**utside **I**nhibitors, or QoI-fungicides (FRAC 2017).

It is generally recommended that fungicides with different modes of action be rotated over the course of the growing season to reduce the chance of resistance development in the plant pathogen population to a particular chemical mode of action (Brent and Hollomon 2007). An example of rotating products with different modes of action would be a rotation of the chemistries penthiopyrad (Dupont™ Fontelis®, DuPont Crop Protection) in FRAC group 7; cyprodinil + fludioxonil in groups 9 and 12, respectively (Switch® 62.5WG, Syngenta Crop Protection, LLC); and fluxapyroxad + pyraclostrobin in groups 7 and 11, respectively (Merivon® Xemium® brand fungicide, BASF Ag Products) (FRAC 2016). This rotation

alternates fungicides with active ingredients in differing FRAC groups. Group 7 is repeated in the rotation, but not sequentially. Caution should be taken to recognize products with multiple active ingredients and active ingredients that differ, but are in the same FRAC group.

Organic production and Organic Materials Review Institute (OMRI)-certified products. The consumer mandate for organic products has increased since the 1990s (USDA, ERS 2017b); in line with this, sales of organic crops increased 69% from 2008 to 2014, putting U.S. sales of organic crops at $3.3 billion (USDA, NASS 2015). With a continuing increase in demand for organic produce (USDA, ERS 2017a), Michigan growers might consider organic production. Michigan growers also have important contracts with the baby food processing industry that rely on the produce complying with low toxic residue guidelines detailed by the company (Hausbeck 2008). Higher price premiums in the organic market (USDA, ERS 2017a) and processor demands are a couple of reasons why growers might want to produce organically-approved products.

The Organic Materials Review Institute (OMRI) is an independent organization that assesses materials used in the production of organically-labeled food to determine if these products meet the United States Department of Agriculture (USDA), National Organic Standards (NOS) for inputs into the organic food production process (OMRI 2017a). Various biopesticide and copper fungicide products are suitable for use in an organic or low-input production system (OMRI 2017b). Biopesticides are defined by the United States Environmental Protection Agency (USEPA) as "certain types of pesticides derived from such natural materials as animals, plants, bacteria, and certain minerals" (USEPA 2016b). Examples of biopesticide fungicidal active ingredients include bacteria from *Streptomyces lydicus* and *Bacillus* spp. and plant extracts from *Reynoutria sachalinensis* and *Azadirachta indica* (aka neem) (USEPA 2016a). Fixed coppers and

copper sulfate are identified by National Organic Program (NOP) regulations as synthetic substances allowable in organic production, as long as they are used in a manner that limits copper build-up in the soil and they are not used as herbicides (United States Government Publishing Office 2017).

Efficacy data based on replicated trials is scarce for organic fungicide products labeled for use on carrots (Seaman, ed. 2016). Various organic products are labeled for use in management of carrot foliar disease caused by *A. dauci* or *C. carotae* (Seaman, ed. 2016; The IR-4 Project 2017). Researchers associated with Cornell University and New York State Integrated Pest Management (NYSIPM) searched for university studies that tested organic pesticides for carrot foliar blights; they were unable to find evidence for the efficacy or inefficacy of most of the biopesticide products suggested, although studies were discovered for copper products such as Badge® X2 (copper hydroxide + copper oxychloride, Gowan Company). Badge X2 was noted as having disease protection efficacy in "less than half of recent university trials" (Seaman, ed. 2016).

Studies have been conducted with organic and biopesticide products for use against fungal and fungal-like (oomycete) pathogens of hosts other than carrot, such as cucumber, summer squash, cantaloupe, potato, and apple (Cromwell et al. 2011; Marine et al. 2016; Olanya and Larkin 2006; Zhang et al. 2011). For example, neem oil and *Bascillus subtilis* were tested on apple trees in Vermont for protection against apple scab (Cromwell et al. 2011). Neem oil protected the tree from the pathogen more than the untreated, but was deemed to have negative side effects, such as phytotoxity, and not be effective enough for commercial use. In the same Vermont study, *B. subtilis* was not effective for disease suppression and also had the negative

effects of causing lenticel blackening and seeming to promote insect infestation (Cromwell et al. 2011).

Evaluation of fungicide products with the following active ingredients was conducted on cucurbits in Maryland: *Reynoutria sachalinesis* extract, *Streptomyces lydicus*, *Bacillus subtilis*; some of the products were effective at management of downy and powdery mildew in combination with use of a copper product (Marine et al. 2016). However, these authors only tested these biopesticide products in rotation with copper. Thus, it is unclear if the products brought much to the table, although it seems that some of them could be used to protect the foliage, while reducing the amount of copper fungicide used (Marine et al. 2016).

Zhang et al. (2011) reported on tests of biorational products on summer squash and cantaloupe in Florida. These researchers did test the biocontrol products alone, and in rotation with a conventional fungicide product. The biocontrol products alone were not effective, although they were sometimes effective in rotation with the conventional product, but not consistently (Zhang et al. 2011).

Finally, in a study where essential oils and *B. subtilis* were tested against *P. infestans in vitro* (on plates) and *in vivo* (in the growth chamber), *B. subtilis* was quite effective *in vitro*, but less so *in vivo*, and probably not effective enough *in vivo* for commercial use. It was certainly less effective than the conventional fungicide product it was compared against, chlorothalonil (Olanya and Larkin 2006).

Copper. Copper is a general biocide and its effects have been explored for use in health, medicine and agriculture for many decades (Borkow and Gabbay 2005). Copper in the form of a copper sulfate solution was first used in agriculture as a seed treatment for pathogenic fungi in 1761 (Borkow and Gabbay 2005). A copper-based mixture was then discovered to be effective

as a foliar treatment for protection against downy mildew on grapes in the 1880s; called the "Bordeaux mixture," this solution was a combination of copper sulfate, water, and lime and has been found to be useful in inhibiting numerous fungal plant diseases (Borkow and Gabbay 2005).

In bacteria, copper disrupts cell function by denaturing DNA, interfering with the plasma membrane, and altering the function of vital proteins (Borkow and Gabbay 2005). Researchers have less knowledge about the exact mechanisms by which copper kills fungal cells versus bacterial cells. However, it appears that in fungal cells copper also compromises the cell wall and plasma membrane, causing increased cell leakage and disrupting normal uptake of essential nutrients (Borkow and Gabbay 2005).

Copper is effective as a fungicide or bactericide only in its solubilized, ionic form (Richardson, ed. 1997). Menkissoglu and Lindow (1991) noted that the cupric ion (Cu^{2+}) seemed to be the only form of copper lethal to the bacterial pathogen *Pseudomonas syringae*. These researchers conducted trials combining solutions of copper sulfate and various organic compounds such as fructose, glucose and citrate; they found that the organic compounds reduced the toxicity of the copper to both copper-sensitive and copper-tolerant *P. syringae* added to the solutions. Having citrate in the solution caused the greatest reduction in lethality out of the compounds tested, illustrating that copper complexes differently with different organic compounds. Thus, the type of compounds in the environment to which copper is applied (such as on a leaf surface) could make a difference in product efficacy (Menkissoglu and Lindow 1991).

Scheck and Pscheidt (1998) found that the disease-protection value of various copper-based bactericide products was most highly correlated with the quantity of free cupric ions, rather than the amount of metallic copper (as specified by the product label) or total dissolved

copper. Scheck and Pscheidt tested products for use against foliar disease caused by *P. syringae* pv. *syringae* on lilac (*Syringa vulgaris* L.). Efficacy was judged by the quantitative suppression of the bacterial population size. Of the forms of copper measured, the quantity of free cupric ions was most highly correlated with a reduction in pathogen population size for products tested with copper-sensitive and copper-tolerant bacterial strains on lilac tissue cultures and for products tested with copper-sensitive bacterial strains on lilacs in the field (Scheck and Pscheidt 1998).

In a study published by Timmer and Zitko (1996), they concluded that metallic copper was the best indicator of fungicide product efficacy for management of melanose (caused by *Diaporthe citri* F.A. Wolf) on grapefruit (*Citrus paradisi* Macfady). However, there were cases in their treatment comparisons where significant differences were found between the efficacy of products with the same quantity of metallic copper, but the results were not generalizable. The total metallic copper in the product represented 37 to 60% of the variability in melanose disease damage (Timmer and Zitko 1996).

Because the fungicidal activity of copper pesticides depends on the release of copper ions, product efficacy is contingent on solubility of the active copper compound and particle size of the product formulation (Richardson, ed. 1997). The size of a particle changes its surface area, with smaller particles having a larger relative surface area (Richardson, ed. 1997). In general, a larger particle surface area for a fixed copper compound increases the chance that copper ions will be able to solubilize in solution and kill pathogenic bacteria and fungi; though, there is a point at which particles could be too small to persist and have any protectant effect *in vivo*, because of weathering (Richardson, ed. 1997). For copper oxychloride, there is a direct relationship between an increase in surface area and an increase in dissolution rate (Richardson, ed. 1997). The dissolution rate of copper hydroxide however, seems to be somewhat

unconstrained by particle size. This is thought to be linked to the chemical additives needed to keep copper hydroxide compounds stable within a mixture (Richardson, ed. 1997).

Copper hydroxides are generally more soluble than copper oxychlorides (Richardson, ed. 1997; Zitter and Rosenberger 2013). Copper hydroxide and copper oxychloride are considered to be "fixed coppers", so their solubility is actually quite limited compared to copper sulfate (Richardson, ed. 1997). Copper sulfate is so soluble that alone it is not even very effective as a foliar fungicide, because it weathers away much too quickly (Richardson, ed. 1997). Use of fixed copper compounds provides enough Cu^{2+} over time to have a protective effect against plant disease, without causing phytotoxicity or losing all of the copper immediately (Richardson, ed. 1997).

Disease forecasting. A plant-disease forecasting system utilizes measurements of environmental factors, as well as information about traits of the pathogen and host, to determine when a disease epidemic is likely to begin or escalate (Campbell and Madden 1990). Forecasting models are developed based on studies of host-pathogen relationships, either fundamental studies that elucidate cause and effect relationships between the environment and host-pathogen interactions, or empirical studies that come to generalizations, based on correlations within the sample data, about the host and pathogen life cycles in relationship to environmental conditions (Campbell and Madden 1990). Some parameters that might be included in disease forecasting systems are average air temperature; rainfall levels; relative humidity, leaf wetness; pathogen inoculum levels (determined directly, such as by counting sclerotia, nematodes or spores); and vector population levels (Campbell and Madden 1990).

Forecasting systems are used to determine when to conduct disease management actions, such as fungicide applications (Hausbeck 2003). There have been disease forecasting systems

developed and tested to establish the timing of fungicide applications for control of disease on different crops and against various pathogens (Campbell and Madden 1990; Hausbeck 2003; Rogers and Stevenson 2006). Some of these systems may be tested and modified to provide control against various pathogens on the same or different crops (Bounds et al. 2006; Hausbeck 2003; Rogers and Stevenson 2006).

In the late 1970s, a disease forecasting program called FAST (Forecasting *Alternaria solani* on Tomato) was developed to provide application scheduling for fungicide use against *Alternaria solani*, the cause of early blight on tomato (Hausbeck 2003; Madden et al. 1978; Rogers and Stevenson 2006). This program was developed using two empirical models developed from previous studies of early blight on potato and tomato (Madden et al. 1978). One model used the leaf wetness period and the mean ambient air temperature during the leaf wetness period to determine a "disease severity value" for each day, indicating conditions advantageous for *A. dauci* spore formation (Madden et al. 1978). The other model used total rainfall over the past seven days, mean ambient air temperature over the last five days, and hours of relative humidity over 90% for the last five days to determine a disease severity rating value for each day, indicating conditions conducive to *A. dauci* spore development and tomato infection (Madden et al. 1978). Madden et al. (1978) found that certain fungicide application schedules derived from the FAST system were able to reduce the number of applications while still providing disease protection statistically similar to that of the fungicide treatments applied every 5 to 7 days. Pitblado, a researcher working on tomato foliar and fruit disease management in Ontario, Canada, was interested in using the FAST system, but reported that the decision-making structure was not straightforward enough for growers and that the weather measurement apparatuses were not easy enough to use (Pitblado 1992).

Use of weather forecasting systems requires that the grower or researcher ideally place weather stations in their field of interest to get localized weather data to input into the program (Hausbeck 2003). The weather stations used by MSU for research trials include a few measurement tools mounted on a steel pole that is placed in the field. The measurement tools are a rain bucket, a leaf wetness sensor, and a WatchDog® Micro Station (Spectrum Technologies, Inc.), also known as a data logger, that can measure temperature and relative humidity and that also collects data from the rain bucket and the leaf wetness sensor. The researcher or farm worker must collect the information from the data logger regularly and upload the data to a computer (Hausbeck 2003; Bounds et al. 2007; Rogers and Stevenson 2006).

TOM-CAST. Pitblado (1992) developed a forecasting system called TOM-CAST (Tomato disease Forecaster) by modifying the FAST program published by Madden et al. (1978). The TOM-CAST system uses one of the two models that went into FAST predictions, the model where leaf wetness duration and temperature during leaf wetness duration are recorded to compute daily "disease severity values" (DSVs). TOM-CAST was developed for commercial tomato growers in Ontario, Canada, to time fungicide applications to protect the plants from Septoria Leaf Spot, Early Blight and fruit Anthracnose (Pitblado 1992). Development of TOM-CAST was facilitated by advances in environmental sensor equipment in the 1980s, as well as progress in leaf wetness sensor design made by academic research groups in Ontario (Pitblado 1992). The TOM-CAST system has been tested for use with multiple diseases and crops, such as purple spot on asparagus, foliar blights on carrot, and Alternaria blight on American ginseng (Bounds et al. 2006; Hausbeck 2003; Rogers and Stevenson 2006; Hill and Hausbeck 2008).

Use of the TOM-CAST program involves determining a DSV threshold at which to spray the appropriate fungicides. The daily DSV ranges from zero to four, with zero being the least

favorable conditions for disease development and four being the most favorable conditions (Pitblado 1992). These daily DSVs are added until the sum reaches the predetermined threshold value, such as 15 or 20 DSVs, at which time the grower would apply fungicides to the crop. The appropriate threshold value is determined by performing trials where treatments are applied at different threshold levels (Pitblado 1992). Previous research has indicated that using a threshold of 15 DSV with foliar fungicides can provide protection of carrot foliage against foliar blight and spot in Michigan (Bounds et al. 2007; Dorman et al. 2009). However, it is important to continue to test and re-evaluate threshold values under different climactic conditions and with different fungicide chemistries, in order to ensure sustained system efficacy.

Researchers, such as those at MSU and the University of Wisconsin, have found that the use of the TOM-CAST weather forecasting system provided adequate or equivalent disease control of fungal foliar diseases on carrots compared to a calendar schedule, when appropriate DSV thresholds were used (Bounds et al. 2007; Dorman et al. 2009; Rogers and Stevenson 2006). Wisconsin found 20 DSV to be an adequate threshold when a known blight-resistant cultivar was used (Rogers and Stevenson 2006). MSU researchers found 15 DSV to be an adequate threshold, especially in the study described by Bounds et al. (2007). However, Dorman et al. (2009) noted that the 10 DSV threshold or even weekly sprays might be necessary in a severe disease year. These results suggest the TOM-CAST system is a promising tool for controlling fungal foliar blights in commercial carrot fields while reducing the number of fungicide sprays.

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CHAPTER 1. LIMITING FUNGAL FOLIAR DISEASES ON CARROTS FOR ORGANIC AND CONVENTIONAL MARKETS

ABSTRACT

Carrots are utilized for both the fresh market and processing industries; Michigan ranks fourth nationally as a supplier for both markets combined. Fungal foliar diseases caused by *Alternaria dauci* and *Cercospora carotae* occur annually in the state, causing necrotic foliar lesions that coalesce resulting in blighted and weakened petioles. Carrots grown for processing are harvested mechanically; when petioles are weakened by disease, the roots may be left in the ground resulting in significant loss. Also, there is interest in producing carrots for the organic market and efficacy data for OMRI-approved products is lacking. Our goal was to update the disease management tactics available to manage *C. carotae* and *A. dauci* by addressing the following objectives: 1) Test seven OMRI-approved products for organic growers and 2) Test twelve conventional fungicides. Field trials were conducted in 2015 and 2016 in collaboration with a commercial carrot grower in Mason and Oceana Counties. Disease severity was visually assessed weekly using the Horsfall-Barratt scale and a petiole health scale; the area under the disease progress curve (AUDPC) was calculated for these parameters. Root yield was determined at harvest.

Based on AUDPC results obtained in 2015 and 2016, the copper-based fungicides (copper hydroxide and copper hydroxide + copper oxychloride) were the only OMRI-approved products that significantly and consistently limited foliar blight. On the final assessment dates in both years, all conventional fungicides limited foliar and petiole blighting compared to the control with one exception; the propiconazole treatment in 2016 was similar to the control for petiole health. Yields differed significantly among the conventional treatments in 2016 but not in 2015. All treatments yielded significantly higher than the control except for iprodione. Treatments of pyraclostrobin + boscalid, fluxapyroxad + pyraclostrobin, and boscalid had statistically higher yields than penthiopyrad, iprodione, and propiconazole.

INTRODUCTION

Michigan is an important producer of carrots in the United States for both the fresh and processing industries. The state is the fourth largest national producer of carrots; California is the top producer. In 2016, Michigan produced approximately 70,920 metric tons of carrots total (USDA, NASS 2017). Oceana County in western Michigan has the largest area planted to carrot in the state at approximately 487 hectares (USDA, NASS 2012b). Michigan had the fourth highest number of hectares of carrots harvested for the processing industry in 2012 at approximately 1,144 hectares (USDA, NASS 2012a).

Two major fungal pathogens, *Alternaria dauci* and *Cercospora carotae*, occur each year on Michigan carrots (Bounds et al. 2007). The conidia of these pathogens are disseminated through wind and water-splash; primary inoculum can originate from overwintering carrot debris, volunteers, wild *Daucus* weeds, or infested seed (Pryor and Strandberg 2002; Raid 2002). *A. dauci* causes necrotic lesions on the foliage and petioles; leaf infections result in dark, brown-black and irregularly-shaped lesions that may begin at the margin (Pryor and Strandberg 2002). Lesions caused by *C. carotae* are round with dark edges and tan centers (Gugino et al. 2004; Raid 2002). Foliar disease results in weakened petioles and blighted foliage that becomes necrotic and dies (Pryor and Strandberg 2002; Raid 2002) resulting in reduced photosynthesis and yield loss (Pryor and Strandberg 2002). Additionally, carrots harvested mechanically may be left in the ground if petioles become weakened from disease and break during harvest (Pryor and Strandberg 2002; Raid 2002).

Michigan carrot growers manage foliar blight caused by *A. dauci* and *C. carotae* using cultural controls and fungicides (Bounds et al. 2007; Dorman et al. 2009; Hausbeck 2008). The disease forecaster TOM-CAST was tested using conventional fungicides (Bounds et al. 2006;

Bounds et al. 2007; Dorman et al. 2009; Hausbeck 2008) and implemented by Michigan growers as an effective tool to reduce reliance on fungicides designated as B2 carcinogens (such as chlorothalonil and iprodione) and maintain contracts with local processors. Fungicides including penthiopyrad (Fontelis®, DuPont Crop Protection) and fluxapyroxad + pyraclostrobin (Merivon® Xemium® brand fungicide, BASF Ag Products) are relatively new products registered for use on root vegetables in 2012 and 2014, respectively (USEPA 2012; USEPA 2014). Penthiopyrad is deemed a "reduced risk" fungicide; considered to reduce harm due to pesticide use to unintended organisms, human health, or the environment (USEPA 2017). Using "reduced risk" fungicides may allow growers to reduce residues of those fungicides that are of concern to processors.

It is recommended that growers rotate different fungicides to delay the development of fungicide resistance in the local pathogen population (Brent and Hollomon 2007; FRAC 2016). Many of the fungicides available to growers represent the Fungicide Resistance Action Committee (FRAC) Codes 7 and/or 11, codes that represent the biochemical mechanism by which the fungicide interferes with pathogen function. If a pathogen develops resistance to a fungicide with a particular mode of action (MOA), it will likely be resistant to other chemistries with the same MOA (FRAC 2016). Thus, fungicides with the same MOA are not as useful for developing a rotational fungicide program.

With an expanding market for organic produce (USDA, ERS 2017) additional management tools with proven efficacy are needed. The U.S. government develops federal guidelines for substances that may be officially used in organic crop production (USDA, AMS). The Organic Materials Review Institute (OMRI) is an independent organization that determines whether fungicides and other pesticides meet the federal guidelines for use in organic production

(OMRI 2016a; OMRI 2016b). Efficacy data for OMRI-certified products labeled for carrot foliar blight protection is limited (Seaman, ed. 2015; Seaman, ed. 2016). Biologically-derived OMRI-certified products often have inconsistent efficacy that may depend on the crop and pathogen system for which they are being used, and whether the environmental conditions favor disease development (Marine et al. 2016).

The objective of this study was to identify effective products that could limit fungal foliar disease on carrots for organic and conventional markets.

MATERIALS AND METHODS

Plot establishment and experimental design. 'Cupar' carrot seeds were placed every 3.8 centimeters into a plant bed consisting of three rows spaced 45.7 centimeters apart, for a rate of approximately 484,326 seeds/hectare on 30 April 2015 and 22 April 2016. The experimental sites were established in a commercial field consisting of sandy soil in 2015 (Oceana Co.) and sandy loam soil in 2016 (Mason Co.). The trial area was previously planted to zucchini in 2015 and corn in 2016. Fields were managed and irrigated overhead by the grower-cooperators according to commercial production standards (Egel et al. eds. 2017). Carrots were fertilized at planting (approximately between the 15th and 30th of April) with approximately 22.4 kilograms (kg) per hectare (ha) of nitrogen, 17.9 kg/ha of phosphorus, 168.1 kg/ha of potassium, 3.4 kg/ha of sulfur, and 1.1 kg/ha of boron. Side dress applications of fertilizer were applied in July, August, and September. In July, the fertilizer application consisted of approximately 44.8 kg/ha of nitrogen, 67.3 kg/ha of potassium, 11.2 kg/ha of sulfur, and 1.1 kg/ha of boron. In August and September, the side dress fertilizer application consisted of approximately 33.6 kg/ha of nitrogen.

Each year two trials, an Organic Materials Review Institute (OMRI) trial and a conventional trial, were established as a randomized complete block design with four replications. Each treatment plot was 6.1 meters in length and one plant bed wide. Each treatment plot was separated by at least a two-foot buffer zone between the rows of plots (aka blocks). The trials each year were buffered by a half bed or more of untreated carrots on either side. The experiments were analyzed as a one-factor design.

Treatment initiation and application. Starting in late June, fields were scouted weekly or biweekly for blight symptoms. Throughout the season, carrot foliage was periodically removed from the field, returned to the laboratory, incubated under high relative humidity conditions, and assessed for disease. Foliar tissue was surface-disinfested and placed on agar media (technical agar, Acumedia®); generally, water agar (16 g agar/1000 mL distilled water) or dilute V-8 agar (16 g agar, 960 mL distilled water, 40 mL V-8 juice, 1.5 g calcium carbonate) mixes were used. Cultures were incubated under fluorescent lights to promote pathogen growth. Foliage or cultured fungi were viewed microscopically at 100x to 400x magnification. Suspect *A. dauci* and *C. carotae* conidia and conidiophores observed on the carrot foliage were identified visually by their distinct morphological features and measurements using a reticle aka eyepiece micrometer.

Two separate trials were conducted in both years near or adjacent to each other within a field. The first trial compared efficacy of seven OMRI-approved products used at the labeled rate, and an untreated control (Table 1). The second trial evaluated twelve conventional products, at the rate recommended by the label, and an untreated control (Table 1). In 2015, applications for both the OMRI- and conventional-product trials (Table 1) were initiated on 2 July at trace disease levels (Bounds et al. 2007). In 2016, treatment for the OMRI and conventional trials was initiated on 6 July (prior to symptom development) or 15 July (trace disease), respectively. Applications were made with a backpack sprayer calibrated to approximately 344.7 kPa with three XR8003 flat-fan nozzles, delivering approximately 467.7 L/hectare. For the OMRI trial, applications were made approximately every 7 to 10 days. Application dates in 2015 were 2, 9, 17, 23, and 31 July; 10, 18, 26 August; 1, 9, 16, 23, and 30 September. Application dates in 2016 were 6, 15, 25 July; 1, 8, 15, 22, 30 August; and 14

September. An exception occurred with the neem oil extract (Trilogy® Fungicide/Miticide/Insecticide, Certis USA, L.L.C.) and *Streptomyces griseoviridis* strain K61 (Mycostop® Mix, Verdera Oy, Finland) treatments that received one less application than the other treatments. In addition, the *S. griseoviridis* strain K61 treatment received a reduced rate for the last application due to lack of product. For the conventional trial, applications were made approximately every 7 to 14 days. The application interval averaged 14.1 days in 2015, when disease pressure was low, and 7.6 days in 2016 when disease pressure was high. Application dates in 2015 were 2, 17, 31 July; 10, 24 August; 14, 23 September; and 7 October. Application dates in 2016 were 15, 25 July; 1, 8, 15, 22, 30 August; 7, 14, 21 September.

Table 1. List of fungicide products tested in two carrot field trials, an OMRI-product trial and a conventional-product trial.

Product*		Product Rate/ Hectare	Active Ingredient	FRAC** Code
OMRI Trial				
Actinovate® AG		840.6 g	*Streptomyces lydicus* WYEC 108	-
Badge® X2***		2.0 kg	copper hydroxide/ copper oxychloride	M 01
Kocide® 3000		2.0 kg	copper hydroxide	M 01
Mycostop® Mix		1120.8 g	*Streptomyces griseoviridis* strain K61	-
Regalia® Biofungicide		9.4 L	*Reynoutria sachalinensis* extract	P 05
Serenade® Opti		1401.1 g	*Bacillus subtilis* strain QST 713	44
Trilogy® Fungicide/Miticide/Insecticide***		4.7 L	neem oil extract	-
Conventional Trial				
Bravo Weather Stik ®		2.3 L	chlorothalonil	M 05
Cabrio® EG Fungicide		840.6 g	pyraclostrobin	11
Dupont™ Fontelis®		1.8 L	penthiopyrad	7
Endura® Fungicide		315.2 g	boscalid	7
Merivon® Xemium® Brand Fungicide		365.4 mL	fluxapyroxad/pyraclostrobin	7/11
Pristine® Fungicide	2015 2016	840.6 g 735.6 g	pyraclostrobin/boscalid	11/7
Quadris® Flowable Fungicide		1132.7 mL	azoxystrobin	11
Quadris® Opti		1.9 L	azoxystrobin/chlorothalonil	11/M 05
Quilt Xcel® Fungicide		584.6 mL	azoxystrobin/propiconazole	11/3
Rovral® 4 Flowable Fungicide		2.3 L	iprodione	2
Switch® 62.5WG		875.7 g	cyprodinil/fludioxonil	9/12
Tilt®		292.3 mL	propiconazole	3

*All products in this table are labeled for use on carrots.

**Fungicide Resistance Action Committee (http://www.frac.info) FRAC groups are based on the modes of action by which the active chemicals in the fungicide products inhibit pathogen functioning. These groups are important to note so that one can determine a disease management program that slows the development of active ingredient resistance in the local pathogen population.

***Badge® X2 and Trilogy® Fungicide/Miticide/Insecticide only used in 2016.

Disease assessments and yield. Disease assessments were made biweekly in 2015 on 1, 15, 29 September; 13 October and weekly in 2016 on 11, 18, 25 August; 1, 8, 15 or 17, 20, and 29 September. Disease incidence was determined by counting the number of plants with one or more petiole lesions within a pre-determined ten-foot section of the center row of each treatment plot. Visual assessment of the foliar and petiole disease severity was made using the Horsfall-Barratt scale (Horsfall and Barratt 1945) to determine a level of diseased tissue as follows: 1=0%, 2=0-3%, 3=3-6%, 4=6-12%, 5=12-25%, 6=25-50%, 7=50-75%, 8=75-87%, 9=87-94%, 10=94-97%, 11=97-100%, 12=100%. Assessments of petiole disease were made according to Bounds et al. (2006) where 1=healthy and vigorous, 2=few petiole lesions, no petiole necrosis, 3=petiole lesions numerous, no petiole necrosis, 4=1 to 20% petiole necrosis, 5=21 to 40% petiole necrosis, 6=41 to 60% petiole necrosis, 7=61 to 80% petiole necrosis, 8=81 to 90% petiole necrosis, 9= >90% petiole necrosis, 10=100% petiole necrosis (Bounds et al. 2006). Carrots were hand-harvested using a digging fork and shovel, topped and weighed at the end of the season to determine yield. For the OMRI trial, carrots were harvested on 13 October and weighed on 14 October 2015. In 2016, roots were harvested 23 September, and topped and weighed on 27 September. For the conventional trial, carrots were topped and weighed on October 15, 2015. In 2016, roots were harvested 30 September, and topped and weighed on 4 October.

Statistical analysis. Statistical analysis was performed using SAS® software, Version 9.4 of the SAS System for Windows. Copyright © 2002-2012 by SAS Institute Inc. SAS and all other SAS Institute Inc. product or service names are registered trademarks or trademarks of SAS Institute Inc., Cary, NC, USA. First, a global analysis of variance (ANOVA) F-test was calculated (using PROC MIXED) for each trial, to determine the presence of any significant differences between treatments. Fungicide treatments were considered as fixed effects, and replicate (block) as a random effect. If the global F-test was significant, all pair-wise comparisons were assessed with Fisher's least significant difference (LSD) test. Where the global F-test was insignificant, Tukey's test was used for mean comparisons instead of Fisher's LSD test, except where the heterogeneous compound symmetry (CSH) variance-covariance model was used. PROC PLM was used to determine mean separation letters.

In general, the default variance-covariance structure was used to assess the data. However, in a few cases where the equal variance assumption was not met and the SAS program could not run all pair-wise comparisons, the CSH variance-covariance structure was used with PROC GLIMMIX. This structure assumes heterogeneous variance between treatments, but equal correlation (Schörgendorfer et al. 2011). It is reasonable to assume equal correlation between treatment responses due to randomization within blocks (Schörgendorfer et al. 2011). The variance-covariance structure is indicated in the random statement with "type=csh".

The presence of normality and equal variance within the data distributions was initially assessed using residuals plots produced with the PLOTS= option in the PROC MIXED statement. Equal variance was also assessed using Levene's test. If the variance values could be considered equal among the treatments based on Levene's test, i.e. the difference in variance was not significant based on an α-level of 0.05, then pairwise comparisons of the treatment means

were made using the original data. The data from some measures were transformed by calculating the natural-logarithm values of the data sets to obtain equal variance based on Levene's test. If the equal-variance assumption was met, mean comparisons were made based on the natural-logarithm-transformed values. The data were back-transformed with the exponential function for reporting on the original scale.

Code adjustments to account for unequal variance were made when a transformation was not found to meet the assumption of equal variance within the data. These adjustments included using PROC GLIMMIX and adding ddfm=kr to the model statement and adding an extra random statement "random intercept /type=csh group=trt;".

The area under the disease progress curve (AUDPC) was calculated based on the methods outlined by Shaner and Finney (1977). This is also called the trapezoidal or mid-point method (Madden et al. 2007) for calculating the AUDPC. Treatments were compared based on their AUDPC values, as well the single-time-point assessments of disease severity and measurements of yield.

RESULTS

Biologically-derived and copper-based fungicides. On the final rating days, diseased petiole area for the treatments ranged from 3.0 (>3 to 6%) to 7.8 (>50 to 75%) in 2015 and from 7.0 (>50 to 75%) to 9.0 (>87 to 94%) in 2016 (Table 2). Significant differences were observed among the treatments in 2015 for diseased petiole and foliar area and petiole health; Kocide® 3000 (DuPont Crop Protection) was significantly more effective than all other treatments included in this trial. Although Kocide 3000 was also most effective in 2016, the data from assessments made at the end of the trial were not sufficient for quantitative analyses because of the lack of residual variation in the mixed ANOVA model (Table 2). However, AUDPC data indicated that the Kocide 3000 treatment was significantly more effective than the controls and all other treatments for the following: diseased petiole area, petiole health, and diseased foliar area (Table 3). Based on the AUDPC values for the diseased petiole area, Regalia® (Marrone Bio Innovations) and Serenade® Opti (Bayer Crop Science) had significantly lower petiole disease severity than one of the controls in 2015, only; these treatments provided a level of protection similar to Actinovate® (Novozymes BioAg Inc.) (Table 3). In 2016, in addition to Kocide 3000, Badge® X2 (Gowan Company) was significantly better than the control for diseased petiole and foliar area and petiole health according to AUDPC data; Kocide 3000 was more effective than Badge X2. Yields ranged from 17.0 kg to 20.2 kg (for mean yields of the four replicates for each treatment) in 2015 and from 14.3 kg to 18.3 kg in 2016; treatments did not differ significantly from the untreated control(s) (Table 2).

Conventional fungicides. Disease development was more advanced in 2016 than 2015. On the final assessments, petiole disease area ratings ranged from 1.4 to 5.4 (2015) and from 5.0 to 8.8 (2016). In both years, all treatments limited the amount of diseased petiole and foliar area and protected petiole health compared to the control with one exception (Table 4); the Tilt® (Syngenta Crop Protection, LLC) treatment in 2016 was similar to the control for petiole health. Merivon® (BASF Ag Products) effectively limited diseased petiole and foliar area and preserved petiole health based on the final assessments for both years and was significantly more effective than many of the other treatments. Azoxystrobin-based treatments including Quadris® Flowable, Quadris® Opti, and Quilt Xcel® (all from Syngenta Crop Protection, LLC) all performed similarly based on the final evaluations for diseased petiole and foliar area and petiole health. Cabrio® (BASF Ag Products), a fungicide similar to Quadris in that they both have active ingredients in FRAC group 11, did not differ significantly from any of the azoxystrobin-based fungicides for the various foliar disease parameters determined at the last rating.

AUDPC data indicated that all treatments were significantly better than the untreated control for diseased petiole area, petiole health (2015 only), and diseased foliar area (2016 only); significant differences were not noted for petiole health (2016) or diseased foliar area (2015) (Table 5). In 2015 and 2016, AUDPC values were statistically lower for Pristine® (BASF Ag Products) for diseased petiole and foliar area, and petiole health compared to Switch® (Syngenta Crop Protection, LLC) and Tilt. During 2016 when disease pressure was high, Pristine also outperformed Rovral® 4 (FMC Corporation) for the same assessments. Yields differed significantly among treatments in 2016 but not in 2015. All treatments yielded significantly higher than the control except for Rovral 4 (Table 4). Treatments of Pristine, Merivon, and

Endura® (BASF Ag Products) had statistically higher yields than Fontelis® (DuPont Crop Protection), Rovral 4, and Tilt (Table 4).

Table 2. Carrot foliar and petiole blight evaluations on 13 October 2015 and 20 September 2016 and root yield following season-long treatment with biologically-derived and copper-based fungicides.

Treatment	HB diseased petiole area[w]			Petiole health[x]			HB diseased foliar area[w]			Yield (kg)			
	2015[y]		2016	2015[y]		2016	2015[y]		2016	2015[z]		2016[z]	
Untreated	7.3	a	9.0	5.0	a	8.0	6.0	a	8.0	7.8	a	7.0	a
Untreated	7.8	a	-	5.0	a	-	6.0	a	-	8.0	a	-	-
Kocide 3000	3.0	b	7.0	2.8	b	6.0	4.3	b	7.0	9.2	a	8.3	a
Badge X2	-	-	9.0	-	-	8.0	-	-	8.0	-	-	7.4	a
Regalia	7.3	a	9.0	5.0	a	8.0	6.0	a	8.0	7.7	a	7.3	a
Serenade Opti	7.3	a	9.0	5.0	a	8.0	6.0	a	8.0	8.1	a	7.3	a
Mycostop Mix	7.5	a	9.0	5.0	a	8.0	6.0	a	8.0	8.6	a	7.1	a
Trilogy	-	-	9.0	-	-	8.0	-	-	8.0	-	-	6.9	a
Actinovate	7.8	a	9.0	5.0	a	8.0	6.0	a	8.0	8.1	a	6.5	a

[w]Rated on the Horsfall-Barratt (HB) scale, where 1=0% tissue area diseased, 2=>0 to 3%, 3=>3 to 6%, 4=>6 to 12%, 5=>12 to 25%, 6=>25 to 50%, 7=>50 to 75%, 8=>75 to 87%, 9=>87 to 94%, 10=>94 to 97%, 11=>97 to <100%, 12=100% tissue area diseased.

[x]Rated on the petiole health scale, where 1=healthy, vigorous; 2=few petiole lesions, no petiole necrosis; 3=petiole lesions numerous, no petiole necrosis; 4=1 to 20% petiole necrosis; 5=21 to 40% petiole necrosis; 6=41 to 60% petiole necrosis; 7=61 to 80% petiole necrosis; 8=81 to 90% petiole necrosis; 9=>90% petiole necrosis; 10=100% petiole necrosis.

[y]Column means with a letter in common are not significantly different (Fisher's protected least significant difference (LSD) test; α=0.05).

[z]Column means with a letter in common are not significantly different (Tukey test; α=0.05).

Table 3. Evaluation of biologically-derived or copper-based fungicides for management of foliar diseases of carrot in 2015 and 2016. Average area under the disease progress curve (AUDPC) values by disease assessment measure and treatment.

Treatment	AUDPC – HB diseased petiole area[xz]				AUDPC – Petiole health[yz]				AUDPC – HB diseased foliar area[xz]			
	2015		2016		2015		2016		2015		2016	
Untreated	199.5	a	167.8	a	112.0	a	169.9	a	190.8	a	206.4	a
Untreated	190.8	ab	-	-	110.3	a	-	-	192.5	a	-	-
Kocide 3000	91.0	c	131.0	c	61.3	b	129.0	c	120.8	b	138.9	c
Badge X2	-	-	150.1	b	-	-	148.8	b	-	-	178.3	b
Mycostop Mix	199.5	a	159.0	ab	108.5	a	159.1	ab	189.0	a	196.8	ab
Serenade Opti	180.3	b	164.3	ab	110.3	a	165.5	a	178.5	a	205.5	a
Regalia	176.8	b	166.9	a	106.8	a	170.5	a	185.5	a	208.1	a
Trilogy	-	-	167.5	a	-	-	165.3	a	-	-	202.0	a
Actinovate	185.5	ab	168.6	a	108.5	a	171.4	a	192.5	a	209.0	a

[x]Rated on the Horsfall-Barratt (HB) scale, where 1=0% tissue area diseased, 2=>0 to 3%, 3=>3 to 6%, 4=>6 to 12%, 5=>12 to 25%, 6=>25 to 50%, 7=>50 to 75%, 8=>75 to 87%, 9=>87 to 94%, 10=>94 to 97%, 11=>97 to <100%, 12=100% tissue area diseased.

[y]Rated on the petiole health scale, where 1=healthy, vigorous; 2=few petiole lesions, no petiole necrosis; 3=petiole lesions numerous, no petiole necrosis; 4=1 to 20% petiole necrosis; 5=21 to 40% petiole necrosis; 6=41 to 60% petiole necrosis; 7=61 to 80% petiole necrosis; 8=81 to 90% petiole necrosis; 9=>90% petiole necrosis; 10=100% petiole necrosis.

[z]Column means with a letter in common are not significantly different (Fisher's protected least significant difference (LSD) test; α=0.05).

Table 4. Carrot foliar and petiole blight evaluations on 13 October 2015 and 29 September 2016 and root yield following season-long treatment with conventional fungicides.

Treatment	HB diseased petiole area[w]				Petiole health[x]				HB diseased foliar area[w]				Yield (kg)			
	2015[y]		2016[y]		2015[y]		2016[y]		2015[y]		2016[y]		2015[z]		2016[y]	
Untreated	5.4	a	8.8	a	4.8	a	7.8	a	5.7	a	7.8	a	8.5	a	7.3	f
Pristine	1.4	d	5.0	d	1.5	e	5.0	ef	2.7	d	5.3	de	9.9	a	10.9	a
Merivon	1.7	cd	5.0	d	1.8	de	5.0	f	2.0	e	4.8	e	9.8	a	10.5	ab
Bravo WS	1.7	cd	6.0	c	1.8	de	5.8	b-f	3.7	bc	5.8	cd	10.2	a	10.3	ab
Cabrio	2.0	b-d	5.8	c	2.0	c-e	5.5	c-f	3.2	cd	5.8	cd	9.1	a	10.3	a-c
Endura	2.0	b-d	5.8	c	2.0	c-e	5.5	c-f	2.7	d	6.0	bc	9.6	a	10.3	ab
Quadris	1.7	cd	5.8	c	1.8	de	5.3	d-f	3.0	cd	5.8	cd	10.5	a	10.1	a-d
Quadris Opti	1.7	cd	5.8	c	1.8	de	5.0	f	3.0	cd	5.3	de	8.9	a	9.8	a-d
Switch	2.4	bc	6.8	b	2.5	bc	6.3	bc	3.1	cd	5.8	cd	9.4	a	9.6	a-d
Quilt Xcel	2.0	b-d	6.0	c	2.3	b-d	5.5	c-f	3.2	cd	6.0	bc	10.0	a	9.5	b-d
Fontelis	1.4	d	6.0	c	1.5	e	6.0	b-e	3.0	cd	5.3	de	10.5	a	8.9	c-e
Tilt	3.0	b	7.3	b	2.8	b	6.8	ab	4.2	bc	6.5	b	9.9	a	8.8	de
Rovral 4	2.2	b-d	7.0	b	2.3	b-d	6.3	b-d	2.7	d	5.8	cd	9.1	a	7.8	ef

[w]Rated on the Horsfall-Barratt (HB) scale, where 1=0% tissue area diseased, 2=>0 to 3%, 3=>3 to 6%, 4=>6 to 12%, 5=>12 to 25%, 6=>25 to 50%, 7=>50 to 75%, 8=>75 to 87%, 9=>87 to 94%, 10=>94 to 97%, 11=>97 to <100%, 12=100% tissue area diseased.

[x]Rated on the petiole health scale, where 1=healthy, vigorous; 2=few petiole lesions, no petiole necrosis; 3=petiole lesions numerous, no petiole necrosis; 4=1 to 20% petiole necrosis; 5=21 to 40% petiole necrosis; 6=41 to 60% petiole necrosis; 7=61 to 80% petiole necrosis; 8=81 to 90% petiole necrosis; 9=>90% petiole necrosis; 10=100% petiole necrosis.

[y]Column means with a letter in common are not significantly different (Fisher's protected least significant difference (LSD) test; α=0.05).

[z]Column means with a letter in common are not significantly different (Tukey test; α=0.05).

Table 5. Evaluation of conventional fungicides for management of foliar diseases of carrot in 2015 and 2016. Average area under the disease progress curve (AUDPC) values by disease assessment measure and treatment.

Treatment	AUDPC – HB diseased petiole area[v]				AUDPC – Petiole health[w]				AUDPC – HB diseased foliar area[v]			
	2015[ux]		2016[x]		2015[x]		2016[yz]		2015[y]		2016[x]	
Untreated	140.9	a	206.9	a	92.8	a	214.8	a	162.8	a	258.3	a
Merivon	67.6	bc	127.3	e	49.0	b-d	132.3	a	84.0	a	144.8	f
Quadris Opti	71.2	bc	138.4	de	49.0	b-d	134.0	a	91.0	a	156.8	ef
Pristine	58.6	c	139.4	de	38.5	d	136.6	a	89.3	a	165.3	d-f
Quilt Xcel	66.8	bc	140.1	de	50.8	b-d	135.4	a	96.3	a	176.3	b-e
Fontelis	66.0	bc	146.0	cd	52.5	bc	142.9	a	91.0	a	160.3	ef
Bravo WS	66.2	bc	147.3	cd	49.0	b-d	140.9	a	110.3	a	169.9	c-e
Cabrio	59.0	c	147.9	cd	40.3	cd	143.3	a	96.3	a	185.6	b-d
Endura	73.2	bc	147.9	cd	54.3	b	141.5	a	89.3	a	169.3	c-e
Quadris	68.0	bc	147.9	cd	49.0	b-d	143.9	a	91.0	a	173.6	b-e
Tilt	81.2	b	160.1	bc	57.8	b	157.1	a	124.3	a	191.8	b
Switch	83.9	b	165.6	b	61.3	b	163.0	a	99.8	a	188.0	bc
Rovral 4	76.8	bc	170.9	b	56.0	b	165.4	a	89.3	a	189.4	bc

[u]Geometric means reported. Mean separation analysis conducted on log-transformed data and log-transformed means back-transformed with the exponential function for reporting on the original scale.

[v]Rated on the Horsfall-Barratt scale, where 1=0% tissue area diseased, 2=>0 to 3%, 3=>3 to 6%, 4=>6 to 12%, 5=>12 to 25%, 6=>25 to 50%, 7=>50 to 75%, 8=>75 to 87%, 9=>87 to 94%, 10=>94 to 97%, 11=>97 to <100%, 12=100% tissue area diseased.

[w]Rated on the petiole health scale, where 1=healthy, vigorous; 2=few petiole lesions, no petiole necrosis; 3=petiole lesions numerous, no petiole necrosis; 4=1 to 20% petiole necrosis; 5=21 to 40% petiole necrosis; 6=41 to 60% petiole necrosis; 7=61 to 80% petiole necrosis; 8=81 to 90% petiole necrosis; 9=>90% petiole necrosis; 10=100% petiole necrosis.

[x]Column means with a letter in common are not significantly different (Fisher's protected least significant difference (LSD) test; α=0.05).

[y]Column means with a letter in common are not significantly different (least significant difference (LSD) test; α=0.05). Global F test insignificant.

[z]Global F test was insignificant. The SAS LINES display did not reflect all significant comparisons. The following additional pairs were reported as significantly different: (Switch, Fontelis), (Switch, Pristine).

DISCUSSION

Fungal foliar blights impact the Michigan carrot crop annually and, when left unmanaged, have the potential to damage the foliage and negatively affect yields (Bounds et al. 2007). When carrots exhibit sufficient blighting caused by *A. dauci* and *C. carotae,* photosynthetic surface area is lost and the weakened petioles may break during mechanical harvest (Pryor and Strandberg 2002; Raid 2002). Our trials tested several OMRI-certified and conventional fungicide products for management of Alternaria and Cercospora blights on carrot. Trials were conducted in the major carrot growing region in Michigan over two years. Disease was more severe in 2016 compared to 2015. Michigan carrot growers are interested in reducing fungicide residuals on their conventional crop and some are interested in transitioning to an organic system.

Overall, the copper-based products were more effective than the biopesticides in providing season-long protection. Biopesticides are defined by the United States Environmental Protection Agency (USEPA) as "certain types of pesticides derived from such natural materials as animals, plants, bacteria, and certain minerals" (USEPA 2016). The biopesticide active ingredients used in the current study included both microorganisms and plant derivatives. Although they are deemed synthetic substances, the copper-based fungicides Badge® X2 and Kocide® 3000 are OMRI-certified and allowable in organic production (OMRI 2017; United States Government Publishing Office 2017).

Based on final AUDPC values for the disease severity ratings, Badge X2 was not as effective as Kocide 3000 in limiting foliar disease. Kocide 3000 and Badge X2 have similar levels of metallic copper equivalent, approximately 30% and 28%, respectively, but other aspects of the product formulations may also influence their disease protection efficacy. Timmer and

Zitko (1996) investigated the impact of the proportion of metallic copper on the efficacy of copper fungicide products, specifically used against melanose disease caused by the ascomycete *Diaporthe citri* F.A. Wolf. Melanose causes lesions on growing citrus leaves and fruit; severe citrus rind lesions may be dark, raised and take on a "mudcake" appearance and/or form a tear-stained pattern (Nelson 2008). Timmer and Zitko (1996) found that 37 to 60% of the variability in their melanose severity rating results was attributable to quantity of metallic copper; thus, the amount of metallic copper explained much, but not all of the difference in efficacy between the products (Timmer and Zitko 1996). Timmer and Zitko recorded significant differences in efficacy between products that provided the same quantity of metallic copper, but were unable to generalize about these differences (1996).

The active copper compound in Kocide 3000 is solely copper hydroxide, whereas the active copper compounds in Badge X2 are copper hydroxide and copper oxychloride. Scheck and Pscheidt (1998) found that the amount of free, solubilized Cu^{2+} was the best predictor of product efficacy, in comparison with the amount of metallic copper or total dissolved copper. In general, the solubility of copper hydroxide compounds is greater than that of copper oxychloride compounds (Zitter and Rosenberger 2013), which could partially explain the greater efficacy of Kocide 3000.

Overall OMRI-certified, biologically-derived products provided inconsistent disease protection against fungal foliar diseases in the field. These findings are consistent with previous biopesticide field performance studies, which have shown that biopesticides are not only inconsistent, but often contribute lower levels of disease protection to the plant tissue than conventional fungicides (Marine et al. 2016). Active ingredients in biopesticide products including *Streptomyces lydicus* WYEC108 (Cuppels et al. 2013) and *Bascillus subtilis* (Olanya

and Larkin 2006), have demonstrated *in vitro* effectiveness for fungal or oomycete suppression. As other researchers have suggested, methods for boosting field efficacy have yet to be fully tested, and it is possible that application recommendations, such as those for adjuvants, droplet dimension, application rate, and spray scheduling, could be improved (Marine et al. 2016; Zhang et al. 2011).

Overall, fungicides in FRAC groups 7 and 11 provided the most effective disease control. Exclusive use of these fungicides is discouraged due to a medium-high and high likelihood that fungal pathogens will develop resistance to fungicides in group 11 and 7, respectively (FRAC 2016). Thus, despite their efficacy, growers should be careful not to overuse products from these FRAC groups, so as not to exert selection pressure for fungicide-resistant fungi.

There are several fungicides available to conventional growers for protecting carrots from fungal foliar disease. Products, such as Pristine® and Merivon®, provided good disease protection and would be helpful tools in a grower's management program. However, these products are both in the FRAC groups 7 and 11. Thus, it is necessary to utilize them in alternation with other products belonging to different FRAC groups, such as Tilt® (group 3), Rovral® 4 (group 2), Switch® (groups 9 and 12), or the protectant Bravo Weather Stik® (group M 05). Not all of the fungicides performed equally but were significantly more effective than the untreated control. Using a disease forecasting system such as TOM-CAST could alert a grower as to when the conditions are most favorable for disease. Future field research studies could test treatment programs that include alternating fungicides that represent different FRAC groups and levels of efficacy.

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CHAPTER 2. EVALUATING TOM-CAST FOR FOLIAR BLIGHTS IN MICHIGAN CARROTS FOR PROCESSING

ABSTRACT

Carrots are utilized for both the fresh market and processing industries; Michigan ranks fourth nationally as a supplier for both markets combined. Fungal foliar diseases caused by *Alternaria dauci* and *Cercospora carotae* occur annually in Michigan, causing necrotic foliar lesions that coalesce resulting in blighted and weakened petioles. Carrots grown for processing are harvested mechanically; when petioles are weakened by disease, the roots may be left in the ground resulting in significant loss.

Michigan growers use the disease forecaster TOM-CAST as a tool to time fungicide sprays for carrot. Bounds et al. (2007) performed experiments substantiating the use of the TOM-CAST system in carrot production with a 15-disease severity value (DSV) threshold. In recent years, Michigan growers have adopted more disease resistant carrot cultivars and new conventional fungicides have become registered for use on carrots whose efficacy within the TOM-CAST framework is unknown.

Field trials were conducted in 2015 and 2016 in collaboration with a commercial carrot grower in Mason and Oceana Counties. Disease severity was visually assessed weekly using the Horsfall-Barratt scale and a petiole health scale; the area under the disease progress curve (AUDPC) was calculated for these parameters. Root yield was determined at harvest.

TOM-CAST 15 and 25 DSV fungicide application schedules effectively reduced foliar blighting in 2015 under relatively light disease pressure. However, the TOM-CAST 25 DSV schedule did not adequately limit disease in 2016 when disease pressure was increased. Recently registered fungicides such as penthiopyrad and fluxapyroxad + pyraclostrobin and using TOM-CAST at the more conservative spray threshold of 15 DSV can help growers limit fungal foliar blight in years with higher disease pressure.

INTRODUCTION

Michigan is the fourth largest United States producer of carrots (USDA, NASS 2017); it has the fourth largest acreage planted to carrots used in processed foods (USDA, NASS 2012). Michigan commercial carrot production is impacted annually by fungal foliar disease (Hausbeck and Donne 2016). Foliar blights caused by the fungal pathogens *Alternaria dauci* and *Cercospora carotae* cause lesions on the foliage which coalesce resulting in necrosis and blighting, reducing photosynthetic area (Pryor and Strandberg 2002; Raid 2002). Petioles, weakened by lesions, break during mechanical harvest resulting in yield loss (Dorman et al. 2009). Yield loss can be substantial under conditions favorable for disease development. Field studies have shown yield losses of 20 to 80% when comparing plots without any fungicide applications to those treated with a fungicide program (Pryor et al. 2002; Rogers and Stevenson 2006).

The severity of carrot fungal foliar blights depends on the weather conditions (Bounds et al. 2006). Moderate to warm temperatures during extended periods of leaf wetness are conducive to blight development (Carisse and Kushalappa 1990; Carisse et al. 1993; Strandberg 1977). Disease forecasting systems are designed to alert growers as to when conditions or characteristics of the weather, pathogen, and crop indicate that disease is likely to develop or intensify (Campbell and Madden 1990); management action, such as a pesticide application, might be recommended (Bounds et al. 2006; Campbell and Madden 1990).

Past researchers have developed disease forecasting systems for various host-pathogen systems including late blight of potato caused by *Phytophthora infestans*, early blight of potato and tomato caused by *Alternaria solani*, early blight on celery caused by *Cercospora apii*, and Alternaria blight on carrot caused by *Alternaria dauci* (Campbell and Madden 1990). Bounds et

al. (2006) tested forecasting systems designed for *C. apii* and *A. dauci* management in Michigan field trials to schedule fungicide applications on carrots. A system originally developed to predict disease outbreaks caused by *A. solani*, named **Tom**ato Fore**cast**er (TOM-CAST), was established as most pragmatic for field use predicting disease symptoms caused by *A. dauci* and *C. carotae* (Bounds et al. 2006). The TOM-CAST system was more effective than the other two forecasters at preserving petiole health and required less monitoring and individual consideration of environmental parameters (Bounds et al. 2006).

TOM-CAST is a modified version of the **F**orecaster for ***A****lternaria* ***s****olani* on **T**omato (FAST), which was developed in the 1970s (Madden et al. 1978). FAST uses two disease models and climatic parameters including average air temperature, leaf wetness hours, hours of relative humidity above 90%, and rainfall accumulation in the last seven days to determine when early blight is likely to increase (Madden et al. 1978). The system was effective at maintaining statistically similar levels of tomato foliar health with fewer fungicide applications (Madden et al. 1978) but was considered to be too arduous for grower use (Pitblado 1992). TOM-CAST only uses leaf wetness period and average air temperature during the leaf wetness period to determine when disease is likely to occur (Madden et al. 1978; Pitblado 1992). Like *A. solani* (Harrison et al. 1965), *A. dauci* and *C. carotae* need extended leaf wetness periods and warmer temperatures during these periods for enhanced sporulation (Carisse et al. 1993; Strandberg 1977). Thus, it is logical that a similar system can be used to predict the occurrence of the fungal foliar blights caused by these pathogens. Likelihood of disease emergence is calculated each day and indicated by a number between zero and four called the disease severity value (DSV), where zero indicates the lowest probability of disease development and four indicates the highest probability (Madden et al. 1978; Pitblado 1992). Spray applications are scheduled when a certain predetermined sum

of DSVs is reached, rather than after a predetermined number of days as would be the case with a calendar schedule.

The DSV-threshold needed to achieve optimum disease protection was the objective of Bounds et al. (2007) who tested 15-, 20-, and 25-DSV-thresholds to determine which was most effective at protecting Michigan carrot foliage from fungal foliar blight. Chlorothalonil alternated with azoxystrobin, applied on a 15-DSV-threshold schedule, was reported to provide effective disease suppression and reduce the number of sprays compared to the 7- to 10-day calendar schedule (Bounds et al. 2007). It was also reported that $21 to $141 per hectare could be saved with the 15-DSV TOM-CAST schedule (Bounds et al. 2007).

The TOM-CAST disease forecasting system was tested in previous studies for use in the management of *Stemphylium vesicarium* in asparagus and *Septoria apiicola* in celery (Bounds and Hausbeck 2008; Meyer et al. 2000). With *S. vesicarium* on newly established 'Jersey Knight' asparagus, the use of the TOM-CAST system with a 10-DSV fungicide application threshold provided equivalent disease control to the 7-day calendar schedule (in terms of number of lesions per fern) with four to six fewer fungicide applications (Meyer et al. 2000). Compared to the grower standard early-start, weekly spray schedule (where fungicide applications were initiated one week after celery transplant into the field), the preventative, TOM-CAST 10-DSV schedule (where fungicide applications were initiated four weeks after transplanting) eliminated two to six fungicide applications for management of late blight on celery caused by *S. apiicola*. This would have translated into savings of $71 to $213 per hectare in fungicide costs. No significant differences in petiole or leaf blight severity or yield were detected between the early, seven-day treatment and the preventative, TOM-CAST 10-DSV treatment, based on analysis of the research farm trial results from 2004 and 2005 (Bounds and Hausbeck 2008). Very little

disease was found in trials conducted in commercial fields during these same two years (Bounds and Hausbeck 2008).

TOM-CAST was tested using conventional fungicides (Bounds et al. 2006; Bounds et al. 2007; Dorman et al. 2009; Hausbeck 2008) and implemented by Michigan growers as an effective tool to reduce reliance on fungicides designated as B2 carcinogens (such as chlorothalonil and iprodione) and maintain contracts with local processors. A baby food processor provides contracts for growers in Michigan; based on the final product, this processor is especially concerned about the type of pesticides used on the produce and the pesticide residues that could result (Hausbeck 2008). Use of rotational fungicide programs, as well as the TOM-CAST forecasting system, can reduce the amount of chlorothalonil that is used on the carrot crop each season. Rogers and Stevenson (2006) reported reductions in the amount of fungicide active ingredient used and fewer total toxicity units compared to the weekly schedule when fungicide applications were scheduled with a TOM-CAST 20-DSV threshold for cultivar 'Bolero' and a TOM-CAST 15-DSV threshold for cultivar 'Fontana.' Rogers and Stevenson (2006) used a rotation of azoxystrobin and chlorothalonil to protect their carrot crop from fungal foliar diseases. Toxicity units were derived from a computer program and were meant to indicate levels of ecological impact, acute and chronic mammalian toxicity, and effects on integrated pest management (IPM) systems and beneficial organisms (Rogers and Stevenson 2006).

Bounds et al. (2007) conducted trials in 2001 and 2002 with blight susceptible carrot cultivars; also, at this time fewer fungicides were registered for carrot fungal foliar diseases. Gugino et al. (2007) reported variation in cultivar susceptibility to Alternaria and Cercospora blights, based on tests of various processing cultivar varieties used by commercial growers in New York. In these tests, less susceptible cultivars took longer to reach a predetermined disease

threshold. It follows that using a less susceptible cultivar could result in fewer fungicide sprays over the season. Experimental results indicated that the cultivars Carson and Bolero were among the least susceptible to both fungal diseases, while Fontana was the most susceptible to both diseases across multiple years (Gugino et al. 2007). Since trial results indicate differences in carrot processing cultivar susceptibility to Alternaria and Cercospora blights, it is worth testing the efficacy of disease management programs with specific, locally preferred carrot cultivars.

Trial objectives were to 1) determine the DSV threshold most appropriate for scheduling fungicide applications using a processing carrot variety widely used by Michigan growers and to 2) determine a fungicide program that provides effective disease protection of carrot foliage. Treatment programs rotated two or more products; a grower standard fungicide program and more recently registered fungicides were included (USEPA 2012; USEPA 2014).

MATERIALS AND METHODS

Plot establishment and experimental design. 'Cupar' carrot seeds were sown by the grower-cooperator with 3.8 centimeter spacing into a plant bed consisting of three rows spaced 45.7 centimeters apart, for a rate of approximately 484,326 seeds/hectare on 30 April 2015 and 22 April 2016. The experimental sites were established in a commercial field consisting of sandy soil in 2015 (Oceana Co.) and sandy loam soil in 2016 (Mason Co.). The trial area was previously planted to sorghum in 2015 and corn in 2016. Fields were managed and overhead irrigated by the grower-cooperators according to commercial production standards (Egel et al. eds. 2017). Carrots were fertilized at planting (approximately between the 15th and 30th of April) with approximately 22.4 kilograms (kg) per hectare (ha) of nitrogen, 17.9 kg/ha of phosphorus, 168.1 kg/ha of potassium, 3.4 kg/ha of sulfur, and 1.1 kg/ha of boron. Side dress applications of fertilizer were applied in July, August, and September. In July, the fertilizer application consisted of approximately 44.8 kg/ha of nitrogen, 67.3 kg/ha of potassium, 11.2 kg/ha of sulfur, and 1.1 kg/ha of boron. In August and September, the side dress fertilizer application consisted of approximately 33.6 kg/ha of nitrogen.

Treatments consisted of combinations of two factors, 'fungicide program' and 'schedule,' each with three possible levels. The three fungicide programs examined were as follows: 1) chlorothalonil alternated (alt.) with azoxystrobin; 2) azoxystrobin alt. with penthiopyrad; and 3) penthiopyrad alt. with cyprodinil and fludioxonil alt. with fluxapyroxad and pyraclostrobin (Table 6). The three fungicide application schedules assessed were as follows: 1) a grower standard 7- to 10-day calendar schedule, 2) a 15-disease severity value (DSV) TOM-CAST-based schedule, and 3) a 25-DSV TOM-CAST-based schedule. Combining the three levels of each factor resulted in nine fungicide treatments plus an untreated control.

Each year the trial was established as a randomized complete block design with four replications. Each treatment plot was 6.1 meters in length and one plant bed consisting of three rows of carrots wide. Each treatment plot was separated by at least a two-foot buffer zone between the rows of plots (aka blocks). The trial each year was buffered by a half bed or more of untreated carrots on either side. The experiment was analyzed as a two-factor design, plus an untreated control treatment.

Table 6. List of fungicide products tested in the TOM-CAST carrot field trial.

Product[x]	Formulation	Product Rate/ Hectare	Proportion of Active Ingredient	FRAC[y] Code
Bravo Weather Stik®	Suspension concentrate (SC)	2.3 L	54% chlorothalonil	M 05
Dupont™ Fontelis®	SC	1.8 L	20.4% penthiopyrad	7
Merivon® Xemium® Brand Fungicide	SC	365.4 mL	21.3% fluxapyroxad/ 21.3% pyraclostrobin	7/ 11
Quadris® Flowable Fungicide	SC	1132.7 mL	22.9% azoxystrobin	11
Switch®	Water-dispersible granule (WG)	980.7 g	37.5% cyprodinil/ 25.0% fludioxonil	9/ 12

[x]All of the products in this table are labeled for use against carrot fungal foliar disease.
[y]**F**ungicide **R**esistance **A**ction **C**ommittee (http://www.frac.info) FRAC groups are based on the modes of action by which the active chemicals in the fungicide products inhibit pathogen functioning. These groups are important to note so that one can determine a disease management program that slows the development of active ingredient resistance in the local pathogen population.

Treatment initiation and application. Starting in late June, fields were scouted weekly or biweekly for blight symptoms. Throughout the season, carrot foliage was periodically removed from the field, returned to the laboratory, incubated under high relative humidity conditions, and assessed for disease. Foliar tissue was surface-disinfested and placed on agar media (technical agar, Acumedia®); generally, water agar (16 g agar/1000 mL distilled water) or dilute V-8 agar (16 g agar, 960 mL distilled water, 40 mL V-8 juice, 1.5 g calcium carbonate) mixes were used. Cultures were incubated under fluorescent lights to promote pathogen growth. Foliage or cultured fungi were viewed microscopically at 100x to 400x magnification. Suspect *A. dauci* and *C. carotae* conidia and conidiophores observed on the carrot foliage were identified visually by their distinct morphological features and measurements using a reticle aka eyepiece micrometer.

Two weather-stations were positioned at diagonal corners of the trial area to collect data for the TOM-CAST disease forecasting system. The equipment for each station, mounted on steel poles, included a Watchdog® Mini Station (Spectrum® Technologies, Inc.) for measurement

of temperature and relative humidity, a tipping bucket rain collector (Spectrum® Technologies, Inc.), and a leaf wetness sensor (Spectrum® Technologies, Inc.). The rain collector was mounted at the top of each pole and the Watchdog® Mini Station was mounted on the upper half of each pole. Each leaf wetness sensor was mounted and adjusted as needed so that it was at a 45° angle to the pole, facing north and approximately three-quarters of the carrot canopy height. The sensors were placed between the rows of carrots; foliage that was in contact with the sensors was removed.

Data were downloaded from the Watchdog® Mini Station to a small laptop computer and uploaded using the installed SpecWare 9 Pro software (Spectrum® Technologies, Inc.). SpecWare 9 Pro runs the TOM-CAST computer package that calculates and graphs the daily DSVs. DSV calculations were derived from the leaf wetness periods and mean temperature ranges reported by Madden et al. (1978) (Table 7). The daily DSVs calculated by SpecWare were recorded and manually summed to determine when the experimental DSV thresholds were reached.

Table 7. Disease severity values (0-4) as a function of leaf wetness and average air temperature during the wetness periods.

Mean temp. (°C)	Leaf wetness periods (hr) required to produce daily disease severity values of:				
	0	1	2	3	4
13-17	0-6	7-15	16-20	21+	
18-20	0-3	4-8	9-15	16-22	23+
21-25	0-2	3-5	6-12	13-20	21+
26-29	0-3	4-8	9-15	16-22	23+

Madden L., S.P. Pennypacker, and A.A. MacNab. Phytopathology 68:1354-1358. Table reproduced from Pitblado 1992.

Fungicide applications were initiated 2 July 2015 and 15 July 2016 at trace disease levels (Bounds et al. 2007). Applications were made with a backpack sprayer calibrated to approximately 344.7 kPa with three XR8003 flat-fan nozzles, delivering approximately 467.7 L/hectare. In 2015, fourteen sprays were applied according to the 7- to 10-day schedule on 2, 9, 17, 23 and 31 July; 10, 18, and 26 August; 1, 9, 16, 23 and 30 September; 7 October. Eight sprays were applied according to the 15-DSV schedule on 2 and 20 July; 4, 14, and 20 August; 1, 9, and 30 September. Four sprays were applied according to the 25-DSV schedule on 2 and 28 July; 18 August; and 9 September. In 2016, eleven sprays were applied according to the 7- to 10-day schedule on 15 and 25 July; 1, 8, 15, 22 and 30 August; 7, 14, 21 and 28 September. Nine sprays were applied according to the 15-DSV schedule on 15 and 25 July; 1, 11, 17, and 25 August; 1, 11, and 21 September. Finally, six sprays were applied according to the 25-DSV schedule on 15 and 27 July; 11 and 22 August; 7 and 21 September.

Disease assessments and yield. Disease assessments were made in 2015 on the following dates: 1, 15, 29 September; 13 and 20 October. The petiole health measure was not assessed on 1 September 2015. Disease assessments were made weekly in 2016 on the following dates: 11, 18, 25 August; 1, 8, 15 or 17, 20, 29 September; and 6 October. However, the number

of plants with one or more petiole lesions was only counted on 11, 18, 25 August; 1 and 8 September, since nearly all of the plants had developed lesions by 8 September.

Disease incidence was determined by counting the number of plants with one or more petiole lesions within a pre-determined ten-foot section of the center row of each treatment plot. Visual assessment of the foliar and petiole disease severity was made using the Horsfall-Barratt scale (Horsfall and Barratt 1945) to determine a level of diseased tissue as follows: 1=0%, 2=0-3%, 3=3-6%, 4=6-12%, 5=12-25%, 6=25-50%, 7=50-75%, 8=75-87%, 9=87-94%, 10=94-97%, 11=97-100%, 12=100%. Assessments of petiole disease were made according to Bounds et al. (2006) where 1=healthy and vigorous, 2=few petiole lesions, no petiole necrosis, 3=petiole lesions numerous, no petiole necrosis, 4=1 to 20% petiole necrosis, 5=21 to 40% petiole necrosis, 6=41 to 60% petiole necrosis, 7=61 to 80% petiole necrosis, 8=81 to 90% petiole necrosis, 9= >90% petiole necrosis, 10=100% petiole necrosis (Bounds et al. 2006). Carrots were hand-harvested using a digging fork and shovel, and topped and weighed at the end of the season to determine yield; weighing occurred on 22 October 2015 and 13 October 2016 (harvest occurred 7 October 2016).

Statistical analysis. Statistical analysis was performed using SAS® software, Version 9.4 of the SAS System for Windows. Copyright © 2002-2012 by SAS Institute Inc. SAS and all other SAS Institute Inc. product or service names are registered trademarks or trademarks of SAS Institute Inc., Cary, NC, USA. Analysis was performed in two steps: 1) treating the experiment as a one-factor design with ten levels to determine whether the treatments with prescribed fungicide applications were significantly different than the control, then 2) removing the untreated control data and running the analysis with both factors, “fungicide program” and

"schedule," in the statistical model and examining both the main effects of fungicide and schedule and their interaction.

The area under the disease progress curve (AUDPC) was calculated for the three disease severity measures (petiole and foliar health assessed on the Horsfall-Barratt scale and petiole health) based on the methods outlined by Shaner and Finney (1977). This is also called the trapezoidal or mid-point method (Madden et al. 2007) for calculating the AUDPC. Mean AUDPC values of the four replications for each treatment were compared. AUDPC values for the nine treatments that make up the three by three factorial part of the experiment were plotted to examine the interaction between the two factors.

For each type of treatment response (i.e. the three disease severity measures and yield), a global analysis of variance (ANOVA) F-test was calculated (using PROC MIXED) for each trial to determine the presence of any significant differences between treatments. If the global F-test was significant, all pair-wise comparisons were assessed with Fisher's least significant difference (LSD) test. Where the global F-test was insignificant, Tukey's test was used for mean comparisons for the one-way model (instead of Fisher's LSD test). For comparisons of all responses with the two-way model, 'fungicide' and 'schedule' were treated as fixed factors, and replicate (block) as a random factor. For the two-way model, Fisher's LSD test was used even if the global F-test for either one of the factors, or the interaction, was insignificant based on an α–level of 0.05. Fisher's LSD test was used as there was interest in a less conservative comparison. Where the global F-test for both factors and the interaction was insignificant, Tukey's test was used. PROC PLM was used to determine mean separation letters.

The presence of normality and equal variance within the data distributions was initially assessed using residuals plots produced with the PLOTS= option in the PROC MIXED

statement. Equal variance was also assessed using Levene's test. If the variance values could be considered equal among the treatments based on Levene's test, i.e. the difference in variance was not significant based on an α-level of 0.05, then pairwise comparisons of the treatment means were made using the original data. The data from some measures were transformed by calculating the natural-logarithm values of the data set to obtain equal variance based on Levene's test. If the equal-variance assumption was met, mean comparisons were made based on the natural-logarithm-transformed values. The data were back-transformed with the exponential function for reporting on the original scale.

If the equal variance assumption was not met by the original or log-transformed data based on Levene's test, pair-wise comparisons were run in PROC MIXED with the addition of ddfm=kr (Kenward-Roger degrees-of-freedom method) to the model statement and a repeated statement "repeated /group=XX", both to account for unequal variance. The "group" was set equal to the factor(s) with unequal variance, e.g., group=trt or group=fung.

Each of the three levels of the two factors was assessed to determine whether that element of the treatment design had a significant impact on the treatment outcomes. Assessment of the impact the factor levels on the experimental outcomes, i.e. comparing the simple effects, was done using the slicing procedure in SAS, PROC GLIMMIX.

RESULTS

Foliar blight and fungicide applications. In 2015, 14 fungicide applications were triggered by the calendar-based interval, 8 were triggered by the TOM-CAST 15 DSV interval and 4 were triggered by the TOM-CAST 25 DSV interval (Table 8). In 2016, 11 fungicide applications were triggered by the calendar-based spray interval, 9 were triggered by the TOM-CAST 15 DSV interval and 6 were triggered by the TOM-CAST 25 DSV interval (Table 8).

Foliar blight affected the carrot crop in each year of the experiment; high disease pressure was observed in 2016. Disease levels in the fungicide-treated plots were low in 2015, regardless of the application schedule. On the final rating day (20 October), the control had a diseased petiole area and health ratings of 7.0 and 4.5, respectively (petiole area, 4= >6 to 12%; petiole health, 1= healthy, 10= necrotic) whereas the fungicide treatments received a rating that did not exceed 2.5 (2=>0 to 3%). The diseased foliar rating for the control was 5.5 (5=>12 to 25%) and the fungicide treatment ratings did not exceed 3.3 (3=>3 to 6%) (Table 8). In 2016, on the final rating day (6 October), fungicide treatments received a diseased petiole area rating ranging from 6.3 to 7.0 (6=>25 to 50%; 7=>50 to 75%), the control had a rating of 9.0 (>87% to 94%). Fungicide treated plots received a rating of 5.0 to 6.8 (5=>12 to 25%; 7=>50 to 75%) for the area of diseased foliage; the control received a rating of 8.0 (>75 to 87%). Petiole health levels ranged from 6.0 to 7.0 and 8.0 (1=healthy, 10=necrotic) for the fungicide treatments and control, respectively (Table 8).

Area under the disease progress curve (AUDPC). Based on the one-way analyses of AUDPC data for 2016, the fungicide program of penthiopyrad, cyprodinil + fludioxonil, and fluxapyroxad + pyraclostrobin was more effective than the program including chlorothalonil and azoxystrobin when fungicides were applied on the same schedule. When applications were made

according to the TOM-CAST 25 DSV schedule, the azoxystrobin, penthiopyrad fungicide program was more effective than the chlorothalonil, azoxystrobin program in 2016 (Table 9).

Based on the 2015 and 2016 AUDPC values for diseased petiole and foliar area and petiole health, the fungicide treatments had significantly reduced disease compared to the control (Table 9). Examining the results of the two-factor analyses, the global F-test did not indicate significant interaction effects for the AUDPC values of any of the three disease severity ratings in 2015. This suggests that variation of the application schedule for each fungicide program did not greatly influence the efficacy of disease protection, and vice versa. The interaction effects were not significant in the two-factor analysis of the AUDPC values for the disease measures in 2016, except for the foliar diseased area.

Assessment of the simple effects for the 2015 AUDPC values based on the area of diseased petiole ratings did not indicate significant differences (see Appendix, Table 13). For the 2015 AUDPC values based on the area of diseased foliar ratings, there were significant differences in the efficacy of the TOM-CAST 15- and 25-DSV schedules depending on the fungicide program used (see Appendix, Table 14). For both TOM-CAST schedules, the chlorothalonil, azoxystrobin fungicide program was significantly less effective than the following: azoxystrobin, penthiopyrad; and penthiopyrad, cyprodinil + fludioxonil, fluxapyroxad + pyraclostrobin (Table 9). Based on the AUDPC values for the 2015 petiole health ratings, significant simple effects were found. The efficacy of the penthiopyrad, cyprodinil + fludioxonil, fluxapyroxad + pyraclostrobin fungicide program was significantly dependent on schedule; the calendar-based application schedule was significantly dependent on fungicide program (see Appendix, Table 15). However, these differences in efficacy indicated by the simple effects were not reflected by significant differences in the pair-wise comparisons (Table 9).

In 2015, the following treatments were significantly more effective in maintaining petiole health than the fungicide program of chlorothalonil and azoxystrobin applied according to TOM-CAST 25 DSV based on a one-way analysis: penthiopyrad, cyprodinil + fludioxonil, and fluxapyroxad + pyraclostrobin applied according to a calendar-based or TOM-CAST 15 DSV schedules; and the azoxystrobin and penthiopyrad program applied according to TOM-CAST 15 DSV (Table 9).

When the 2016 fungicide program simple effects were assessed based on the AUDPC values for the diseased petiole area ratings, the efficacy of the chlorothalonil and azoxystrobin, and penthiopyrad, cyprodinil + fludioxonil, and fluxapyroxad + pyraclostrobin programs varied significantly based on the application schedule factor. The efficacy of the application schedules varied significantly in 2016 based on fungicide program (see Appendix, Table 17). In 2016, AUDPC values for diseased petiole area indicated that the penthiopyrad, cyprodinil + fludioxonil, and fluxapyroxad + pyraclostrobin program applied according to a calendar-based or TOM-CAST 15-DSV schedule was significantly more effective than the other fungicide programs. For the TOM-CAST 25-DSV application schedule, the chlorothalonil and azoxystrobin fungicide program was significantly less effective than the other two fungicide programs in 2016; the other two fungicide programs performed similarly when applied according to this schedule (Table 9).

Based on 2016 AUDPC values derived from petiole health ratings, the efficacy of the chlorothalonil and azoxystrobin program varied significantly based on the application schedule (see Appendix, Table 19). The chlorothalonil and azoxystrobin program was significantly more effective when applied according to the TOM-CAST 15-DSV schedule compared to the TOM-CAST 25-DSV schedule (Table 9). Also for the 2016 AUDPC values derived from petiole health

ratings, the efficacy of each application schedule differed significantly based on the fungicide program (see Appendix, Table 19). Regardless of the application schedule, the penthiopyrad, cyprodinil + fludioxonil, fluxapyroxad + pyraclostrobin fungicide program was more effective than the chlorothalonil and azoxystrobin program (Table 9). The azoxystrobin and penthiopyrad program was statistically similar in petiole health protection to the penthiopyrad, cyprodinil + fludioxonil, and fluxapyroxad + pyraclostrobin program for every application schedule except for TOM-CAST 15 DSV, based on the one-way analysis. The azoxystrobin and penthiopyrad program was significantly more effective at protecting petiole health than the chlorothalonil and azoxystrobin program when applied according to the calendar-based and TOM-CAST 25-DSV schedules (Table 9).

Yield. In 2016, yields ranged from approximately 8.9 to 11.9 kilograms (kg) among the fungicide treatments; the yield from the control treatment was approximately 8.0 kg (Table 8). In 2016, significant differences in yield were detected among treatments. Based on the one-way analysis, all of the treatment yields were significantly greater than the control except for chlorothalonil and azoxystrobin applied according to TOM-CAST 25-DSV (*P* value: 0.15) (Table 8). The treatment with the highest yield was chlorothalonil and azoxystrobin applied according to the calendar-based schedule (Table 8). There was a significant interaction effect between the two factors (fungicide program and schedule) for yield in 2016, based on the two-factor analysis. Looking at the simple effects of the treatments, the efficacy of the chlorothalonil and azoxystrobin program depended significantly on the application schedule; the efficacy of the calendar-based schedule depended significantly on the fungicide program (see Appendix, Table 20). The chlorothalonil and azoxystrobin program was most effective when applied according to the calendar-based schedule, and vice versa (Table 8 and Appendix, Table 12). In 2015, no

significant differences were determined among the yields for ten treatments. Yields ranged from 9.6 kg for the control to 10.6 kg for the calendar-based schedule using the fungicide program of penthiopyrad, cyprodinil + fludioxonil, and fluxapyroxad + pyraclostrobin (Table 8).

Table 8. Carrot foliar and petiole blight evaluations on 20 October 2015 and 6 October 2016 and root yield following season-long treatment applied per the TOM-CAST disease forecasting system.

Application schedule	Applications (no.)		HB diseased petiole area[w]		Petiole health[x]		HB diseased foliar area[w]		Yield (kg)			
	2015	2016	2015	2016	2015	2016	2015	2016	2015[y]		2016[z]	
Untreated control	-	-	7.0	9.0	4.5	8.0	5.5	8.0	9.6	a	8.0	d
Bravo WeatherStik SC 2.3 L/ha alternated with Quadris SC 1.1 L/ha												
7- to 10-day intervals	14	11	2.0	6.8	2.0	6.3	2.8	6.0	9.8	a	11.9	a
TOM-CAST 15 DSV	8	9	2.0	7.0	2.5	6.8	3.3	6.0	10.1	a	10.0	bc
TOM-CAST 25 DSV	4	6	2.3	7.0	2.5	7.0	3.3	6.8	9.8	a	8.9	cd
Quadris SC 1.1 L/ha alternated with Fontelis SC 1.8 L/ha												
7- to 10-day intervals	14	11	2.0	7.0	2.0	6.0	2.3	6.0	9.6	a	10.0	b
TOM-CAST 15 DSV	8	9	2.0	7.0	2.0	6.0	2.0	5.8	10.3	a	9.6	bc
TOM-CAST 25 DSV	4	6	2.0	7.0	2.0	6.5	3.0	6.3	10.0	a	10.3	b
Fontelis SC 1.8 L/ha alternated with Switch WG 1.0 kg/ha alternated with Merivon SC 0.4 L/ha												
7- to 10-day intervals	14	11	2.0	6.3	2.0	6.0	2.0	5.0	10.6	a	10.3	b
TOM-CAST 15 DSV	8	9	2.0	6.8	2.0	6.0	2.3	5.3	10.0	a	10.2	b
TOM-CAST 25 DSV	4	6	2.0	7.0	2.0	6.3	2.8	6.3	10.1	a	9.9	bc

[w]Rated on the Horsfall-Barratt (HB) scale, where 1=0% tissue area diseased, 2=>0 to 3%, 3=>3 to 6%, 4=>6 to 12%, 5=>12 to 25%, 6=>25 to 50%, 7=>50 to 75%, 8=>75 to 87%, 9=>87 to 94%, 10=>94 to 97%, 11=>97 to <100%, 12=100% tissue area diseased.

[x]Rated on the Petiole health scale, where 1=healthy, vigorous; 2=few petiole lesions, no petiole necrosis; 3=petiole lesions numerous, no petiole necrosis; 4=1 to 20% petiole necrosis; 5=21 to 40% petiole necrosis; 6=41 to 60% petiole necrosis; 7=61 to 80% petiole necrosis; 8=81 to 90% petiole necrosis; 9=>90% petiole necrosis; 10=100% petiole necrosis.

[y]Column means with a letter in common are not significantly different (Tukey test α=0.05). Performed as one-way analysis with one factor, treatment.

[z]Column means with a letter in common are not significantly different (least significant difference (LSD) test α=0.05). Performed as one-way analysis with one factor, treatment.

Table 9. One-way comparisons of 2015 and 2016 area under the disease progress curve (AUDPC) values for each of the ten treatments.

Application schedule	AUDPC of HBP[y]				AUDPC of PH[y]				AUDPC of HBF[y]			
	2015[x]		2016		2015		2016[x]		2015		2016	
Untreated control	193.2	a	314.4	a	116.4	a	287.8	a	197.8	a	315.1	a
Bravo WeatherStik SC 2.3 L/ha alternated with Quadris SC 1.1 L/ha												
7- to 10-day intervals	84.1	bcd	207.4	bc	69.1	bc	205.7	bc	121.6	bcd	216.3	cd
TOM-CAST 15 DSV	88.9	bcd	200.3	cd	70.0	bc	197.1	cd	133.0	bc	218.3	c
TOM-CAST 25 DSV	93.6	b	218.0	b	81.4	b	214.0	b	139.1	b	242.1	b
Quadris SC 1.1 L/ha alternated with Fontelis SC 1.8 L/ha												
7- to 10-day intervals	89.9	bc	198.8	cd	67.4	bc	191.0	de	105.0	d	209.5	cd
TOM-CAST 15 DSV	78.3	cd	195.3	d	61.3	c	191.2	de	104.1	d	201.4	d
TOM-CAST 25 DSV	87.3	bcd	199.4	cd	68.3	bc	193.6	d	119.0	cd	208.6	cd
Fontelis SC 1.8 L/ha alternated with Switch WG 1.0 kg/ha alternated with Merivon SC 0.4 L/ha												
7- to 10-day intervals	76.7	d	179.6	e	57.8	c	183.7	ef	105.9	d	177.0	e
TOM-CAST 15 DSV	84.6	bcd	176.9	e	65.6	c	180.0	f	107.6	d	182.6	e
TOM-CAST 25 DSV	88.9	bcd	198.3	cd	68.3	bc	189.9	de	118.1	cd	203.1	cd

[x]Column reported as geometric means (rather than arithmetic means) since one-way analysis was done on the natural-log-transformed data.

[y]Column means with a letter in common are not significantly different (least significant difference (LSD) test; α=0.05). HBP = Horsfall-Barratt diseased petiole area ratings, PH = petiole health scale ratings, HBF = Horsfall-Barratt diseased foliar area ratings.

DISCUSSION

Michigan carrot growers have used the TOM-CAST program to assist in timing fungicide sprays for managing foliar blight caused by *A. dauci* and/or *C. carotae* since it was tested and found to be effective in 2005 (Hausbeck, unpublished data). At the time of initial field testing of the TOM-CAST program, the primary fungicides available were limited to chlorothalonil, azoxystrobin, and copper hydroxide; additional fungicides are now registered. Also, the blight susceptible processing carrot 'Goliath' is no longer grown and has been replaced by cultivars that are considered to be less susceptible. The current study serves to update management guidelines and recommendations to Michigan carrot growers for fungal foliar blights.

When DSVs accumulate quickly due to favorable environmental conditions, a reduced fungicide application interval may be needed to keep the foliage healthy. Conversely, in times when DSVs are accumulating slowly, weather conditions are not conducive to disease development and a longer application interval may be appropriate. In 2015, when conditions were less conducive to disease development, all fungicide programs limited disease regardless of the application schedule. Disease levels remained under 3.0 on the petiole health scale and 4.0 for both diseased petiole and foliar area for all fungicide treatments. In previous field observations, Bounds et al. (2006) reported that noticeable yield loss from carrots left in the ground during mechanical harvest, occurred when the disease level was 5.0 or higher on the petiole health scale. The relationship between petiole or foliar disease levels and yield loss warrants further investigation.

Final disease ratings were higher overall in 2016 than in 2015. None of the final petiole health ratings were below 5.0 in 2016 which indicates that yield losses would likely be greater for a commercial grower than indicated by our data; our plots were harvested by hand. The

calendar and TOM-CAST 15 DSV schedules for the azoxystrobin and penthiopyrad, and penthiopyrad, cyprodinil + fludioxonil, fluxapyroxad + pyraclostrobin programs had the lowest petiole health ratings of 6.0 on the last rating day for 2016. In comparison, the control had a final petiole health rating level of 8.0.

In 2015, the application schedule did not significantly impact the efficacy of the fungicide program. In the same way, variation of the fungicide program often did not significantly impact the efficacy of a given application schedule, although this depended on the disease parameter assessed. There was not a significant interaction between the fungicide program and application schedule in 2015; thus, in a low disease pressure year a range of fungicide programs and application schedules could effectively manage fungal foliar blight in commercial carrot fields.

In 2016, based on the global F-test interaction factor results, the amount of diseased foliar area was influenced by variation of the fungicide program or application schedule. When the levels of each factor (fungicide program or application schedule) were examined separately, numerous simple effects were found to be significant and there was corresponding treatment mean separation. The penthiopyrad, fludioxinil + cyprodinil, fluxapyrad + pyraclostrobin fungicide program outperformed the chlorothalonil and azoxystrobin program in disease control. Under the least frequent application schedule, TOM-CAST 25 DSV, the standard chlorothalonil and azoxystrobin spray schedule was less effective than the other two fungicide programs based on three disease severity measures.

Based on the results of the current study, it appears that a fungicide application threshold of 20 or 25 DSV could be effective in years with light disease pressure. However, a 15 DSV threshold should be used in years with severe disease pressure. Prior research found that a 20 or

25 DSV threshold was insufficient to limit fungal foliar disease for commercial carrot production (Bounds et al. 2007; Dorman et al. 2009). For instance, Dorman et al. (2009) found that using a TOM-CAST 20 DSV fungicide application schedule did not adequately protect the carrot foliage. These researchers used fungicide programs comprised of combinations of chlorothalonil, azoxystrobin, and copper hydroxide. Dorman et al. (2009) also noted that while 15 DSV could be an effective threshold level for reducing the number of fungicide applications, in years with more severe disease pressure, using a 10 DSV schedule could be necessary. Bounds et al. (2007) also concluded that, despite reducing the number of applications of the chlorothalonil alternated with azoxystrobin program, the TOM-CAST 20 and 25 DSV schedules were not optimal in limiting disease.

The current study indicates that recently registered fungicides, such as penthiopyrad or fluxapyroxad mixed with pyraclostrobin, protected foliage better under high disease pressure than the standard program of chlorothalonil and azoxystrobin used by Michigan carrot growers. The standard program was not as effective as the penthiopyrad, cyprodinil + fludioxonil, and fluxapyroxad + pyraclostrobin program for foliar and petiole health in 2016, based on the AUDPC values of three disease severity measures.

The grower standard fungicide program includes azoxystrobin, a reduced-risk product due to its reduced impact on the environment and human health (USEPA 2017) that has been registered since 1997; its label was amended in 2000 to include carrot fungal foliar diseases (Kenny 2000; USEPA). Azoxystrobin is considered at high risk for the pathogen population to develop resistance or tolerance (FRAC 2016). Azoxystrobin has been an effective fungicide option for Michigan carrot growers (Bounds et al. 2007; Hausbeck 2008). There have been reports of *Alternaria* spp. including *A. solani* and *A. alternata* developing reduced sensitivity to

this fungicide (Pasche et al. 2004; Ma et al. 2003). Pasche et al. (2004) found that isolates with the F129L mutation had reduced sensitivity to azoxystrobin rather than the complete resistance to the chemical which other researchers reported with a G143A mutation. The chlorothalonil and azoxystrobin fungicide program did not perform as favorably in 2016 as expected. The local Michigan *A. dauci* pathogen population has not been tested for reduced sensitivity to azoxystrobin.

Pasche et al. (2004) found that reduced sensitivity to azoxystrobin was significantly correlated with reduced sensitivity to pyraclostrobin and to a lesser extent, trifloxystrobin; both are quinone outside inhibitor (QoI) fungicides (FRAC 2017; Pasche et al. 2004). For the fungicide program that included penthiopyrad, cyprodinil + fludioxonil, and fluxapyroxad + pyraclostrobin used in the current study, a QoI fungicide (pyraclostrobin) was included as part of a tank mix with fluxapyroxad. The fluxapyroxad may increase the efficacy of the product against *A. dauci* or *C. carotae* individuals in the local population with reduced sensitivity to QoI fungicides. Future research could investigate whether the local Michigan *A. dauci* and *C. carotae* populations have mutations correlated with reduced sensitivity to QoI fungicides. This information could help growers make informed decisions regarding their use of QoI fungicides in their management programs.

In years with high disease pressure, such as 2016, a reduced application interval is necessary, regardless of the fungicide program used; a TOM-CAST threshold of 15 DSVs or less may be adequate. However, in a light disease year such as 2015, the 25 DSV threshold managed disease sufficiently. Use of newly-registered fungicides, such as Fontelis and Merivon, could allow growers to use a higher TOM-CAST DSV threshold in a light to moderate disease-pressure year.

FUTURE WORK

Michigan carrot growers can benefit from university research conducted to assess different products and approaches for managing fungal foliar blights. It can also be helpful to review the assessment methods themselves. In our trials, evaluations of the efficacy of fungicide products and TOM-CAST thresholds were made using three different visual disease severity assessments and by measuring yield. Making three disease severity assessments is more time consuming and complex to analyze than simply using one assessment. Future work could examine which disease severity parameter best predicts yield loss.

Since yield is the primary concern of growers, it would be helpful to more precisely quantify what level of foliar or petiole disease severity causes significant yield loss. Bounds et al. (2006) reported that field observations indicated that visually evident yield loss during mechanical harvest often occurred when petiole health levels reached an average of 5.0 or greater. However, a replicated field trial where disease severity assessments are made and compared to yield values derived from mechanically-harvested plots would provide more substantial evidence to better define the relationship between foliar health and yield loss.

An important part of designing fungicide programs is taking into consideration the potential development of resistance in the local pathogen populations. Our studies provided evidence for the efficacy level of various fungicide options for management of fungal foliar blights on carrot. Six out of twelve synthetic fungicides tested in the conventional product trial have an active ingredient in FRAC group 11, the quinone outside inhibitors (QoIs) (FRAC 2017). In order to determine the prudency of relying on fungicides in this group, researchers could test the local Michigan *A. dauci* and *C. carotae* populations for reduced sensitivity to QoI fungicides.

APPENDIX

APPENDIX

Table 10. One-way[v] and two-way[v] comparisons of 2015 area under the disease progress curve (AUDPC) values for each of the ten treatments.

Application schedule	AUDPC HBP				AUDPC PH[x]			AUDPC HBF[x]		
	One-way[wx]		Two-way[y]		One-way	Two-way[z]		One-way	Two-way	
Untreated control	193.2	A	-	-	116.4	A	-	197.8	A	-
Bravo WeatherStik SC 2 pt alternated with Quadris SC 15.5 fl oz										
7- to 10-day intervals	84.1	**BCD**	84.9	**b**	69.1	BC	bc	121.6	BCD	bcd
TOM-CAST 15 DSV	88.9	**BCD**	89.3	**b**	70.0	BC	bc	133.0	BC	bc
TOM-CAST 25 DSV	93.6	B	93.6	b	81.4	B	b	139.1	B	b
Quadris SC 15.5 fl oz alternated with Fontelis SC 24 fl oz										
7- to 10-day intervals	89.9	**BC**	90.1	**b**	67.4	BC	bc	105.0	D	d
TOM-CAST 15 DSV	78.3	**CD**	78.8	**b**	61.3	C	c	104.1	D	d
TOM-CAST 25 DSV	87.3	**BCD**	87.5	**b**	68.3	BC	bc	119.0	CD	cd
Fontelis SC 24 fl oz alternated with Switch WG 14 oz alternated with Merivon SC 5 fl oz										
7- to 10-day intervals	76.7	**D**	77.0	**b**	57.8	C	c	105.9	D	d
TOM-CAST 15 DSV	84.6	**BCD**	84.9	**b**	65.6	**C**	**bc**	107.6	D	d
TOM-CAST 25 DSV	88.9	**BCD**	89.3	**b**	68.3	BC	bc	118.1	CD	cd

[v]Analyses were done with one factor, treatment, in the model (i.e. one-way analysis), as well as with "schedule" and "fungicide program" listed as two separate factors (i.e. two-way analysis).

[w]Column reported as geometric means (rather than arithmetic means) since one-way analysis was done on the natural-log-transformed data.

[x]Column means with a letter in common are not significantly different (least significant difference (LSD) test; α=0.05).

[y]Column means with a letter in common are not significantly different (Tukey test; α=0.05).

[z]For the two-way analysis, the SAS LINES display did not reflect all significant comparisons. The following additional pairs are significantly different: (QF, TOM-CAST 25 DSV; FSM, calendar); (FSM, TOM-CAST 25 DSV; FSM, calendar); (QF, calendar; FSM, calendar); (FSM, TOM-CAST 15 DSV; FSM, calendar), where QF = Quadris alternated with Fontelis and FSM = Fontelis alternated with Switch alternated with Merivon.

Table 11. One-way[w] and two-way[w] comparisons of 2016 area under the disease progress curve (AUDPC) values for each of the ten treatments.

Application schedule	AUDPC HBP[x]			AUDPC PH[xy]			AUDPC HBF[x]		
		One-way	Two-way		One-way	Two-way		One-way	Two-way[z]
Untreated control	314.4	A	-	287.8	A	-	315.1	A	-
Bravo WeatherStik SC 2 pt alternated with Quadris SC 15.5 fl oz									
7- to 10-day intervals	207.4	**BC**	**c**	205.7	BC	bc	216.3	**CD**	**c**
TOM-CAST 15 DSV	200.3	CD	cd	197.1	CD	cd	218.3	C	c
TOM-CAST 25 DSV	218.0	B	b	214.0	B	b	242.1	B	b
Quadris SC 15.5 fl oz alternated with Fontelis SC 24 fl oz									
7- to 10-day intervals	198.8	CD	cd	191.0	DE	de	209.5	**CD**	**c**
TOM-CAST 15 DSV	195.3	D	d	191.2	DE	de	201.4	**D**	**cd**
TOM-CAST 25 DSV	199.4	CD	cd	193.6	D	d	208.6	**CD**	**c**
Fontelis SC 24 fl oz alternated with Switch WG 14 oz alternated with Merivon SC 5 fl oz									
7- to 10-day intervals	179.6	E	e	183.7	EF	ef	177.0	E	e
TOM-CAST 15 DSV	176.9	E	e	180.0	F	f	182.6	**E**	**de**
TOM-CAST 25 DSV	198.3	CD	cd	189.9	DE	de	203.1	**CD**	**c**

[w]Analyses were done with one factor, treatment, in the model (i.e. one-way analysis), as well as with "schedule" and "fungicide program" listed as two separate factors (i.e. two-way analysis).

[x]Column means with a letter in common are not significantly different (least significant difference (LSD) test; α=0.05).

[y]Treatment means are reported as the geometric means, as the one-way and two-way analyses were done on the natural-log-transformed data.

[z]The SAS LINES display did not reflect all significant comparisons. The following additional pair is significantly different: (BQ, calendar; FSM, TOM-CAST 25DSV), where BQ = Bravo WeatherStik alternated with Quadris and FSM = Fontelis alternated with Switch alternated with Merivon.

Table 12. One-way[x] and two-way[x] comparisons of 2015 and 2016 yield values for each of the ten treatments.

Application schedule	Yield 2015[y]			Yield 2016[z]		
		One-way	Two-way		One-way	Two-way
Untreated control	21.1	a	-	17.7	d	-
Bravo WeatherStik SC 2 pt alternated with Quadris SC 15.5 fl oz						
7- to 10-day intervals	21.7	a	a	26.2	a	a
TOM-CAST 15 DSV	22.2	a	a	22.1	bc	bc
TOM-CAST 25 DSV	21.7	a	a	19.6	**cd**	**c**
Quadris SC 15.5 fl oz alternated with Fontelis SC 24 fl oz						
7- to 10-day intervals	21.2	a	a	22.1	**b**	**bc**
TOM-CAST 15 DSV	22.8	a	a	21.1	bc	bc
TOM-CAST 25 DSV	22.1	a	a	22.6	b	b
Fontelis SC 24 fl oz alternated with Switch WG 14 oz alternated with Merivon SC 5 fl oz						
7- to 10-day intervals	23.3	a	a	22.7	b	b
TOM-CAST 15 DSV	22.0	a	a	22.4	b	b
TOM-CAST 25 DSV	22.2	a	a	21.9	bc	bc

[x]Analyses were done with one factor, treatment, in the model (i.e. one-way analysis), as well as with "schedule" and "fungicide program" listed as two separate factors (i.e. two-way analysis).
[y]Column means with a letter in common are not significantly different (Tukey test; α=0.05).
[z]Column means with a letter in common are not significantly different (least significant difference (LSD) test; α=0.05).

Table 13. Simple effects of fungicide programs and application schedules for area under the disease progress curve (AUDPC) for Horsfall-Barratt petiole ratings, 2015.

Treatment simple effects	AUDPC	F value*	*P* value*
Fungicide program	-	-	-
Bravo WS alt. Quadris	89.3	1.37	0.2738
Quadris alt. Fontelis	85.5	2.53	0.1003
Fontelis alt. Switch alt. Merivon	83.7	2.75	0.0838
Application interval	-	-	-
7- to 10-day interval	84.0	3.12	0.0625
TOM-CAST 15-DSV	84.3	1.99	0.1589
TOM-CAST 25-DSV	90.1	0.71	0.5011

**P* values and F values are from "Tests of Effect Slices for fung*sched" tables in SAS, GLIMMIX procedure output. The *P* values for "fungicide program" are sliced by "fung," while the *P* values for application schedule sliced by "sched."

Table 14. Simple effects of fungicide programs and application schedules for area under the disease progress curve (AUDPC) for Horsfall-Barratt foliar ratings, 2015.

Treatment simple effects	AUDPC	F Value*	*P* value*
Fungicide program	-	-	-
Bravo WS alt. Quadris	131.3	2.12	0.1424
Quadris alt. Fontelis	109.4	1.87	0.1759
Fontelis alt. Switch alt. Merivon	110.5	1.18	0.3250
Application interval	-	-	-
7- to 10-day interval	110.8	2.35	0.1170
TOM-CAST 15-DSV	114.9	6.66	0.0050
TOM-CAST 25-DSV	125.4	3.79	0.0372

**P* values and F values are from "Tests of Effect Slices for fung*sched" tables in SAS, GLIMMIX procedure output. The *P* values for "fungicide program" are sliced by "fung," while the *P* values for application schedule sliced by "sched."

Table 15. Simple effects of fungicide programs and application schedules for area under the disease progress curve (AUDPC) for petiole health ratings, 2015.

Treatment simple effects	AUDPC	F value*	*P* value*
Fungicide program	-	-	-
Bravo WS alt. Quadris	73.5	0.92	0.4341
Quadris alt. Fontelis	65.6	2.04	0.1979
Fontelis alt. Switch alt. Merivon	63.9	7.18	0.0152
Application interval	-	-	-
7- to 10-day interval	64.8	4.47	0.0314
TOM-CAST 15-DSV	65.6	1.13	0.3505
TOM-CAST 25-DSV	72.6	1.54	0.2492

**P* values and F values are from "Tests of Effect Slices for fung*sched" tables in SAS, GLIMMIX procedure output. The *P* values for "fungicide program" are sliced by "fung," while the *P* values for application schedule sliced by "sched."

Table 16. Simple effects of fungicide programs and application schedules for yield, 2015.Table 16.

Treatment simple effects	AUDPC	F value*	*P* value*
Fungicide program	-	-	-
Bravo WS alt. Quadris	21.9	0.14	0.8729
Quadris alt. Fontelis	22.1	0.92	0.4133
Fontelis alt. Switch alt. Merivon	22.5	0.69	0.5089
Application interval	-	-	-
7- to 10-day interval	22.1	1.70	0.2048
TOM-CAST 15-DSV	22.3	0.26	0.7755
TOM-CAST 25-DSV	22.0	0.12	0.8906

**P* values and F values are from "Tests of Effect Slices for fung*sched" tables in SAS, GLIMMIX procedure output. The *P* values for "fungicide program" are sliced by "fung," while the *P* values for application schedule sliced by "sched."

Table 17. Simple effects of fungicide programs and application schedules for area under the disease progress curve (AUDPC) for Horsfall-Barratt petiole ratings, 2016.

Treatment simple effects	AUDPC	F value*	*P* value*
Fungicide program	-	-	-
Bravo WS alt. Quadris	208.5	6.42	0.0059
Quadris alt. Fontelis	197.8	0.40	0.6764
Fontelis alt. Switch alt. Merivon	184.9	10.87	0.0004
Application interval	-	-	-
7- to 10-day interval	195.3	16.22	<0.0001
TOM-CAST 15-DSV	190.8	12.18	0.0002
TOM-CAST 25-DSV	205.2	9.89	0.0007

**P* values and F values are from "Tests of Effect Slices for fung*sched" tables in SAS, GLIMMIX procedure output. The *P* values for "fungicide program" are sliced by "fung," while the *P* values for application schedule sliced by "sched."

Table 18. Simple effects of fungicide programs and application schedules for area under the disease progress curve (AUDPC) for Horsfall-Barratt foliar ratings, 2016.

Treatment simple effects	AUDPC	F value*	*P* value*
Fungicide program	-	-	-
Bravo WS alt. Quadris	225.5	13.97	0.0003
Quadris alt. Fontelis	206.5	0.56	0.5835
Fontelis alt. Switch alt. Merivon	187.6	13.83	0.0003
Application interval	-	-	-
7- to 10-day interval	200.9	46.80	<0.0001
TOM-CAST 15-DSV	200.8	6.62	0.0171
TOM-CAST 25-DSV	218.0	30.46	<0.0001

**P* values and F values are from "Tests of Effect Slices for fung*sched" tables in SAS, GLIMMIX procedure output. The *P* values for "fungicide program" are sliced by "fung," while the *P* values for application schedule sliced by "sched."

Table 19. Simple effects of fungicide programs and application schedules for area under the disease progress curve (AUDPC) for petiole health ratings, 2016.

Treatment simple effects	AUDPC[x]	F value[y]	*P* value[y]
Fungicide program	-	-	-
Bravo WS alt. Quadris	205.5	6.92	0.0042
Quadris alt. Fontelis	191.9	0.23	0.7928
Fontelis alt. Switch alt. Merivon	184.5	3.00	0.0688
Application interval	-	-	-
7-to 10-day interval	193.3	13.59	0.0001
TOM-CAST 15-DSV	189.3	8.79	0.0014
TOM-CAST 25-DSV	198.9	16.87	<0.0001

[x] Values are reported as the geometric means, as the analysis was done on the natural-log-transformed data.

[y] *P* values and F values are from "Tests of Effect Slices for fung*sched" tables in SAS, GLIMMIX procedure output. The *P* values for "fungicide program" are sliced by "fung," while the *P* values for application schedule sliced by "sched."

Table 20. Simple effects of fungicide programs and application schedules for yield, 2016.

Treatment simple effects	AUDPC	F value[*]	*P* value[*]
Fungicide program	-	-	-
Bravo WS alt. Quadris	22.6	13.23	0.0001
Quadris alt. Fontelis	22.0	0.72	0.4967
Fontelis alt. Switch alt. Merivon	22.3	0.16	0.8546
Application interval	-	-	-
7- to 10-day interval	23.6	5.75	0.0091
TOM-CAST 15-DSV	21.8	0.51	0.6043
TOM-CAST 25-DSV	21.4	3.07	0.0650

[*] *P* values and F values are from "Tests of Effect Slices for fung*sched" tables in SAS, GLIMMIX procedure output. The *P* values for "fungicide program" are sliced by "fung," while the *P* values for application schedule sliced by "sched."

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