EVALUATING SUSTAINABLE MANAGEMENT PRACTICES WITH TOMCAST FORECASTING MODEL TO LIMIT STEMPHYLIUM VESICARIUM ON ASPARAGUS FERN

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ABSTRACT

Michigan is the United States' leading producer of asparagus. Purple spot, a foliar disease caused by the fungal pathogen *Stemphylium vesicarium*, renders spears unmarketable and causes premature defoliation of the fern, impacting spear yield and quality. Purple spot is managed by fungicide applications to the fern according to the TOMCAST disease forecaster at 15 disease severity values (DSVs). The goal was to improve management recommendations by i) evaluating 12 fungicides, alternated with chlorothalonil for efficacy under field conditions and ii) evaluating 10-day, TOMCAST 15 DSV and 20 DSV application timings for four fungicides, alternated with chlorothalonil, in 2022 and 2023. Relative area under the disease progress curve (rAUDPC) data indicated that all treatments limited disease compared to the control except for fluopyram + pyrimethanil (2022), and pyrimethanil (2022). For industry standards, azoxystrobin had a lower disease severity than the control. Pydiflumetofen + fludioxonil and fluxapyroxad + pyraclostrobin consistently had the lowest rAUDPC among unregistered fungicides. Data of rAUDPC indicated that all treatments limited purple spot disease compared to the control in 2022 and 2023 except for mancozeb applied according to TOMCAST 20 DSV (2022). For the industry standards, only azoxystrobin applied every 10 days or according to TOMCAST 15 DSV had less foliar disease at the final rating than the control each year. The rAUDPC data for pydiflumetofen + fludioxonil or fluxapyroxad + pyraclostrobin were similar regardless of application timing each year. The TOMCAST 20 DSV treatment received 6 (2022) or 4 (2023) applications and the 10-day treatment received 8 applications each year. The registration of these fungicides could protect asparagus fern from purple spot and reduce the number of applications by 25 to 50% when used with TOMCAST 20 DSV compared to a 10-day treatment.

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LITERATURE REVIEW

Introduction

Asparagus (*Asparagus officinalis* L.) is a perennial vegetable crop that produces tender, edible spears. In 2021, 8,900 acres were harvested across Michigan's 9500 acres of established asparagus. The state ranks first in the U.S. in asparagus production followed by Washington, California, and New Jersey (USDA, NASS 2022). Michigan's production is valued at approximately $22.9 million (USDA, NASS 2022) with most of the crop grown in the west region along Lake Michigan. Michigan's top three asparagus producing counties are Oceana, Van Buren, and Mason (USDA, NASS 2017). Michigan produces asparagus for the fresh and processing (canned or frozen) markets (USDA, NASS 2022). Michigan's production of asparagus for the fresh market in 2021 ranked second nationally with a value of $13.1 million, exceeded only by California (USDA, NASS 2022). In 2021, Michigan ranked first in total state processing output valued at $9.9 million (USDA, NASS 2022).

Asparagus is a member of the family Asparagaceae, although earlier taxonomy classification systems placed it in the Liliaceae family. Other important crops in the Asparagaceae family include hosta, hyacinth, ornamental asparagus, agave, and yucca. *A. officinalis* is the only species of asparagus cultivated for consumption although several other *Asparagus* spp. are grown as ornamentals. Asparagus is classified within the stem vegetable crop grouping. Asparagus spears may be green, white, and purple. Green asparagus is preferred in the U.S. market and white is more popular in Europe. White asparagus is grown in the absence of sunlight but otherwise is similar to green asparagus. Specialty cultivars, including 'Purple Passion', are bred to produce purple spears.

Asparagus is a dioecious perennial plant (Blasberg 1932). In the spring, shoots emerge from the crown and are either harvested or left to develop into fern; spear emergence is optimal

at temperatures between 24.5°C and 33°C (Dean 1999). Unharvested shoots develop into stems and branches emerge from the stem in a whorl like pattern; cladophylls emerge from the branches (Blasberg 1932). Cladophylls are needle-like structures that serve as the primary photosynthetic tissue of the plant, while the true leaves develop into scale leaves with limited function (Blasberg 1932). The foliage comprised of lateral branches and cladophylls are colloquially referred to as the fern, although it is not a true fern (APG III 2009). Once the fern has established, carbohydrates are produced and sent to the storage roots in the crown replenishing the reserves that were depleted during harvest (Robb 1984; Downton and Torokfalvy 1975). Enzyme activity is affected by seasonal changes in temperature, leading to different concentrations of soluble sugars in the spear depending on the time of year (Bhowmik et al. 2001). Kelly and Bai (1999) observed new fern growth in late fall following warmer than average temperatures. In the fall, low temperature and shorter day length result in the senescence of fern tissue (Pressman et al. 1989; Woolley et al. 2002). Long term drought can also induce senescence (Pressman et al. 1989). Drought is utilized as a senescence mechanism in year round asparagus production systems.

The crown is a rhizome with several un-elongated basal internodes of old stems (Blasberg 1932). At the growing tip of the crown, buds of varying size develop and eventually elongate into spears; the bud closest to the last emergent spear is the next to emerge (Blasberg 1932). During the first year of growth the crown develops laterally and storage roots form at the base of the bud clusters. The size of the crown's roots correlate to the size of the emergent spear (Blasberg 1932).

Asparagus seeds are closely planted (15 cm) in sandy loam soil nurseries and grown for one year. During this time, a dense crown develops and is comprised of bud clusters, feeder, and storage roots. Crown transplant is the more common method of transplanting; it uses one year

old crowns dug up in the spring which are stored for a short period of time before being planted in production fields (Phillips et al. 2024). Production fields can also be planted using seedlings transplants; these use seedlings 10- to 14- weeks in age (Phillips et al. 2024). Crowns are transplanted into sandy loam production fields in rows between mid-April to mid-May at a density of 14,000-15,000 crowns per acre (Phillips et al. 2024). During the first two years in the production field a limited harvest occurs to ensure the plant has enough nutrients to develop (Phillips et al. 2024, Shelton and Lacy 1980).

In Michigan, asparagus is harvested twice a day to every four days, depending on the weather, from approximately mid-May through June. Spear harvest depletes storage carbohydrates in the crown (Shelton and Lacy 1980). Marketable spear sizes (> 1 cm in diameter, 12 cm from the tip) are reduced in plots that have been extensively harvested (Shelton and Lacy 1980). Asparagus spears in Michigan are harvested manually by hand snapping the emergent spear at the base of the stem which protects the crown from wounding from mechanical or instrument use. Asparagus plantings may be profitable for 10 to 20 years, but this longevity can be reduced by poor disease management (Elmer et al. 1996).

Commercial asparagus fields are established with crown transplants with 3 to 4 plants/m^2 (Phillips et al. 2024). Michigan asparagus growers typically use insecticides, herbicides, and fungicides (Phillips et al. 2024). Spear pathogens can weaken spear integrity causing wilt or collapse and may cause blemishes resulting in an unmarketable product. Pathogens that impact the fern can cause chlorosis and premature defoliation of the fern, which can reduce the carbohydrate content of crown by reducing the photosynthetic area (Menzies et al. 1992; Conway et al. 1990; Johnson and Lunden 1992). The two primary causes of premature

defoliation in Michigan's asparagus fields are the diseases purple spot incited by *Stemphylium vesicarium* and asparagus rust caused by *Puccinia asparagi* (Elmer et al. 1996).

Diseases of asparagus. Soilborne pathogens limit asparagus production by decreasing crown health, spear production, and eventual causing plant death. Fusarium crown and root rot is caused by several *Fusarium* species: *Fusarium oxysporum* f.sp. *asparagi* (Schlecht.), *F. proliferatum* (Matsush.), and *F. verticillioides*, previously identified as *F. moniliforme* (Seifert et al. 2003; Elmer et al. 1996). *Fusarium* spp. have been identified and classified on asparagus crowns across Michigan several commercial relevant asparagus cultivars (Getson 2021). Phytophthora crown and root rot (*Phytophthora asparagi*) also is prevalent in seedbeds and production fields in Michigan (Saude et al. 2008).

Foliar diseases of primary concern to Michigan growers include rust (*Puccinia asparagi*) (Elmer et al. 1996), and purple spot (*Stemphylium vesicarium,* teleomorph *Pleospora herbarum*) (Lacy 1982). Globally, other foliar diseases include Phomopsis stem blight (*Phomopsis asparagi* Sacc.), Cercospora blight (*Cercospora asparagi* Sacc.), and several asparagus viruses (Elmer et al. 1996). Symptoms of Phomopsis stem blight are characterized as brown/dark red oval lesions on the stem. As the Phomopsis stem blight develops lesions have ashy-white centers, the foliage exhibits symptoms and prematurely defoliates (Elena 2006). Symptoms of Cercospora blight are characterized as gray-tan, oval lesions developing at the base of fern and moving upwards (Cooperman et al. 1986). Viruses include asparagus virus I, asparagus II ilavirus, asparagus virus III, cucumber mosaic virus, and tobacco streak virus (Elmer et al. 1996).

Stemphylium vesicarium. *Stemphylium vesicarium* was first described by Wallroth in 1833 and given the name *Helminthosporium vesicarium* (Wallroth 1833). The current pathogen designation is *Stemphylium vesicarium* (Wallr.) Simmons, teleomorph *Pleospora herbarum,* as

described by E.G. Simmons in 1969 (Simmons 1969). Purple spot, the disease caused by this pathogen, has been reported globally including Australia (Cunnington and Irvine 2005), New Zealand (Falloon 1982), Korea (Han et al. 2019), and the U.S. including Washington (Johnson and Lunden 1986), California (Falloon et al. 1984) and Michigan (Lacy 1982). The pathogen may infect other hosts including sugar beet (Metheny et al. 2022) and onion (Sharma and Sharma 1999). Isolates of *S. vesicarium* from onion can cause disease symptoms on asparagus. The reverse is also true; however, in general, the symptoms were less aggressive when the isolate originates from a different host (Foster et al. 2019). The use of host specific toxins (HSTs) from *S. vesicarium* on asparagus have not been studied, however HSTs from the species have been observed in infection of European pear (Singh et al. 1999).

On asparagus, the purple spot disease causes necrotic lesions on the stem and foliage that reduce photosynthetic capacity of the plant, negatively impacting yield (Menzies et al. 1992). *Stemphylium vesicarium* can infect emergent spears in the spring, causing purple lesions on the outer tissue (Lacy 1982). The pathogen can infect foliage in summer and fall, causing dark brown lesions on stems, branches, and cladophylls. Occasionally referred to as *Stemphylium* leaf spot, the pathogen causes chlorosis and defoliation of the cladophylls (Falloon and Tate 1986). Lesions appear around stomata that have been penetrated with appressoria, and in wounds caused by wind-blown sand and soil, typically on the wind exposed side of the spear (Falloon et al. 1987; Lacy 1982).

Stemphylium vesicarium belongs in the kingdom Fungi, phylum Ascomycota, class Dothideomycetes, order Pleosporales, family Pleosporaceae, and genus *Stemphylium*. The sexual stage of *S. vesicarium* has black pseudothecia (396 μm in diameter) (Falloon et al. 1984), asci (35 x 170 μm) and ascospores (18 x 38 μm) (Simmons 1969). The pseudothecia produce

bitunicate asci containing eight muriform yellow tan ascospores that darken in color as they age (Falloon and Tate 1986). Ascospores are the primary inoculum source and are released from pseudothecia between March and July in response to rainfall events (Hausbeck et al. 1999; Bohlen-Janssen et al. 2018a). Purple spot infections typically occur after rain and wetting events due to the release of ascospores from pseudothecia from increased turgor pressure (Atanasoff 1919). Ascospores or conidia that come in contact with asparagus tissue develop germ tubes, which seek out opened stomata (Falloon et al. 1987). It is unclear the process by which germ tubes recognize opened stomata, but once identified, the germ tube develops an appressorium to penetrate (Falloon et al. 1987). Spears exposed to rain can display purple spot symptoms within 24 hours, highlighting the speed at which *S. vesicarium* can infect asparagus after an infection event (Hausbeck et al. 1999). Ascospores released during rain events incite purple spot outbreaks during spring spear harvest (Granke and Hausbeck 2010). Ascospore concentrations in the atmosphere peak during spring up until early summer in North America, and when temperatures develop from cool to warm in the southern hemisphere (Falloon and Tate 1986; Granke and Hausbeck 2012; Menzies et al. 1992). Purple spot disease development caused by ascospore infection is optimal when temperatures are between 0°C to 20°C following rain events (Falloon et al. 1987).

Ascospore germination rate increases as leaf wetness periods are longer and temperatures fall between 25°C to 30°C (Bohlen-Janssen et al. 2018a). Germination can occur over a wide temperature range, but the length of the germ tube is shorter at lower temperatures, suggesting infection is more effective at warmer temperatures (Bohlen-Janssen et al. 2018a). On pear, *Stemphylium vesicarium* was able to germinate after 60 minutes at optimal temperatures (Llorente et al. 2006). When asparagus fern becomes established after harvest, ascospores can

infect shoots, branches, and fern (Falloon and Tate 1986). Lesions on wounded and non-wounded plants increase as wet periods increase (Hausbeck et al. 1999). *Stemphylium vesicarium* produces conidiophores radially from a basal mass or compactly in a palisade from basal cells (Simmons 1969). The shape of the conidiophore ranges from straight to curved, with some limited branching although the majority of conidiophores are unbranched (Simmons 1969). Conidia are oblong, sometimes inequilateral with 1-5 transverse septa and 1-2 longitudinal septa. Conidia have an average size of 17.7 x 33.4 μm (Simmons 1969) and are released during rainfall and wind events (Bohlen-Janssen et al. 2018b; Falloon and Tate 1986). Optimal conidial germination occurs from 20°C to 30°C, but conidia will only germinate when relative humidity is 98 to 100% (Montesinos and Vilardell 1992). Conidia can spread within or between plantings following wind events (Falloon and Tate 1986). When fern senesces in the fall, pseudothecia begin to develop on debris (Falloon and Tate 1986) and may overwinter. *Stemphylium vesicarium* may also survive on volunteer asparagus seedlings on outskirts of production fields (Elmer et al. 1996).

Puccinia asparagi. *Puccinia asparagi* is in the kingdom Fungi, phylum Basidiomycota, class Pucciniomycetes, order Pucciniales, and family Pucciniaceae. This is another foliar pathogen of concern for Michigan asparagus growers. The pathogen incites rust and impacts asparagus globally (Cheah and Davis 2002; Davis 2002; Elmer et al. 1996; Norton 1913) and was first reported in the U.S. in the Midwest in 1986 (Halsted 1898). This pathogen infects stems and foliage, causing raised pustules of varying colors based on the spore stage, differentiating it from *S. vesicarium* (Elmer et al. 1996). The disease cycle begins in early spring when basidiospores infect emergent spears and produce pycnia (Elmer et al. 1996). The pycnia form light green lesions (6 x 16 mm) on spear and stem tissue (Elmer et al. 1996). Orange aecia

develop in the lesions, producing aeciospores which are dispersed via wind to adjacent foliage (Elmer et al. 1996). Infecting aeciospores develop into red uredinia, which are primarily present in established foliage (Elmer et al. 1996). In the late fall, the pathogen develops telia, and the teliospores overwinter in crop debris (Elmer et al. 1996). Consecutive years of premature defoliation from *P. asparagi* infection can lead to cumulative yield losses (Elmer et al. 1996). Yield reductions in 'Mary Washington' asparagus plantings were 19% in year one, but increased to 50% after two years of consecutive infection (Johnson and Lunden 1992). Weight and spear number of susceptible cultivars can be reduced after one year of infection (Johnson and Lunden 1992). Two consecutive years of infection can reduce the total weight of yield in slow rusting cultivars (Johnson and Lunden 1992).

Foliar disease management. Historically, the captafol fungicide was used to control for *S. vesicarium* on asparagus in New Zealand but was withdrawn for food use in the 1980s (Menzies et al. 1992). Another historical control option was tillage. Following fern senescence in the fall growers would incorporate fern debris into their soil using tillage, however this practice was discontinued due to the injuries it caused crown tissue, enabling soilborne pathogens such as *Fusarium oxysporum* f. sp. *asparagi* to infect (Putnam and Lacy 1977; Elmer et al. 1996). The adoption of a no-till system exacerbated purple spot, due to the surface level inoculum sources. Other methods of fern debris management have been explored, but have been found to impact plant health in the long term (Kelly and Bai 1999). Herbicide use to break down debris has been evaluated, but have been reported to have a negative impact on fern health and subsequent yield (Rodriguez-Salamanca et al. 2012).

Volunteer seedlings may serve as an inoculum source for *S. vesicarium* and may lead to infection on established fern in production fields (Elmer et al. 1996). Cover crops and wind

barriers can prevent wounding from soil abrasion to the wind-facing side of asparagus plantings thereby reducing the number of *S. vesicarium* infections (Elmer et al. 1996). *Stemphylium vesicarium* has also been isolated from necrotic rye tissue, a common cover crop planted in autumn to prevent wind erosion of asparagus (Foster et al. 2019). Currently no cultivars are resistant to *S. vesicarium,* but some cultivars displayed a lower rate of defoliation (Foster and McDonald 2018b). Other cultivars appear to be tolerant, but it is unclear if this is a result of climate rather than genetic resistance (Falloon and Tate 1986). Cultivars can respond differently to fungicide programs; this is suspected to be as a result of fern density (Meyer et al. 2000). 'Guelph Millennium' which is commonly grown in Michigan was not among the cultivars with a reduced rate of defoliation (Foster and McDonald 2018b). It is speculated that variation in tolerance to purple spot is, in part, due to fern growth; cultivars with short compact fern might provide a microclimate that favors pathogen development (Broadhurst 1996). Disease susceptibility varies among *Asparagus* spp. with several species exhibiting more tolerance to *Stemphylium* spp. than *Asparagus officinalis* (Bansal et al. 1986).

Fungicide management is the primary method for purple spot disease control. Although fungicide diversity is limited for asparagus foliar applications, the main products include the protectants chlorothalonil and mancozeb, as well as the systemic azoxystrobin (Hausbeck et al. 2008; Foster and McDonald 2018b). Evaluation of fungicides found that chlorothalonil is effective in purple spot disease control (Hausbeck et al. 2008). Mancozeb and trifloxystrobin are also registered for asparagus (Phillips et al. 2024). Although protectant fungicides have reduced concerns for resistance development, these fungicides are limited to the plant surface and do not offer long lasting control (Lukens 1971).

Azoxystrobin fungicides, classified as strobilurins, effectively reduce disease severity (Foster and McDonald 2018b). However, resistance to strobilurin fungicides by *Stemphylium vesicarium* has been reported in pear orchards in Spain (Alberoni et al. 2010a). *Stemphylium vesicarium* was also found to be resistance to dicarboximide fungicides in Italian pear orchards (Alberoni et al. 2010b). In New York, *S. vesicarium* isolates on onion were found to be insensitive to strobilurin fungicides, including pyraclostrobin and azoxystrobin (Hay et al. 2019). Fungicides with a demethylation inhibitor (DMI) and quinone outside inhibitors (QoI) mode of action provided effective control against foliar pathogens of asparagus (Foster and McDonald 2018b). Fungicides applied with TOMCAST were able to reduce 3-5 applications yearly compared to a 7-day application interval (Hausbeck et al. 2008).

Puccinia asparagi disease management includes sanitation and cultural controls which can be useful in limiting exposure to infection. The removal of spears through spring to early summer can prevent aecia development, but young plantings that cannot be harvested are at risk for becoming an inoculum source to adjacent fields (Elmer et al. 1996). There are no current cultivars that are completely resistant to *Puccinia asparagi,* but several cultivars have displayed a slow rusting phenotype (Foster and McDonald 2018b). However, one of the most common cultivars used in Michigan, 'Guelph Millennium', did not display the slow rusting phenotype (Foster and McDonald 2018b). Control of *Puccinia asparagi* includes tebuconazole alternated with chlorothalonil (Hausbeck et al. 2008). Mancozeb and azoxystrobin are also registered for rust control on asparagus (Phillips et al. 2024).

Fungicide chemistries. Fungicides are often classified as systemic or protectants. Systemic fungicides are capable of apoplastic and/or symplastic motility. However, literature sometimes refers to acropetal movement as a trait of systemic fungicides (Hewitt 1998).

Protectants are applied preventively targeting the early stages of infection including germination and penetrations as they cannot penetrate the plant tissue or interact with the pathogen once it has entered the plant; they are only effective when applied before infection (Hewitt 1998). These modes of action are identified and grouped by the Fungicide Resistance Action Committee (FRAC). Fungicides are identified with a FRAC code, which signals how the fungicide interacts with the pathogen. Fungicides can target several aspects of a pathogen (multi-site), a single aspect of the pathogen (single site) or interact with the host to boost plant defenses (Hewitt 1998).

Resistance is a serious issue in fungicide programs and can lead to a reduction in economic viability. Resistance is primarily an issue for systemic single-site inhibitors (Hewitt 1998). Fungicide resistance can be quantitative, where a pathogen displays lower sensitivity, as a result higher rates of the fungicide are required to maintain the previous level of control (Hewitt 1998). Qualitative resistance occurs when the pathogen displays complete resistance to a product, even at higher rates. Pathogens are considered field resistant when levels of resistance and frequency are high and consistent (Hewitt 1998). The development of resistant pathogens is an expected evolutionary process when environmental conditions and genetic variance are abundant (Hewitt 1998).

Multi-site fungicides are commonly used by Michigan growers. Chlorothalonil (FRAC M05) is a multi-site fungicide and is recommended to be sprayed in alternation with products from other groups to reduce the risk of resistance development (Brent and Hollomon 2007). A docket from EPA 'EPA-HQ-OPP-2011-0840' is proposing a reduced limit for chlorothalonil on asparagus for the season. This change in policy could result in fewer applications or applications at a lower rate for asparagus growers. The docket and proposed change will have disease control

implications for Michigan growers. Mancozeb (FRAC M03) is classified as an ethylene bis-dithiocarbamate (EBDC) and is a multi-site fungicide registered for asparagus. Some processors have refused to purchase asparagus spears if EBDC fungicides were applied to the fern during the previous year (Hausbeck et al. 2008). Mancozeb has been found to alter human KCNQ2 potassium channels, which can lead to neurotoxicity and neurodegeneration (Li et al. 2013).

Azoxystrobin (FRAC 11) is classified as a QoI fungicide. It is a single site fungicide with a high risk of the pathogen developing resistance. Azoxystrobin is part of a group of fungicides referred to as strobilurin fungicides. Strobilurins are antifungal compounds discovered from the basidiomycete, *Strobilurus tenacellus* (Anke et al. 1977). Strobilurins inhibit the mitochondrial electron transport chain, resulting in less energy for the pathogen (Becker et al. 1981). QoI fungicides target a broad spectrum of fungi pathogens, but resistant fungi develop cross resistance to all strobilurin fungicides (Damicone and Smith 2009).

QoI fungicides have been effective for controlling asparagus foliar diseases (Hausbeck et al. 2008; Foster and McDonald 2018b). However, strobilurin resistance is of high concern. *Stemphylium vesicarium* resistance to strobilurins have been reported in both onion and pear (Hay et al. 2019; Alberoni et al. 2010a). In addition, insensitivity to strobilurin in *Stemphylium solani* isolates on tomato have also been reported (Lin and Fan 2023). Although azoxystrobin is currently effective at managing purple spot, with limited options for rotation, fungicide resistance development is inevitable.

Tebuconazole (FRAC 3) is classified as a DMI fungicide. DMI fungicides are site specific and target a variety of foliar and soilborne pathogens. In onions, fungicides within the DMI group were found to inhibit *S. vesicarium* growth (Mishra and Singh 2017). The mode of action is the disruption of sterol synthesis which prevents pathogen growth (Damicone and Smith

2009). Triazoles, a group within the DMI fungicides, kill the pathogen through sterol synthesis inhibition (Kwok and Loeffler 1993). Although pathogens can develop resistance to DMI fungicides, it comes at the cost of a fitness penalty, making resistance management possible (Damicone and Smith 2009).

Group 7 fungicides are classified as Succinate dehydrogenase inhibitors (SDHI). Their efficacy against *Stemphylium* spp. of garlic has been studied (Galvez et al. 2016). SDHI fungicides target mitochondrial respiration by blocking the pathogen's transporting of electrons to ubiquinone sites (Avenot and Michailides 2010). SDHI fungicides are classified as a medium to high risk for pathogen resistance development (FRAC 2022). Resistance to SDHI fungicides have been reported in two pathogens; *Botrytis cinerea* and *Fusarium asiaticum* (Li et al. 2022; Chen et al. 2021).

Phenylpyrroles are a fungicide group classified in a FRAC Group 12. Fludioxonil, a fungicide in FRAC group 12, is a non-systemic surface fungicide (Kilani and Fillinger 2016). The fungicide induces stress and death via hyperactivation of the high osmolarity glycerol pathway (Jacob et al. 2015). Phenylpyrroles are designated to be low to medium risk for pathogen resistance development (FRAC 2022). *Stemphylium solani* has been reported to be insensitivity to phenylpyrroles (Wu et al. 2015).

Anilino-pyrimidine fungicides (AP fungicides) are classified in FRAC group 9. Pyrimethanil, a fungicide within FRAC 9, has been demonstrated to inhibit the ability of the pathogen to secrete cell wall degrading enzymes at a post-translational stage (Milling and Richardson 1995).

Biological control may use antagonist species to outcompete pathogens, produce or secrete anti-fungal chemicals, or induce resistance or growth in host plants (Hewitt 1998).

Currently there are no registered biocontrol options available to control purple spot disease in Michigan.

Disease forecasting. Disease forecasting utilizes models to predict how a pathogen develops over time and environmental conditions. The objective of these models is oftentimes to reduce the number of fungicide applications needed for control or to measure population growth. Reduced applications can reduce the risk of exposure to the applicator, fungicide resistance, management cost (Hewitt 1998). Models use a set of variables to calculate and predict disease risk and increase. Forecasting requires historical datasets to determine environmental conditions for optimal pathogen development (Campbell and Madden 1990). Depending on the objective of the forecaster, initial inoculum or pathogen development can be vital parameters of the model (Campbell and Madden 1990). In order for a forecaster to be adopted by growers it must have its value demonstrated (Campbell and Madden 1990). Successful forecasters are reliable, easy to use, and have visible cost effectiveness (Campbell and Madden 1990).

In Michigan, asparagus growers utilize the disease forecaster TOMCAST as a purple spot disease management tool (Meyer et al. 2000). TOMCAST was derived from a previous forecaster called FAST. FAST is a disease forecasting model developed to time fungicide applications on tomato for control of *Alternaria solani,* the causal agent for early blight disease (Madden et al 1978).

FAST utilized two models to identify periods of environmental conditions that favored disease development and looked at several parameters including leaf wetness duration, average temperature during leaf wetness, relative humidity, and rainfall (Madden et al. 1978). FAST uses a second model to derive daily severity-rating values based on average air temperature and hours of relative humidity over 90% from the previous five days, and rainfall from the past seven days

(Madden et al. 1978). Early sensors were limited in their accuracy, and the use of two models made application complicated, highlighting the need for a streamlined and accessible model (Pitblado 1992).

In the 1990's TOMCAST was developed from FAST, taking leaf wetness duration and temperature during leaf wetness periods to calculate a daily disease severity value (DSV) (Pitblado 1992). As DSVs accumulate, a predetermined threshold is reached and an application is recommended, resetting the counter to 0. The disease models generated fewer applications while providing similar levels of disease control compared to a timed application (Madden et al. 1978). Temperature and moisture conditions for the germination of *S. vesicarium* are similar to that of *Alternaria solani*, suggesting FAST could be useful in predicting *S. vesicarium* disease development (Montesinos and Vilardell 1992). The simple metrics by which FAST evaluates disease pressure led Montesinos and Vilardell (1992) to evaluate its efficacy for control of *S. vesicarium* on pear. Applications with FAST resulted in a similar level of control to the 7-day application schedule with nine fewer applications (Montesinos and Vilardell 1992).

TOMCAST. Historically, Michigan growers applied fungicides to asparagus fern using a calendar-based program. However, the variability in disease severity from year to year and the fungicide cost made management expensive and time consuming (Meyer et al. 2000). TOMCAST was designed from the FAST model and used one of the two models from FAST to assign a DSV (Pitblado 1992). Fungicides applied at different DSV thresholds were evaluated for anthracnose control on tomato and were found to provide effective management with fewer overall applications (Pitblado 1992). This model performed better due to advances in sensor equipment; leaf wetness sensor development increased the accuracy of the model (Pitblado 1992). Although TOMCAST was designed for tomato, it has been verified to manage *Alternaria*

dauci and *Cercospora carotae* on carrot (Dorman et al. 2009) and *Septoria apiicola* on celery (Bounds and Hausbeck 2008). TOMCAST is flexible due to its simple input, making it accessible to a wide population.

The TOMCAST model evaluates weather data over the course of 24 hours, assigning a DSV at 1100 hr each day. Daily values can range from 0-4 based on leaf wetness periods in hours and the mean temperature during leaf wetness periods. DSVs calculated at 1100 hr include the wetness period of night and morning dew period into a single day. Warmer temperatures and longer leaf wetness periods result in higher DSVs (Madden et al. 1978). DSVs accumulate after each day; once the DSVs have reached a determined threshold, a grower spray is recommended and the cumulative DSVs are reset to 0.

Meyer et al. (2000) evaluated TOMCAST to time fungicide sprays on two asparagus cultivars. Chlorothalonil applied using TOMCAST decreased disease severity and increased stand count and size compared to applications on a 14-day schedule. Using TOMCAST did not result in exceeding the maximum application amount whereas the 7-day schedule did (Meyer et al. 2000). The efficacy of TOMCAST was variable, depending on the fungicide and cultivar (Meyer et al. 2000). The optimal threshold of application could vary depending on a cultivar's disease susceptibility and the efficacy of a fungicide product. Meyer et al. (2000) examined the two contact fungicides that were registered for asparagus at the time. Currently, it is recommended that growers use TOMCAST with fungicide applications occurring at 15 DSV (Meyer et al. 2000; Hausbeck et al. 2008).

TOMCAST is designed for an annual crop, and the buildup of inoculum in a perennial crop over the years is not factored into the model (Foster and McDonald 2018a). Cultivar susceptibility to purple spot is a factor in determining the optimal DSV threshold as susceptible

cultivars require fungicide sprays at lower thresholds compared to less susceptible cultivars (Foster and McDonald 2018a).

The disease forecaster TOMCAST utilizes leaf wetness duration to calculate DSVs, requiring a sensor to determine when the fern is wet. Leaf wetness sensors vary in shape and form. Electric sensors measure changes in electrical resistance using a circuit grid. However, there is variability in sensors making a standardized detection method difficult. The evaporation rate of sensors can be dependent on color, angle, and size of the sensor (Gillespie and Kidd 1978). Physical orientation of sensors can also influence evaporation rate, including height and direction of the sensor (Sentelhas et al. 2004). The customization of leaf sensors means they can be altered to increase or decrease the threshold that 'wet' is confirmed. The customization and lack of standard in measuring leaf wetness can lead to difficulties when using established disease forecasters with new equipment.

Historically, asparagus foliar applications ended in early September, prior to frost when night temperatures fell below 12.8°C. In recent years warm temperatures have persisted into September (NOAA, NCEI 2024). Conidial concentrations can peak in August and September and concentrations are influenced by warm temperatures (Bohlen-Janssen et al. 2018b; Granke and Hausbeck 2012). This presents a potential upcoming challenge for asparagus growers, as historical end dates for application intervals become premature and disease pressure persists. This problem is compounded by the low number of registered fungicides available; expanding treatment beyond the historical end date would require more fungicide applications. Resistance and economic concerns are of primary focus for growers. The need for effective fungicides and forecasters to optimize applications will enable growers to spend less time and money on disease management with similar effective control.

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CHAPTER 1: EVALUATION OF FUNGICIDES FOR CONTROL OF *STEMPHYLIUM VESICARIUM* ON ASPARAGUS FERN

Abstract

Purple spot, a fungal disease caused by *Stemphylium vesicarium*, renders spears unmarketable and on the fern, causes premature defoliation which can decreases next year's yield and quality. Fungicides, including azoxystrobin, mancozeb, and chlorothalonil, are applied to the foliage according to the TOMCAST disease forecaster at 15 disease severity values (DSVs) in order to manage purple spot disease. The objective of our study was to identify fungicides that control purple spot disease on asparagus fern. The ability of fungicides to provide extended protection was of interest. Twelve fungicides, alternated with chlorothalonil, were applied every 10 days and evaluated and compared to an untreated control in 2022 and 2023. Relative area under the disease progress curve (rAUDPC) data indicated that all treatments within and beyond the interval period limited purple spot disease compared to the control except for fluopyram + pyrimethanil (2022), and pyrimethanil (2022). For industry standards, azoxystrobin had a lower disease severity than the control both within and beyond the treatment interval. Pydiflumetofen + fludioxonil, and fluxapyroxad + pyraclostrobin consistently had the lowest rAUDPC among unregistered fungicides within and beyond the treatment interval. The registration of new fungicides can protect the fern from purple spot and expand management options for growers.

Introduction

Michigan is the nation's leading producer of the perennial crop asparagus (*Asparagus officinalis* L.) for both the fresh and processing industries. In 2022, the total value from Michigan's asparagus industry was $22.9 million (USDA, NASS 2022). Other important asparagus production states include Washington, California, and New Jersey. In 2021, Michigan growers planted and harvested 9,800 and 9,200 acres of asparagus, respectively (USDA, NASS

2022). Production is concentrated in the state's lower peninsula along Lake Michigan where sandy loamy soils are prevalent.

Purple spot, a fungal disease caused by the ascomycete *Stemphylium vesicarium* (Wallr.) E.G. Simmons (teleomorph *Pleospora herbarum* (Pers. Ex Fr.) Rabenh.), is the primary foliar disease of concern for Michigan's asparagus growers. This disease is sometimes referred to as Stemphylium leaf spot when it impacts the asparagus fern (Foster and McDonald 2018). The pathogen causes purple lesions on emerging spears in the spring, rendering them unmarketable (Lacy 1982). *Stemphylium vesicarium* also causes necrotic lesions on the stem, branches, and cladophylls (Menzies et al. 1992). Dark brown lesions on the fern (a colloquial term for the branches and cladophylls of a mature asparagus planting) can lead to premature defoliation (Falloon and Tate 1986). Foliage of an asparagus plant replenishes nutrients expended during spear production; premature defoliation can lead to a reduction in yield (Conway et al. 1990; Johnson and Lunden 1992; Menzies et al. 1992).

Pseudothecia overwintering on asparagus debris release ascospores during rain events; infection of spears and fern typically occurs after rain or wetting events (Atanasoff 1919; Hausbeck et al. 1999). Since harvestable spears in spring are primarily infected by ascospores, growers can anticipate potential disease outbreaks following rainfall (Hausbeck et al. 1999). Atmospheric ascospore concentrations peak from spring to early summer in North America (Falloon and Tate 1986; Granke and Hausbeck 2012). In the southern hemisphere, ascospore concentrations follow a similar trend, increasing as temperatures begin to warm (September to January) and decreasing during the hottest months (February to April) (Menzies et al. 1992). Ascospores germinate and produce germ tubes at temperatures from 25°C to 30°C (Bohlen-Janssen et al. 2018a). On pear, optimal temperatures prompted *S. vesicarium* germination in 1

hour (Llorente et al. 2006). After germination, the ascospore develops an appressorium which may penetrate via stomata or wounds (Falloon et al. 1987).

In Michigan, atmospheric conidial concentrations of *S. vesicarium* are low during the spring and increase as the season progresses (Hausbeck et al. 1999). Atmospheric concentrations of conidia exhibit a diurnal periodicity with concentrations peaking from 0700 to 1300 h (Granke and Hausbeck 2010). Conidial germination requires high relative humidity (98 to 100%), and growth is optimized when temperatures range from 20°C to 30°C (Montesinos and Vilardell 1992). Conidial germ tube growth is optimized at 28.7°C, with tube length increasing with leaf wetness duration (Bohlen-Janssen et al. 2018b). High conidial concentrations have been linked to increased purple spot disease severity (Granke and Hausbeck 2010).

Michigan's asparagus growers have relied on fungicides to limit purple spot on the fern since adopting a no tillage production system. Historically, fields were tilled following fern senescence in the fall; however, this practice damaged crown tissue, making the plant susceptible to Fusarium crown and root rot caused by *Fusarium oxysporum* f. sp. *asparagi* (Putnam and Lacy 1977; Elmer et al. 1996). Without tillage, the asparagus fern is chopped in the fall or spring and left on the soil surface facilitating the overwintering of the pathogen and acting as a reservoir for primary inoculum. Managing the debris without jeopardizing long term plant health is challenging and options are limited (Kelly and Bai 1999). Although herbicides can be used to breakdown debris, some herbicides have been linked to a negative impact on fern health with yield reduction implications (Rodriguez-Salamanca et al. 2012).

Fungicides currently registered for purple spot control on asparagus fern include the protectant fungicides chlorothalonil and mancozeb, and the locally systemic fungicide azoxystrobin (Hausbeck et al. 2008; Foster and McDonald 2018). Fungicide Resistance Action

Committee (FRAC) classifies *S. vesicarium* at medium risk of developing resistance to fungicides (FRAC 2019). Protectant fungicides remain on the plant's surface and do not typically offer long lasting control (Lukens 1971) and are generally not considered to prompt pathogen resistance (Hewitt 1998). Azoxystrobin, a group 11 fungicide, is a Quinone outside inhibitor (QoI) and is at an increased risk for resistance development due to the broad spectrum of pathogens targeted (Damicone and Smith 2009). Resistance to strobilurin fungicides has been reported in *S. vesicarium* collected from Italian pear orchards (Alberoni et al. 2010a) and New York onions (Hay et al. 2019). Additionally, *S. vesicarium* isolates from Italian pear orchards were resistant to dicarboximide fungicides (Alberoni et al. 2010b).

Michigan's asparagus growers adopted the disease forecaster TOMCAST as a tool to manage purple spot disease (Meyer et al. 2000). TOMCAST uses the duration of leaf wetness periods and the average temperature during the leaf wetness periods to determine a daily disease severity value (DSV) (Pitblado 1992). After 1100 h each day, the TOMCAST model establishes a DSV calculated using weather data from the previous 24 hours. The DSVs accumulate until a predetermined threshold is reached and a fungicide application recommended. When used as a management tool for *S. vesicarium* on asparagus fern, TOMCAST reduced the number of fungicide applications without sacrificing disease control (Meyer et al. 2000).

Michigan growers typically discontinue fungicide applications to the asparagus fern in early September as night temperatures cool, limiting purple spot disease. In recent years, average September temperatures have increased (a trend of +1.4 °F) prompting continued disease development (NOAA, NCEI 2024). Airborne conidial concentrations of *S. vesicarium* peak in late August to September and favorable temperatures coupled with extended dew periods may prompt disease escalation (Bohlen-Janssen et al. 2018b; Granke and Hausbeck 2012) at time

when growers have stopped protecting the crop. Evaluating fungicides for their ability to provide extended control and limit purple spot disease beyond the final application could be helpful, reducing the number of applications required to protect the fern through the fall. The objective of our study was to identify fungicides that control purple spot disease on asparagus fern. The ability of fungicides to provide extended protection was of interest.

Materials and Methods

Plot establishment and experimental design. Field trials were conducted in a commercial grower's 'Sequoia' asparagus field in Oceana County, Michigan in 2022 and 2023. The field had been established in 2011 in sandy loam soil. Insects and fertilization were managed by the grower cooperator each year of the trial. Each year, the trial was established as a randomized complete block design with four replications per treatment. Each treatment plot was 6.1 m in length and comprised of a single row of asparagus separated by at least a 1.5 m buffer between treatments within the row. Treatment rows were separated from each other by unsprayed rows.

Treatment initiation and application. Twelve fungicides were evaluated and compared to an untreated control in 2022 and 2023 (Table 1.1). Each fungicide treatment was alternated with chlorothalonil. Fungicide applications were initiated after the harvest concluded and the fern was fully emerged on 7 July (2022) and 28 June (2023) but before purple spot symptom development. Applications were made with a backpack sprayer calibrated to 241.3 kPa with three XR8003 flat-fan nozzles spaced 45.7 cm apart, delivering approximately 467.7 L/hectare. Each year, applications were made every 9 to 11 days on 7, 18, 28 July; 9, 18, 29 August; and 9 September 2022 and 29 June; 7, 17, 28 July; 7, 18, 28 August; and 7 September 2023. An exception occurred with pydiflumetofen + fludioxonil which was initially applied at a rate of

11.4 fl oz/acre on 7 and 28 July in 2022 before being increased to 13.4 fl oz/acre at the registrant's request. Chlorothalonil applications were made both years on even number sprays.

Table 1.1. Registered and unregistered fungicide products tested for efficacy against *Stemphylium vesicarium* on asparagus fern in field trials.

Product	Active Ingredient	Registrant[z]	Product Rate/Hectare	FRAC[y] Code
Registered				
Manzate® Pro-Stick™	mancozeb	UPL	2.2 kg	M 03
Quadris® Flowable	azoxystrobin	Syngenta Crop Protection	1.1 L	11
Bravo® Weather Stik[x]	chlorothalonil	Adama	2.8 L	M 05
Unregistered[w]				
Aprovia® Top	difenoconazole + benzovindiflupyr	Syngenta Crop Protection	986.6 ml	3/7
Cabrio® EG	pyraclostrobin	BASF Corporation	560.4 g	11
Luna Experience®	tebuconazole + fluopyram	Bayer CropScience, LP	1.2 L	3/7
Luna Sensation®	fluopyram + trifloxystrobin	Bayer CropScience, LP	555.4 ml	7/11
Luna Tranquility®	fluopyram + pyrimethanil	Bayer CropScience, LP	818.5 ml	7/9
Merivon® Xemium® Brand	fluxapyroxad + pyraclostrobin	BASF Corporation	803.9 ml	7/11
Miravis® Prime	pydiflumetofen + fludioxonil	Syngenta Crop Protection	[v]833.1 ml 979.2 ml	7/12
Omega® 500F	fluazinam	Syngenta Crop Protection	1.2 L	29
Scala® Brand SC	pyrimethanil	Bayer CropScience, LP	1.3 L	9
Tanos®	famoxadone + cymoxanil	Corteva Agriscience LLC	560.4 g	11/27

[z]: Registrant: UPL, King of Prussia, PA; Syngenta Crop Protection, Greensboro, NC; Adama, Raleigh, NC; BASF Corporation, Research Triangle Park, NC; Bayer CropScience LP, St. Louis, MO; Corteva Agriscience LLC, Indianapolis, IN.

[y]: Fungicide Resistance Action Committee (http://www.frac.info) FRAC groups are classified by mode of action, the process by which active chemicals inhibit pathogen function. Group classification is used to monitor development of active ingredient resistance in pathogen populations.

[x]: Bravo® Weather Stick was used in alternation with all fungicide treatments tested.

[w]: Product rate for fungicides unregistered for asparagus were calculated using established rates for *Stemphylium vesicarium* control on onion.

[v]: Rate of Miravis® Prime applied on 7 and 28 July 2022, prior to rate recommendation from company.

Disease assessments. Purple spot disease was assessed on 9, 22, 26 August; and 2, 8, 15, 29 September 2022, and 20, 27 July; 10, 18, 31 August; and 7, 21, 28 September 2023. The fern was visually assessed for foliar lesions, chlorosis, and defoliation using a 0 to 100% continuous scale and was used to calculate the area under disease progress curve (AUDPC). Relative AUDPC (rAUDPC) was calculated by standardizing the AUDPC from both years using the methods outlined in Fry (1978) and was used to compare disease progression for treatments across both years. Treatments were compared using rAUDPC, and disease severity ratings.

Statistical analysis. Statistical analysis was performed using RStudio, Version 4.3.2. of R for Apple. Copyright © 2023 by The R Foundation for Statistical Computing, Vienna, Austria. Ratings and relative area under the disease progression curve (rAUDPC) at the date of traditional last application and 14-20 days after last application were analyzed to evaluate treatment efficacy within application period and extended control, respectively. First a linear mixed effects model was made using the lmer function from the lme4 package (Bates et al. 2015) in RStudio. Mixed model analysis consisted of treatment, year, and interactions between treatment and year as fixed effects, blocks nested in treatment and blocks nested in year were treated as random effects. Normality was assessed by evaluating the residual plots generated by the resid_panel function in the ggResidpanel package (Goode and Rey 2022) which also generated a histogram and QQ plot of the residuals. The presence of equal variance was visually assessed using the plot function in RStudio followed by a Levene's test conducted using the leveneTest function from the cars package (Fox and Weisberg 2019). A global analysis of variance (ANOVA) was performed using the Anova() function from the cars package. If the ANOVA F-test was significant, all pairwise comparisons were assessed with the Bonferroni test using the cld function in the multcomp

package (Horthorn et al. 2008). The p-value (<0.05) was used to determine statistical significance.

Results

Within the treatment interval, significant differences of rating and rAUDPC were identified for fungicide, year, and interaction between fungicide and year (Table 1.2). Beyond the treatment interval, significant differences between final rating were found for fungicide products (Table 1.3). Beyond the treatment interval, significant differences between rAUDPC were found for fungicide, year, and interaction between fungicide and year (Table 1.3).

Within application interval. Disease severity in the untreated control increased from <20% to 75-80% from 26 August to 2 September (2022) and from 10 to 18 August (2023) (Fig 1.1 and 1.2). On 8 September 2022 and 7 September 2023, final disease severity in the untreated plots ranged from 83.8 to 87.5% (Table 1.4). In 2022, all fungicides controlled purple spot compared to the untreated control except for fluazinam (63.8% foliar disease), pyrimethanil (77.5% foliar disease), and fluopyram + pyrimethanil (77.5% foliar disease). In 2023, all fungicide treatments had a lower disease severity (3.8 to 35%) compared to the untreated control (87.5%) (Table 1.4). In 2022, fluxapyroxad + pyraclostrobin and pydiflumetofen + fludioxonil (ranged 2.5 to 3.0%) were more effective than difenoconazole + benzovindiflupyr, famoxadone + cymoxanil, fluazinam, mancozeb, fluopyram + pyrimethanil, and pyrimethanil (ranged 33.8 to 77.5%) (Table 1.4). In 2023, pydiflumetofen + fludioxonil was more effective than mancozeb and pyrimethanil.

According to the rAUDPC values, the untreated control had a higher disease severity in 2023 compared to 2022. Based on 2022 rAUDPC data, all fungicides limited purple spot disease compared to the untreated control except for pyrimethanil and fluopyram + pyrimethanil (Table

1.4). All fungicides were more effective than the untreated control according to rAUDPC data in 2023. In 2022, according to rAUDPC data, fluxapyroxad + pyraclostrobin, pydiflumetofen + fludioxonil, and azoxystrobin were more effective than famoxadone + cymoxanil, fluazinam, mancozeb, fluopyram + pyrimethanil, and pyrimethanil (Table 1.4). In 2023, fluxapyroxad + pyraclostrobin and pydiflumetofen + fludioxonil were more effective than fluopyram + pyrimethanil and pyrimethanil based on rAUDPC values.

Beyond application interval. The untreated plots ranged from 87.5 to 94.8% for disease beyond the application interval (29 September 2022 and 28 September 2023), (Table 1.5). In 2022, several fungicide treatments had less disease compared to the untreated control including pydiflumetofen + fludioxonil, fluxapyroxad + pyraclostrobin, azoxystrobin, difenoconazole + benzovindiflupyr, and famoxadone + cymoxanil. All other treatments were similar to the untreated control. In 2023, fungicides with lower disease ratings compared to the untreated control included tebuconazole + fluopyram, pydiflumetofen + fludioxonil, fluxapyroxad + pyraclostrobin, azoxystrobin, difenoconazole + benzovindiflupyr, and pyraclostrobin (Table 1.5).

Disease severity ratings for treatments beyond the fungicide interval did not differ between years (Table 1.3). Based on 2022 rAUDPC values, all fungicides provided disease protection beyond the application interval compared to the untreated control except for fluopyram + pyrimethanil and pyrimethanil. In 2023, all treatments limited disease beyond the application interval compared to the untreated control based on rAUDPC values (Table 1.5). In 2022, based on the rAUDPC values, pydiflumetofen + fludioxonil and fluxapyroxad + pyraclostrobin were more effective in controlling purple spot disease than all other fungicides with the exception of azoxystrobin (Table 1.5). In 2023, the fungicides pydiflumetofen +

fludioxonil and fluxapyroxad + pyraclostrobin were more effective than fluazinam, mancozeb, fluopyram + pyrimethanil, and pyrimethanil.

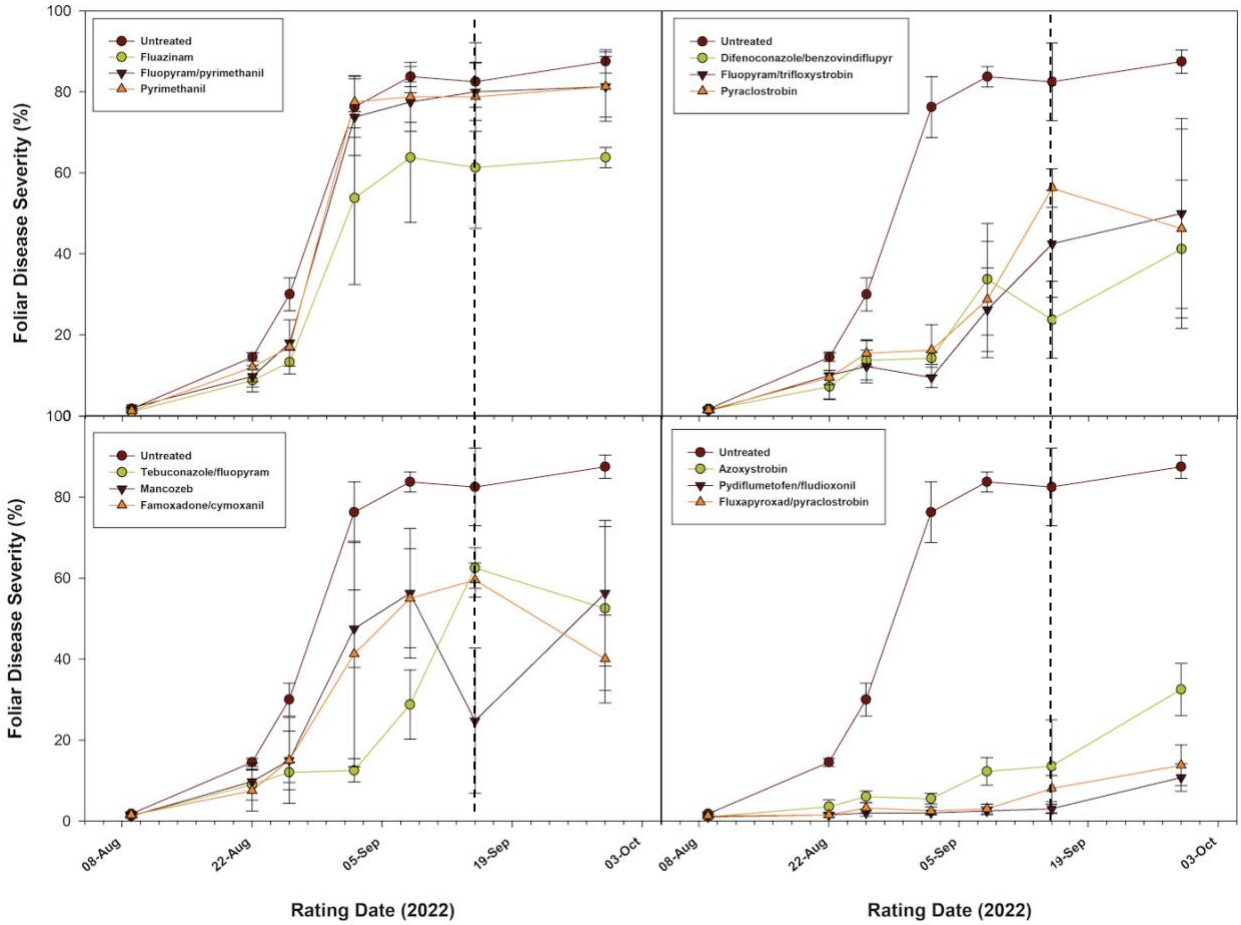

Figure 1.1. Disease progress curves of *Stemphylium vesicarium* on 'Sequoia' asparagus fern when treated with fungicides applied in alternation with chlorothalonil in 2022. Dotted line represents final application (9 Sep).

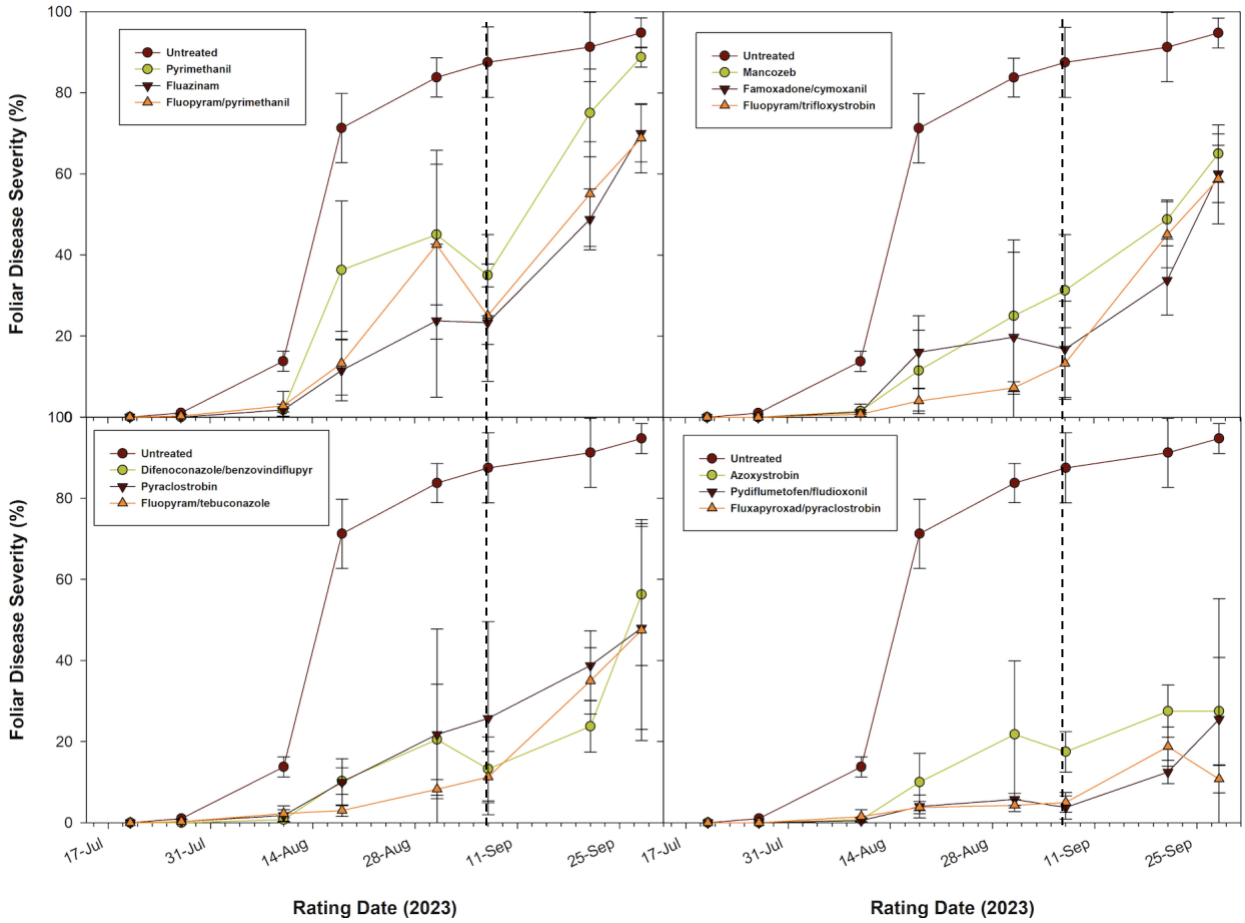

Figure 1.2. Disease progress curves of *Stemphylium vesicarium* on 'Sequoia' asparagus fern when treated with fungicides applied in alternation with chlorothalonil in 2023. Dotted line represents final application (7 Sep).

Table 1.2. Analysis of variance (ANOVA) for the effect of fungicide treatment, year, and interactions between the two on rating date within the application interval and relative area under disease progress curve (rAUDPC).

	Type II Tests of Fixed Effects			
	Degrees of Freedom			
Response Variable/Effect[z]	Numerator	Denominator	*F-value*	*P-value*
Within App. Interval				
fungicide	12	37.5	33.8	<0.0001
year	1	4.6	84.5	0.0004
fungicide*year	12	36.8	8.7	<0.0001
rAUDPC				
fungicide	12	36.4	42.9	<0.0001
year	1	5.6	22.6	0.0038
fungicide*year	12	36.3	5.6	<0.0001

[z]: Within App. Rating: Rating conducted within the application interval (8 Sep 2022 and 7 Sep 2023), rAUDPC calculated from rating dates and visual assessment of disease severity using a 0-100% scale in 2022 and 2023.

Table 1.3. Analysis of variance (ANOVA) for the effect of fungicide treatment, year, and interactions between the two on rating date beyond the application interval and relative area under disease progress curve (rAUDPC).

	Type II Tests of Fixed Effects			
	Degrees of Freedom			
Response Variable/Effect[z]	Numerator	Denominator	*F-value*	*P-value*
Beyond App. Interval				
fungicide	12	38.2	15.5	<0.0001
year	1	3.7	4.2	0.1152
fungicide*year	12	36.5	1.2	0.3104
rAUDPC				
fungicide	12	36.7	63.6	<0.0001
year	1	4.8	75.7	0.0004
fungicide*year	12	36.3	9.9	<0.0001

[z]: Final Rating occurred on 29 Sep 2022 and 28 Sep 2023, rAUDPC calculated from rating dates and visual assessment of disease severity using a 0-100% scale in 2022 and 2023.

Table 1.4: Foliar disease severity and relative area under disease progress curve (rAUDPC) for fungicide treatments within application interval.

		Foliar Disease (%)[z]		rAUDPC	
Treatment[y]	FRAC Code	2022 8 Sep	2023 7 Sep	2022	2023
Untreated	-	83.8 a[x]	87.5 a	**0.34 a**	**0.41 a**
fluxapyroxad + pyraclostrobin	7/11	3.0 f	5.0 bd	0.02 g	0.02 d
pydiflumetofen + fludioxonil	7/12	2.5 f	3.8 d	0.01 g	0.02 d
fluopyram + trifloxystrobin	7/11	26.3 ef	13.3 b-d	**0.10 fg**	**0.03 cd**
tebuconazole + fluopyram	3/7	**28.8 d-f**[w]	**11.3 b-d**	**0.10 fg**	**0.03 cd**
difenoconazole + benzovindiflupyr	3/7	**33.8 c-e**	**13.3 b-d**	0.11 e-g	0.07 cd
azoxystrobin	11	12.3 ef	17.5 b-d	0.04 g	0.08 cd
famoxadone + cymoxanil	11/27	**55.0 b-d**	**16.8 b-d**	**0.19 c-f**	**0.08 cd**
pyraclostrobin	11	28.8 d-f	25.8 b-d	0.12 d-g	0.08 cd
fluazinam	29	**63.8 ab**	**23.3 b-d**	**0.23 b-d**	**0.09 b-d**
mancozeb	M3	**56.3 bc**	**31.3 bc**	**0.21 b-e**	**0.10 b-d**
fluopyram + pyrimethanil	7/9	**77.5 ab**	**25.0 b-d**	**0.30 a-c**	**0.13 bc**
pyrimethanil	9	**77.5 ab**	**35.0 b**	**0.31 ab**	**0.19 b**
P-value		*<0.05*		*<0.05*	

[z]: Based on a visual estimation of the foliage diseased, 0-100% scale with 0=0% foliar disease and 100=100% foliar disease.
[y]: Applications made for all programs except for the untreated control included a chlorothalonil alternation. Number of applications at time of rating 6 (2022) and 7 (2023).
[x]: Columns with letters in common are not statistically different from each other (Bonferroni; *P=0.05).*
[w]:Bold: Rows with bolded values represent significant differences between years for each treatment (Bonferroni; *P=0.05*).

Table 1.5. Foliar disease severity and relative area under disease progress curve (rAUDPC) of fungicide treatments beyond the application interval, at end of season.

		Foliar Disease (%)[z]		rAUDPC	
Treatment[y]	FRAC Code	2022 29 Sep	2023 28 Sep	2022	2023
Untreated	-	87.5 a[x]	94.8 a	0.55 a	0.56 a
pydiflumetofen + fludioxonil	7/12	10.8 e	25.5 de	0.03 g	0.05 e
fluxapyroxad + pyraclostrobin	7/11	13.8 de	10.8 e	0.05 g	0.05 e
tebuconazole + fluopyram	3/7	52.5 a-c	47.5 c-e	**0.28 c-e[w]**	**0.11 de**
azoxystrobin	11	32.5 c-e	27.5 de	0.10 fg	0.12 c-e
difenoconazole + benzovindiflupyr	3/7	41.2 c-e	56.2 b-d	**0.19 ef**	**0.12 c-e**
fluopyram + trifloxystrobin	7/11	81.2 ab	58.8 a-d	**0.23 de**	**0.13 c-e**
famoxadone + cymoxanil	11/27	40.0 c-e	60.0 a-d	**0.33 cd**	**0.15 c-e**
pyraclostrobin	11	81.2 ab	48.0 cd	**0.27 de**	**0.16 c-e**
fluazinam	29	63.8 a-c	70.0 a-c	**0.39 bc**	**0.19 cd**
mancozeb	M3	56.2 a-c	65.0 a-c	**0.29 c-e**	**0.20 cd**
fluopyram + pyrimethanil	7/9	81.2 ab	68.8 a-c	**0.50 ab**	**0.23 bc**
pyrimethanil	9	81.2 ab	88.8 ab	**0.51 ab**	**0.33 b**
P-value		<0.05		<0.05	

[z]: Based on a visual estimation of the foliage diseased, 0-100% scale with 0=0% foliar disease and 100=100% foliar disease. Final disease ratings were taken 20 days (2022) and 21 days (2023) after last application. Total applications were 7 (2022) and 8 (2023).

[y]: Applications made for all treatments except for the untreated control included a chlorothalonil alternation.

[x]: Columns with letters in common are not statistically different from each other (Bonferroni; *P=0.05*).

[w]:Bold: Rows with bolded values represent significant differences between years for each treatment (Bonferroni; *P=0.05*).

Discussion

Purple spot outbreaks in asparagus have occurred in Michigan for over 40 years (Lacy 1982) impacting spear quality and yield and fern health (Meyer et al. 2000). Michigan growers use no-till practices (Kelly and Bai 1999) which allow the overwintering of the pathogen on fern debris left on the soil surface. In the spring, purple spot outbreak during spear harvest are incited by ascospores released during rain events (Granke and Hausbeck 2010). Since fungicides cannot be applied to spears to be harvested it is recommended that Michigan growers limit inoculum levels during the previous year's fern growth period.

While commercial asparagus cultivars are susceptible to purple spot, a previous study showed that cultivars may respond differently to fungicide treatments with fern density playing a role (Meyer et al. 2000). Asparagus is included in the stem vegetable crop grouping and has relatively few registered fungicides available. To control purple spot on the fern, growers apply fungicides after completing the harvest season and the fern has fully developed. Registered fungicides are limited and include azoxystrobin, and the protectants chlorothalonil and mancozeb. Recently, EPA (docket EPA-HQ-OPP-2011-0840-0141) proposed a limit reduction for chlorothalonil in asparagus to 6.5 lb a.i. from 9.0 lb a.i. grown on sandy loam soil, the primary soil type for Michigan asparagus plantings. Michigan growers time their fungicide applications based on the TOMCAST disease forecaster (Meyer et al. 2000) with applications continuing into early September until night temperatures begin to cool (<12.8°C), becoming unfavorable for purple spot disease development (Bohlen-Janssen et al. 2018b). When temperatures remain warm into the Fall, resurgent fern growth can be observed in the field (Kelly and Bai 1999). This was observed in our field trials, causing a temporary decrease in foliar ratings on select dates.

Fungicides are classified based on their mode of action and identified by a FRAC code (FRAC 2022). Fungicides that share a FRAC code are at an increased risk of developing cross resistance. Our study identified fungicides that protected asparagus fern from purple spot during the fungicide application interval and beyond and included pydiflumetofen + fludioxonil (FRAC 7/12), fluxapyroxad + pyraclostrobin (FRAC 7/11), and azoxystrobin (FRAC 11).

In our study, there were six premixed products that contained a FRAC 7 group fungicide. Fungicides in the FRAC 7 group, succinate dehydrogenase inhibitors (SDHI), target the pathogen's ability to respire by blocking the transport of electrons to ubiquinone sites (Avenot and Michailides 2010). These fungicides are at medium to high risk for pathogen resistance (FRAC 2022). Resistance to SDHI fungicides has been reported for *Botrytis cinerea* and *Fusarium asiaticum* (Li et al. 2022; Chen et al. 2021). Within the application interval, all premixed products containing a FRAC 7 group fungicide that were included in our study were more effective than the untreated control for both foliar disease and rAUDPC data for both years with the exception of fluopyram + pyrimethanil (FRAC 7/9) that was similar to the untreated in 2022. Beyond the application interval, programs containing fungicides in the FRAC 7 group were among the most effective. However, there was no program evaluated that contained only a FRAC 7 product, and it remains unclear how effective the chemicals from this class are. Fluxapyroxad + pyraclostrobin, pydiflumetofen + fludioxonil, and difenoconazole + benzovindiflupyr were consistently more effective beyond the application interval than the untreated control based on the foliar disease and the rAUDPC data for 2022 and 2023. According to rAUDPC data from beyond the application interval, tebuconazole + fluopyram and fluopyram + trifloxystrobin reduced disease compared to the untreated in both years. Fluopyram +

pyrimethanil was similar to the untreated control for both years beyond that application interval with the exception of the 2023 rAUDPC data.

The strobilurin fungicides, pyraclostrobin and azoxystrobin (FRAC 11), are quinone outside inhibitors (QoI), with a high risk for pathogen resistance development (FRAC 2022). Azoxystrobin is currently registered for asparagus and effectively controls foliar diseases (Hausbeck et al. 2008; Foster and McDonald 2018). *Stemphylium vesicarium* resistance to strobilurins has been reported in onion (Hausbeck et al. 2019; Hay et al. 2019) and pear (Alberoni et al. 2010a). Strobilurin resistance in *Stemphylium solani*, a pathogen of tomato, has also been reported (Lin and Fan 2023).

We tested five products that included a QoI fungicide (FRAC 11) as a premixed partner or as the sole active ingredient. Within the application interval, all tested products with a FRAC 11 component were more effective than the untreated control based on foliar disease and rAUDPC data for both years. Beyond the application interval, fluxapyroxad + pyraclostrobin (FRAC 7/11) and azoxystrobin (FRAC 11) were consistently effective in 2022 and 2023 based on foliar disease and rAUDPC values. Based on rAUDPC values for 2022 and 2023, fluopyram + trifloxystrobin (FRAC 7/11), famoxadone + cymoxanil (FRAC 11/27), and pyraclostrobin (FRAC 11) were more effective than the untreated control for the period beyond the application interval.

In our study, fludioxonil (FRAC 12) was included in a premix as pydiflumetofen + fludioxonil (FRAC 7/12) and was among the most effective products within and beyond the application interval. Fludioxonil is a non-systemic surface acting fungicide and is included in the phenylpyrroles fungicide group (Kilani and Fillinger 2016). The fungicide may induce hyperactivation of the high osmolarity glycerol pathway, causing stress and pathogen death

(Jacob et al. 2015). Phenylpyrroles are classified as low to medium risk for pathogen resistance development with resistance reported in *S. solani* isolates (FRAC 2022; Wu et al. 2015).

Two fungicides in our study contained a demethylation inhibitor (DMI) fungicide, tebuconazole and difenoconazole (FRAC 3), premixed with a SDHI fungicide (FRAC 7) Tebuconazole and difenoconazole are in the triazole chemical group and considered to be at medium risk for pathogen resistance (FRAC 2022). Triazoles, along with other DMI fungicides, inhibit sterol synthesis (Kwok and Loeffler 1993) and effectively inhibited growth of *S. vesicarium* isolated from onion (Mishra and Singh 2017). Tebuconazole + fluopyram and difenoconazole + benzovindiflupyr were more effective than the untreated control for 2022 and 2023 based on foliar disease and the rAUDPC data within and beyond the application interval with the exception of foliar disease in 2022 for tebuconazole + fluopyram for data beyond the application interval.

An anilino-pyrimidine (AP) fungicide, pyrimethanil (FRAC 9) was included in our study as a premix with fluopyram (FRAC 7) and alone. Within the application interval, the fluopyram + pyrimethanil and pyrimethanil treatments were similar to the untreated control for the 2022 foliar disease and rAUDPC data. Beyond the application interval, the fluopyram + pyrimethanil and pyrimethanil treatments were similar to the untreated control for foliar disease and the rAUDPC data with the exception of the rAUDPC data for 2023. A premix of fluopyram + pyrimethanil is registered for onion application, however, isolates of *S. vesicarium* from onion were found to be insensitive to pyrimethanil in 2019 (Stricker et al. 2021).

Including multi-site fungicides in a disease management program reduces the risk of pathogen resistance (Brent and Hollomon 2007). Chlorothalonil (FRAC M05) is a multi-site fungicide with a low risk for pathogen resistance development and is commonly used by

Michigan's asparagus growers. Mancozeb (FRAC M3), an ethylene bis-dithiocarbamate fungicide, is also a multisite fungicide and was also alternated with chlorothalonil in this study. Mancozeb is registered for asparagus, however, some processors prefer that this product not be used (Hausbeck et al. 2008). Both mancozeb and chlorothalonil have been evaluated for purple spot disease control in previous studies. Although both fungicides limited disease compared to the untreated control, chlorothalonil was found to be more effective than mancozeb in years with heavy disease pressure (Meyer et al. 2000). This study found that within the application interval, mancozeb alternated with chlorothalonil was more effective than the untreated control for both years based on foliar disease and rAUDPC data. Beyond the application interval, mancozeb alternated with chlorothalonil was consistently more effective than the untreated control based on rAUDPC values, only.

In summary, *S. vesicarium* has a medium risk of developing fungicide resistance (FRAC 2019). A management program that includes multi-site protectant fungicides can limit the risk of pathogen resistance developing. Both chlorothalonil and mancozeb were effective when used in fungicide programs, however chlorothalonil remains the preferred product by growers. As of this study chlorothalonil is still accepted by processors while mancozeb is not readily accepted by processors due to health concerns. Programs containing fungicides in the FRAC 7 and 11 groups consistently limited purple spot disease. Pydiflumetofen + fludioxonil and fluxapyroxad + pyraclostrobin, and azoxystrobin consistently controlled purple spot disease within and beyond the application interval. Pydiflumetofen + fludioxonil has been found to be effective at controlling *Stemphylium vesicarium* on onion (Perla et al. 2020).

These products could protect the crop health into the fall without an additional investment of time or money. The high risk of pathogen resistance developing to these products

highlights the need to also consider fungicides that belong to different FRAC groups. When compared to the untreated control, several fungicides were effective within the application interval. The registration of new fungicides for purple spot control will expand disease management options.

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CHAPTER 2: EVALUATING FUNGICIDES WITH TOMCAST TO LIMIT *STEMPHYLIUM VESICARIUM* ON ASPARAGUS FERN

Abstract

Stemphylium vesicarium, the causal agent of purple spot disease on asparagus, renders spears unmarketable and causes premature browning and defoliation of the fern which can impact subsequent spear yield and quality. Purple spot on the fern is managed with the industry standard fungicides including azoxystrobin, mancozeb and/or chlorothalonil applied according to the TOMCAST disease forecaster at 15 disease severity values (DSVs). We evaluated TOMCAST using the industry's standard fungicides compared to unregistered fungicides including pydiflumetofen + fludioxonil and fluxapyroxad + pyraclostrobin. Each fungicide was alternated with chlorothalonil and applied every 10 days or according to TOMCAST at 15 or 20 DSVs or not treated. Relative area under the disease progress curve (rAUDPC) data indicated that all treatments limited purple spot disease compared to the control in 2022 and 2023 except for mancozeb applied according to TOMCAST 20 DSV (2022). For the industry standards, only azoxystrobin applied every 10 days or according to TOMCAST 15 DSV had less foliar disease at the final rating than the control each year. The rAUDPC data for pydiflumetofen + fludioxonil or fluxapyroxad + pyraclostrobin were similar regardless of application timing each year. The TOMCAST 20 DSV treatment received 6 (2022) or 4 (2023) applications and the 10-day treatment received 8 applications each year. The registration of these fungicides could protect asparagus fern from purple spot and reduce the number of applications by 25 to 50% when used with TOMCAST 20 DSV compared to a 10-day treatment.

Introduction

Michigan is the largest producer of asparagus (*Asparagus officinalis* L.) in the United States. In 2022, approximately 13,914 metric tons of spears were harvested with a value of $26.3 million (USAA, NASS 2022). Asparagus production in Michigan is concentrated primarily along Lake Michigan where the sandy loam soils provide good drainage; smaller production sites are

scattered throughout the state. Asparagus is a perennial vegetable crop whose spears are harvested in the spring. Asparagus spears emerge from the crown, a dense root system responsible for storing carbohydrates. Following the harvest of the spears, the carbohydrates stored in the crowns must be replenished for subsequent harvests (Shelton and Lacy 1980). In late June, depending on the weather conditions, growers allow the spears to mature into stems and develop fern, which replenishes the nutrients expended during harvest (Robb 1984; Downton and Torokfalvy 1975).

Asparagus fern is susceptible to foliar pathogens that cause chlorosis and premature defoliation. Diseased foliage reduces the carbohydrate content of the crown by reducing the photosynthetic area of the plant (Menzies et al. 1992). The two primary pathogens associated with premature defoliation in Michigan's asparagus fields are the fungi *Stemphylium vesicarium* (Wallr.) E.G. Simmons (teleomorph *Pleospora herbarum* (Pers. Ex Fr.) Rabenh.), Simmons, and *Puccinia asparagi* (Elmer et al. 1996), the causal agents of asparagus purple spot and rust, respectively.

Purple spot occurs annually in Michigan and is a threat to asparagus spears and fern. Prior to the 1980s the disease was not an issue, but once growers adopted a no-tillage production system and stopped incorporating fern debris into the soil, purple spot became a priority issue for the state's growers (Lacy 1982). Fungicides are the primary means of controlling purple spot on the fern (Meyer et al. 2000). Following spear emergence in the spring, the pathogen can cause purple lesions, rendering the spears unmarketable (Lacy 1982). Once the fern becomes established following spear harvest, disease symptoms including necrotic lesions on stem, branches, and cladophylls may develop (Menzies et al. 1992). If the disease progresses, the fern becomes chlorotic and the cladophylls fall (Falloon and Tate 1986). Consecutive years of

premature defoliation from foliar pathogens can reduce in nutrient replenishment and yield (Johnson and Lunden 1992; Meyer et al. 2000).

Stemphylium vesicarium ascospores are released from the overwintering pseudothecia that form on asparagus debris (Elmer et al. 1996; Hausbeck et al. 1999). A shift in turgor pressure within the pseudothecia from moisture, typically from rain, results in the release of ascospores (Atanasoff 1919; Hausbeck et al. 1999). Ascospores penetrate asparagus spears via open stomata or wounds (Falloon et al. 1987; Lacy 1982) causing purple lesions (Lacy 1982) rendering the spears unmarketable. Purple spot outbreaks on the harvestable spears may follow a rainfall especially if the harvest is delayed with few management options available (Hausbeck et al. 1999). Thus, fungicide applications during the fern stage to control purple spot has been the primary method of limiting the disease on the following year's spears.

Atmospheric ascospore concentrations increase as temperatures increase from cold to warm (spring in the northern hemisphere, and September to January in the southern hemisphere) and decrease in the hottest months (Falloon and Tate 1986; Granke and Hausbeck 2012; Menzies et al. 1992). Conidia serve as secondary inoculum and are disseminated during rainfall and wind events (Falloon and Tate 1986). Conidial concentrations in the atmosphere increase during the summer, with concentrations peaking between 0700 and 1300 h (Hausbeck et al. 1999; Granke and Hausbeck 2010).

Extended leaf wetness periods and temperatures of 25°C to 30°C are optimal for germination rate and germ tube length (Bohlen-Janssen et al. 2018a). Infection rate is fastest at temperatures between 0°C to 20°C while the fern is still wet (Falloon et al. 1987; Hausbeck et al. 1999). When conditions were optimal *S. vesicarium* isolates on pear were able to germinate in an hour (Llorente et al. 2006). Conidial germination and germ tube length also benefit from

increased leaf wetness, but the temperature range ideal for germination is wider, ranging from 20°C to 30°C, while the optimal temperature for germ tube length is 28.7°C (Montesinos and Vilardell 1992; Bohlen-Janssen et al. 2018b). Granke and Hausbeck (2012) found similarities in diurnal patterns of *S. vesicarium* and *Alternaria* sp. conidia. *Stemphylium vesicarium* germination has been associated with the key parameters of TOMCAST: temperature and leaf wetness duration (Falloon et al. 1987; Granke and Hausbeck 2012).

Stemphylium vesicarium is at medium risk of developing resistance to fungicide by the Fungicide Resistance Action Committee (FRAC) (FRAC 2019). Fungicides interact with the pathogen in different ways and are categorized by their mode of action into a number group (FRAC code). Fungicides currently registered for use on asparagus fern include the protectants chlorothalonil (FRAC M05) and mancozeb (FRAC M03), and the locally systemic fungicide, azoxystrobin (FRAC 11). Although these fungicides effectively manage purple spot disease (Hausbeck et al. 2008; Meyer et al. 2000; Foster and McDonald 2018) the protectant fungicides remain on the surface of plant tissue where they are susceptible to degradation which limits their efficacy (Lukens 1971). Azoxystrobin (FRAC 11), a strobilurin fungicide, is at high risk of resistance development. Strobilurin fungicides have been used to control *S. vesicarium* on onion and pear with fungicide resistance reported (Alberoni et al. 2010; Hay et al. 2019).

Currently the disease forecaster TOMCAST is used by Michigan's asparagus growers as a tool to time fungicide applications for purple spot control (Meyer et al. 2000; Hausbeck et al. 2008). TOMCAST was derived from FAST, a disease forecasting model developed to time fungicide applications on tomato for control of *Alternaria solani*, the causal agent of early blight (Madden et al. 1978). The TOMCAST model uses the duration of leaf wetness period and the average temperature during the leaf wetness period (Pitblado 1992). Both leaf wetness and

average temperature are then compared to the table outlined in Madden et al. (1978) to assign a daily disease severity value (DSV). The DSVs accumulate until a predetermined threshold is reached and a fungicide application is triggered. The DSVs are then reset to 0. Leaf wetness sensors are key receptors in the use of forecasting models. Electric sensors use a grid of circuits to measure changes in electrical resistance caused by condensation; while these are effective the rate of evaporation from these sensors can be variable, depending on color and angle (Gillespie and Kidd 1978). In some cases, sensors can be modified to increase or decrease the threshold which determines when the leaves are 'wet'. The physical orientation of the sensor can also play a role in the evaporation rate including height and angle of the sensor (Sentelhas et al. 2004).

When TOMCAST was evaluated to limit purple spot control on asparagus (Meyer et al. 2000), only chlorothalonil and mancozeb were widely used by Michigan growers. Chlorothalonil used with TOMCAST was effective for both cultivars tested compared to mancozeb that was effective on only one of the cultivars (Meyer et al. 2000). Azoxystrobin is a locally systemic fungicide registered for asparagus but has not been evaluated for use with TOMCAST for purple spot. When TOMCAST 15 DSV was evaluated to time applications of copper, chlorothalonil, and/or azoxystrobin for efficacy of foliar blight on carrot, control was similar to the 7-day application treatment with fewer applications (Dorman et al. 2009). The development of new, highly effective fungicides could extend DSV thresholds further reducing the number of fungicide applications while maintaining effective control.

We evaluated fungicide treatments for purple spot control on 'Sequoia' asparagus using application timings every 10-days or using TOMCAST at 15 DSV or 20 DSVs or not sprayed. The fungicide treatments evaluated included fungicides registered and unregistered for asparagus.

Materials and Methods

Plot establishment and TOMCAST. Field trials were conducted in a commercial grower's 'Sequoia' asparagus field in Oceana County, Michigan in 2022 and 2023. The field had been established in 2011 in sandy loam soil. Insects and fertilization were managed by the grower cooperator each year of the trial. Each year, the trial was established as a randomized complete block design with four replications per treatment. Each treatment plot was 6.1 m in length and comprised of a single row of asparagus separated by at least a 1.5 m buffer between treatments within the row. Treatment rows were separated from each other by unsprayed rows.

A WatchDog® Wireless Weather Station and a leaf wetness sensor (3000 Series, Spectrum Technologies Inc., 3600 Thayer Court, Aurora, IL) were mounted on a 1.5 m steel pole and placed in the center of the treatment plot to monitor temperature, relative humidity, rainfall, and leaf wetness. The weather station containing the solar panel, temperature reader, and wireless modem were attached at the top of the steel pole and oriented with solar panel facing south according to user manual, while the leaf wetness sensor was placed near the top of the fern, oriented north and raised as the fern grew. Care was taken so that nearby asparagus foliage did not touch the leaf wetness sensor. The leaf wetness sensor was placed at fern height facing north, per manufacture recommendations. Weather data were automatically collected every 15-min and sent to a corresponding SpecConnect® account (Spectrum Technologies Inc.). In 2022, weather station was established on 5 July and removed 14 October. In 2023 the weather station was established on 1 July and removed 1 October.

The TOMCAST disease model used in this study was purchased from Spectrum Technologies Inc. and was identical to that described by Pitblado (1992); it was used with a SpecConnect® account. To determine the daily DSV, the TOMCAST disease model on

SpecConnect® website was checked at 1100 h each day for the daily and accumulated DSVs. Once accumulated DSVs reached a predetermined threshold, corresponding treatments were applied and cumulative DSVs were reset to zero. If the weather forecast indicated a high risk of rain, applications were made when the accumulated DSVs were 1-2 values lower than the designated threshold. If an application was delayed due to weather, it was applied as soon as possible.

Treatment application. The fungicides mancozeb, azoxystrobin, fluxapyroxad + pyraclostrobin, and pydiflumetofen + fludioxonil were each alternated with chlorothalonil (Table 2.1). Fungicide applications were initiated each year after spear harvest concluded and the fern was fully emerged on 5 July (2022) and 30 June (2023) but before purple spot symptoms developed. Subsequent applications were applied every 9-11 days or according to TOMCAST 15 or 20 DSVs or not treated (Table 2.2). Applications were made with a backpack sprayer calibrated to 241.3 kPa with three XR8003 flat-fan nozzles spaced 45.7 cm apart, delivering approximately 467.7 L/hectare. Fungicides registered for asparagus were applied at labeled rates, fungicides not registered for asparagus were applied at labeled rates for *S. vesicarium* control on onion. An exception occurred with pydiflumetofen + fludioxonil which was initially applied at a rate of 11.4 fl oz/acre prior to 24 August 2022 before being increased to 13.4 fl oz/acre at the registrant's request.

Table 2.1. Registered and unregistered fungicides tested in asparagus field trials for their efficacy against *Stemphylium vesicarium*.

Product	Active Ingredient	Registrant[z]	Product Rate/Hectare	FRAC[y] Code
Registered				
Manzate® Pro-Stick™	mancozeb	UPL	2.2 kg	M 03
Quadris® Flowable	azoxystrobin	Syngenta Crop Protection	1.1 L	11
Bravo® Weather Stik[x]	chlorothalonil	Adama	2.8 L	M 05
Unregistered[w]				
Merivon® Xemium® Brand	fluxapyroxad + pyraclostrobin	BASF Corporation	803.9 ml	7/11
Miravis® Prime	pydiflumetofen + fludioxonil	Syngenta Crop Protection	[v]833.1 ml 979.2 ml	7/12

[z]: Registrant: UPL, King of Prussia, PA; Syngenta Crop Protection, Greensboro, NC; Adama, Raleigh, NC; BASF Corporation, Research Triangle Park, NC; Bayer CropScience LP, St. Louis, MO; Corteva Agriscience LLC, Indianapolis, IN.

[y]: Fungicide Resistance Action Committee (http://www.frac.info) FRAC groups are classified by mode of action, the process by which active chemicals inhibit pathogen function. Group classification is used to monitor development of active ingredient resistance in pathogen populations.

[x]: Bravo® Weather Stick was used in alternation with all fungicide treatments tested.

[w]: Product rate for fungicides unregistered for asparagus were calculated using established rates for *Stemphylium vesicarium* control on onion.

[v]: Rate of Miravis® Prime applied on 7 and 28 July 2022, prior to rate recommendation from company.

Table 2.2. Forecaster and calendar programs used to control *Stemphylium vesicarium* in 2022 and 2023 in a commercial asparagus farm in Shelby, MI.

Application Timing	Software Used	Threshold	Application Number		Application Dates	
			2022	2023	2022	2023
Calendar	**N/A**	**10-day**	**8**	**8**	**5[z], 14, 25[z] Jul; 4, 15[z], 26 Aug; 5[z], 15 Sep**	**30 Jun; 10[z], 20, 31[z] Jul; 10, 21[z], 31 Aug; 12[z] Sep**
TOM-CAST	**SpecConnect**	**15 DSV[y]**	**8**	**6**	**5[z], 14, 21[z] Jul; 1, 9[z], 22 Aug; 1[z], 12 Sep**	**30 Jun; 13[z], 27 Jul; 10[z], 24 Aug; 19[z] Sep**
		20 DSV	**6**	**4**	**5[z], 18 Jul; 1[z], 11, 26[z] Aug; 9 Sep**	**30 Jun; 20[z] Jul; 7, 28[z] Aug**

[z]Application of chlorothalonil
[y]Daily Disease Severity Value

Disease Assessments. Asparagus fern was visually assessed for foliar lesions, chlorosis, and defoliation caused by *S. vesicarium* on 9, 22, 26 August; and 2, 8, 15, 29 September 2022, and 20, 27 July; 10, 18, 31 August; and 7, 21 September 2023. A 0 to 100% continuous scale was used to calculate the area under the disease progress curve (AUDPC). The relative AUDPC (rAUDPC) was calculated by standardizing the AUDPC from both years using the methods outlined in Fry (1978). Disease severity ratings and the rAUDPC were used to compare disease progression for application timing and fungicide treatments each year.

Statistical Analysis. Statistical analysis was performed using RStudio, Version 4.3.2. of R for Apple. Copyright © 2023 by The R Foundation for Statistical Computing, Vienna, Austria. A linear model was created using the lm function in RStudio to conduct basic assumption testing. Linear model analysis was conducted on product, application timing, and treatment (product and

application timing combined) for each year of the trial. Normality was visually assessed by evaluating the residual plots, histogram, and QQ plot of the residuals. Variance was assessed for homoskedasticity using the plot function in RStudio followed by a Levene's test conducted using the leveneTest function from the cars package (Fox and Weisberg 2019). In cases where assumptions of variance and normality were violated, data were transformed using Box-Cox functions using boxcox function from the MASS package in RStudio (Venables and Ripley 2002). Transformed data were then re-checked for normality and variance using the same methods described above. If variance continued to be violated a Welch's ANOVA was conducted using the oneway.test function in RStudio. If the ANOVA F-test was significant, all pairwise comparisons were assessed with the Bonferroni post-hoc test using the cld function in the multcomp package, with significant differences determined using a p-value <0.05 (Horthorn et al. 2008).

Results

Disease severity in the untreated control increased from ~10% to 70-75% from 22 August to 2 September (2022) and 15% to 70% from 10 to 18 August (2023) (Figs 2.1 and 2.2). Significant differences were identified for application timing, fungicide, and treatments (fungicide and application timing) for both disease years for ratings and rAUDPC values (Tables 2.3 and 2.4). On the final rating date of 29 September 2022 and 21 September 2023, disease severity in the untreated plots was 87.5% (2022) and 85.0% (2023) (Table 2.5).

Fungicide. All fungicides significantly reduced final foliar disease severity compared to the untreated control in 2022 and 2023, with the exception of mancozeb (Table 2.6). Each year, pydiflumetofen + fludioxonil was more effective than both azoxystrobin and mancozeb based on the final disease severity but was similar to fluxapyroxad + pyraclostrobin. According to each

year's rAUDPC values, all fungicides were more effective than the untreated control except for mancozeb (2022) (Table 2.6). Pydiflumetofen + fludioxonil and fluxapyroxad + pyraclostrobin were more effective in controlling *S. vesicarium* than azoxystrobin and mancozeb in 2022 and 2023, according to rAUDPC values (Table 2.6).

Application timing. Based on final disease severity, the average 10 day and TOMCAST 15 DSV application timings were more effective than the untreated control in 2022 and 2023; the untreated control and average TOMCAST 20 DSV application timings were similar. However, the rAUDPC data indicated that all application timings significantly decreased disease compared to the untreated control each year (Table 2.6). The average 10-day, TOMCAST 15 DSV, and TOMCAST 20 DSV treatments were similar based on the final disease severity (2022) and the rAUDPC data (2022 and 2023) (Table 2.6). In 2023, the average 10-day application timing was more effective than the TOMCAST 20 DSV treatment but was similar to TOMCAST 15 DSV for the final disease rating.

Application number. The highest number of applications (eight) sprayed over the course of our two-year study were made to the 10-day (2022, 2023) and TOMCAST 15 DSV plots (2022). The TOMCAST 15 DSV plots received six applications in 2023 (Table 2.2). The TOMCAST 20 DSV plots received the least number of applications with six (2022) and four (2023) applications for their respective years (Table 2.2).

Treatment. Each year, all treatments effectively reduced disease severity compared to the untreated control, except for mancozeb at all application timings except the 10-day interval (2023) and azoxystrobin applied at TOMCAST 20 DSV (Table 2.5). When comparing foliar disease severity among programs more effective than the untreated in 2022, they were similar except that pydiflumetofen + fludioxonil applied at TOMCAST 20 DSV (12% foliar disease)

was more effective than azoxystrobin applied every 10 days (42.5% foliar disease). In 2023, while most of the treatments were similar, pydiflumetofen + fludioxonil and fluxapyroxad + pyraclostrobin, each applied every 10-days or according to TOMCAST 15 DSV (ranging from 8.5 to 13% foliar disease), had lower disease severity ratings than fluxapyroxad + pyraclostrobin at TOMCAST 20 DSV (51.2% foliar disease), azoxystrobin at TOMCAST 15 DSV (48.8% foliar disease), azoxystrobin applied at TOMCAST 20 DSV (67.5% foliar disease) and mancozeb applied every 10 days (53.8 % foliar disease), TOMCAST 15 DSV (80% foliar disease) and TOMCAST 20 DSV (81.2% foliar disease) (Table 2.5).

According to the rAUDPC data for each year, all treatments were effective compared to the untreated control except for mancozeb at TOMCAST 20 DSV (2022). In both years, pydiflumetofen + fludioxonil and fluxapyroxad + pyraclostrobin had similar rAUDPC values at the 10-day, TOMCAST 15 DSV and 20 DSV application timings (Table 2.5). Azoxystrobin at 10-day and TOMCAST 15 DSV controlled purple spot more effectively than azoxystrobin at TOMCAST 20 DSV, according to 2022 rAUDPC data (Table 2.5). In 2023, azoxystrobin at 10-day intervals provided purple spot disease control that was similar to azoxystrobin at TOMCAST 15 DSV but had a lower rAUDPC value than azoxystrobin at TOMCAST 20 DSV (Table 2.5). In 2022, mancozeb applied at 10-day intervals had a lower rAUDPC value compared to the TOMCAST 20 DSV but was similar to TOMCAST 15 DSV (Table 2.5). In 2023, mancozeb applied at all three timings were similar in efficacy according to rAUDPC values (Table 2.5).

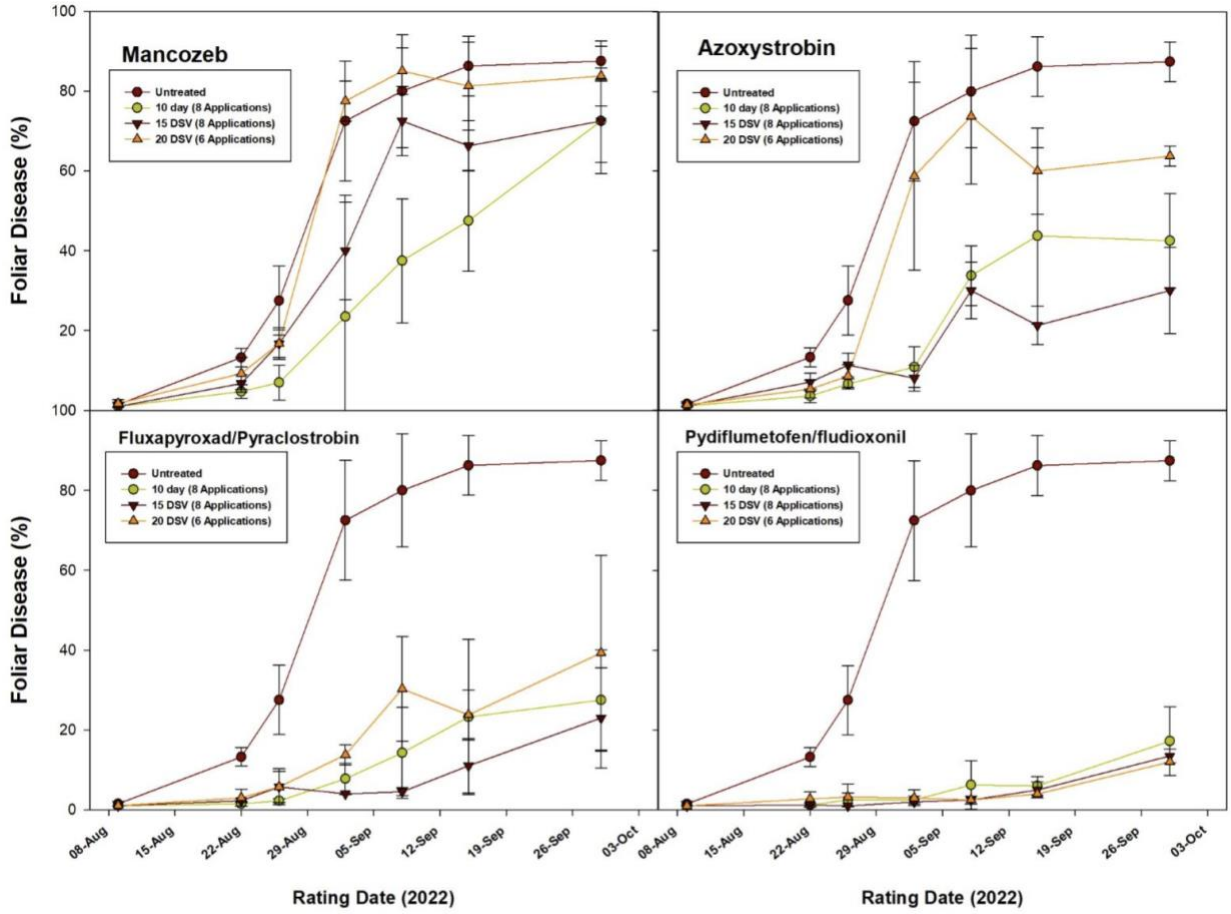

Figure 2.1. Disease progress curves of *Stemphylium vesicarium* on 'Sequoia' asparagus fern when treated with fungicides applied in alternation with chlorothalonil at 10-day, TOMCAST 15 DSV, TOMCAST 20 DSV, or untreated in 2022.

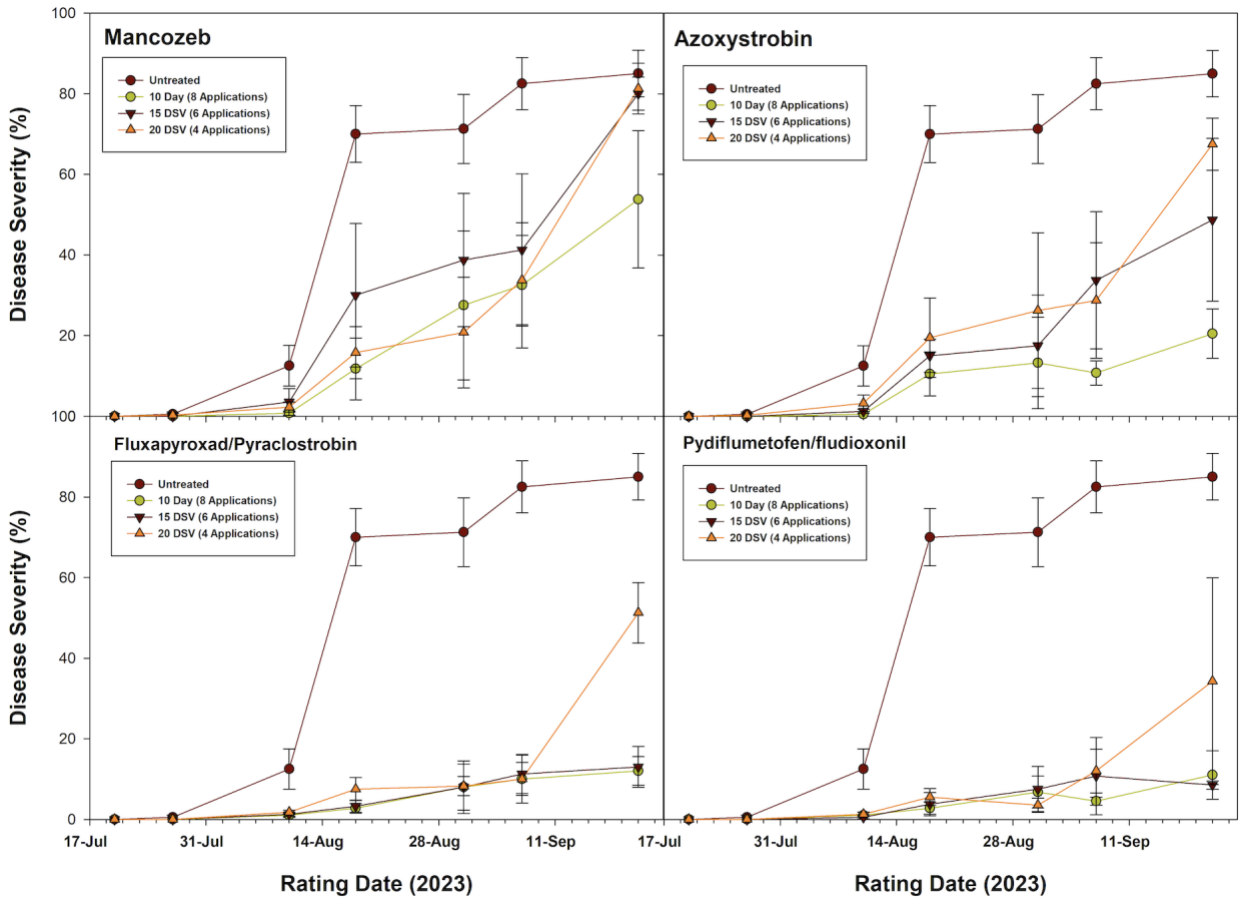

Figure 2.2. Disease progress curves of *Stemphylium vesicarium* on 'Sequoia' asparagus fern when treated with fungicides applied in alternation with chlorothalonil at 10-day, TOMCAST 15 DSV, TOMCAST 20 DSV, or untreated in 2023.

Table 2.3. Welch's analysis of variance (ANOVA) for the effect of product, application timing, and fungicide treatment on disease severity ratings.

	Welch's ANOVA			
	Degrees of Freedom			
Response Variable/Effect	**Numerator**	**Denominator**	***F-value***	***P-value***
Product				
2022	4	17.3	177.7	<0.0001
2023	4	21.8	42.2	<0.0001
Application timing				
2022	3	25.9	35.3	<0.0001
2023	3	24.0	40.5	<0.0001
Treatment				
2022	12	14.9	129.8	<0.0001
2023	12	14.8	148.1	<0.0001

Table 2.4. Welch's analysis of variance (ANOVA) for the effect of application product, timing, and fungicide treatment on relative area under disease progress curve (rAUDPC).

	Welch's ANOVA			
	Degrees of Freedom			
Response Variable/Effect	**Numerator**	**Denominator**	***F-value***	***P-value***
Product				
2022	4	13.8	77.7	<0.0001
2023	4	18.9	367.1	<0.0001
Application timing				
2022	3	16.6	24.5	<0.0001
2023	3	24.9	209.7	<0.0001
Treatment				
2022	12	14.8	126.7	<0.0001
2023	12	15.0	132.0	<0.0001

Table 2.5. Foliar disease severity and relative area under disease progress curve (rAUDPC) for fungicide treatments.

		Foliar Disease (%)[z]		rAUDPC	
Treatment[y]	FRAC Code	2022 29 Sep	2023 21 Sep	2022	2023
Untreated	-	87.5 a[x]	85.0 a	0.54 a	0.48 a
pydiflumetofen + fludioxonil	7/12				
10-day		17.2 cd	11.0 g	0.05 f	0.04 f
TOMCAST 15 DSV		13.5 cd	8.5 g	0.04 f	0.05 f
TOMCAST 20 DSV		12.0 d	34.2 e-g	0.04 f	0.08 ef
fluxapyroxad + pyraclostrobin	7/11				
10-day		27.5 cd	11.0 g	0.12 ef	0.04 f
TOMCAST 15 DSV		23.0 cd	13.0 g	0.08 f	0.05 f
TOMCAST 20 DSV		39.2 b-d	51.2 c-e	0.17 d-f	0.10 d-f
azoxystrobin	11				
10-day		42.5 bc	20.5 fg	0.21 de	0.08 ef
TOMCAST 15 DSV		30.0 cd	48.8 d-f	0.16 d-f	0.17 c-e
TOMCAST 20 DSV		63.8 ab	67.5 a-d	0.39 bc	0.20 b-d
mancozeb	M3				
10-day		72.5 a	53.8 b-e	0.29 cd	0.18 b-e
TOMCAST 15 DSV		72.5 a	80.0 a-c	0.41 bc	0.27 b
TOMCAST 20 DSV		83.8 a	81.2 ab	0.52 ab	0.21 bc
P-value	*N/A*	*<0.05*		*<0.05*	

[z]: Based on a visual estimation of the foliage diseased, 0-100% scale with 0=0% foliar disease and 100=100% foliar disease.
[y]: Applications made for all treatments with the exception of the untreated control included a chlorothalonil alternation. Days after last application: 10-day: 14 (2022) and 9 (2023); TOMCAST 15 DSV: 17 (2022) and 2 (2023); TOMCAST 20 DSV: 20 (2022) and 24 (2023).
[x]: Columns with letters in common are not statistically different from each other (Bonferroni; *P=0.05).*

Table 2.6. Average foliar disease severity and relative area under disease progress curve (rAUDPC) for product and application timing.

		Foliar Disease (%)[z]		rAUDPC[y]	
Treatment	FRAC Code	2022 29 Sep	2023 21 Sep	2022	2023
Product	-				
Untreated	-	87.5 a[x]	85.0 a	0.54 a	0.48 a
Pydiflumetofen + fludioxonil	7/12	14.2 c	17.9 c	0.04 c	0.05 d
Fluxapyroxad + pyraclostrobin	7/11	29.9 bc	25.1 bc	0.12 c	0.07 d
Azoxystrobin	11	45.4 b	45.6 b	0.26 b	0.15 c
Mancozeb	M3	76.2 a	71.7 a	0.40 a	0.22 b
Application timing					
Untreated		87.5 a	85.0 a	0.55 a	0.48 a
10-day		39.9 b	24.1 c	0.17 b	0.09 b
TOMCAST 15 DSV		34.8 b	37.6 bc	0.17 b	0.14 b
TOMCAST 20 DSV		49.7 ab	58.6 ab	0.28 b	0.15 b
P-value	*N/A*	*<0.05*		*<0.05*	

[z]: Based on visual estimation of the foliage diseased, 0-100% scale with 0=0% foliar disease and 100=100% foliar disease. Values represent an average calculated from programs containing product and application timing, respectively.
[y]: rAUDPC values represent an average calculated from programs containing product and application timing, respectively.
[x]: Columns with letters in common are not statistically different from each other (Bonferroni; *P=0.05).*

Discussion

Historically, Michigan growers tilled their asparagus fields in late fall or spring to incorporate fern debris into the soil. However, this practice can damage crown tissue, increasing susceptibility to Fusarium crown and root rot (Putnam and Lacy 1977; Elmer et al. 1996). Michigan growers adopted no-till management practices enabling *S. vesicarium* pseudothecia to remain on the surface in the fern debris, providing inoculum for emerging spears (Kelly and Bai 1999). Since the adoption of this practice, 40 years ago, purple spot has been a top foliar disease concern for Michigan growers (Lacy 1982). Purple spot outbreaks result in blemished spears that are unmarketable and decrease yield and fern health (Meyer et al. 2000; Lacy 1982). Debris management options, including the use of herbicides, are limited and have been linked to decline in long term plant health and yield (Kelly and Bai 1999; Rodriguez-Salamanca et al. 2012). Fungicides cannot be applied to spears prior to or during harvest, and poor disease management on the fern can impact yield and inoculum levels (Conway et al. 1990; Johnson and Lunden 1992; Menzies et al. 1992). There are relatively few fungicides registered for use on asparagus fern and include azoxystrobin, mancozeb, and chlorothalonil.

When Granke and Hausbeck (2012) monitored a Michigan asparagus field using a Burkard volumetric spore trap, they found similar patterns between atmospheric concentrations of an *Alternaria* spp. and *S. vesicarium* conidia suggesting that TOMCAST, developed for control of *Alternaria solani* on tomato, could help time fungicide applications for purple spot control. TOMCAST's simple parameters facilitated its implementation among Michigan's asparagus growers who have used it as a management tool for more than 20 years. Typically, growers make chlorothalonil applications between TOMCAST 15 to 20 DSV, depending on their experience and personal risk aversion. TOMCAST is typically used by growers through August

and discontinued in early September as *S. vesicarium* development is slowed by the cool fall temperatures (Bohlen-Janssen et al. 2018b). However, warming September temperatures (NOAA, NCEI 2023) may prompt DSV accumulation and prolong disease development. Warm temperatures have been observed to induce resurgent fern growth later in the season. This was observed in our trials, seen by the decrease in foliar disease ratings on certain dates.

When Meyer et al. (2000) validated the use of TOMCAST 15 DSV using chlorothalonil and mancozeb on two asparagus cultivars, efficacy was influenced by both fungicide and cultivar. Since this time, new asparagus cultivars and the fungicide azoxystrobin have become available and are used by Michigan's growers. When TOMCAST 10 DSV was evaluated for *Septoria apiicola* control on celery, disease was controlled with fewer applications compared to the calendar when using azoxystrobin alternated with chlorothalonil (Bounds and Hausbeck 2008). An updated approach could determine if azoxystrobin or other unregistered fungicides are compatible with TOMCAST to control purple spot on asparagus.

Using a forecasting model may reduce the number of fungicide applications required to limit disease thereby reducing the risk of exposure to the applicator, pathogen resistance to fungicide, and cost of management (Hewitt 1998). A recent EPA proposal (docket EPA-HQ-OPP-2011-0840-0141) suggests a limit reduction for chlorothalonil. For Michigan's asparagus production systems that are concentrated on sandy loam soils, the proposed reduction is from 9.0 lb a.i./A to 6.5 lb a.i./A per year. Currently a total of six applications at the lowest recommended rate can be made in a season without surpassing the maximum, under the proposed reduction the total number of applications would be four. Only the TOMCAST 20 DSV program in 2023 required four applications. In our study, the TOMCAST 15 DSV treatments did not reduce the

number of applications compared to the 10-day treatment in 2022, however, there was a 25% reduction in number of applications in 2023.

Treatments of chlorothalonil at TOMCAST 15 DSV were previously verified to be effective (Meyer 1997). In our study, chlorothalonil was applied in alternation with other fungicides. If the use of chlorothalonil must be reduced according to the EPA proposal, azoxystrobin could be used to maintain fern health. According to the rAUDPC values, azoxystrobin TOMCAST 20 DSV was more effective than the untreated control each year. Mancozeb TOMCAST 20 DSV was similar to the untreated in 2022 but more effective in 2023.

Meyer et al. (2000) found that the benefit of mancozeb applications used with TOMCAST was not consistent among asparagus cultivars. In our study, mancozeb was similar to the untreated control for final disease severity, regardless of application timing in 2022. Mancozeb applied using TOMCAST 15 or 20 DSV had a similar disease rating to the untreated control in 2023. However, according to rAUDPC values only mancozeb at TOMCAST 20 DSV failed to decrease purple spot disease in 2022. In 2023, mancozeb at TOMCAST 20 DSV had a similar final disease rating compared to the untreated control but was more effective at reducing disease according to rAUDPC. This multi-site fungicide is classified as an ethylene bis-dithiocarbamate (EBDC) and has not been preferred by some processors due to health concerns (Meyer et al. 2000).

Azoxystrobin was more effective than mancozeb according to rAUDPC data over both years. Mancozeb was similar to the untreated control in 2022 but was effective in 2023 according to the rAUDPC values. At the final disease rating, mancozeb applied using TOMCAST 20 DSV was similar to the untreated control, while applications every 10-days or according to TOMCAST 15 DSV were effective compared to the untreated control. However, according to

rAUDPC in both years, all application timings were more effective than the untreated control. In 2022, the 10-day and TOMCAST 15 DSV had the same number of applications, but in 2023 the TOMCAST 15 DSV had two fewer applications. TOMCAST 15 DSV treatments had fewer applications while maintaining control similar to the 10-day as had been demonstrated in a previous study (Meyer et al. 2000).

Evaluating new fungicides that are not registered for use on asparagus for use with TOMCAST could advance disease control programs. The unregistered fungicides pydiflumetofen + fludioxonil and fluxapyroxad + pyraclostrobin were consistently more effective than the labeled fungicides, azoxystrobin and mancozeb, according to rAUDPC values over both years. Fungicides are categorized based on the way the chemistry interacts with the pathogen, these categories are grouped and identified using FRAC codes (FRAC 2022). Fungicides from FRAC groups 7, 11, and 12 provided effective disease control when alternated with chlorothalonil (FRAC M05). Among the fungicides registered for purple spot on asparagus, azoxystrobin (FRAC 11) was most effective in our study but is at high risk of pathogen resistance developing (FRAC 2022). Azoxystrobin-resistant *S. vesicarium* isolates have been recovered from onion fields in New York (Hay et al. 2019), additionally resistance to azoxystrobin had been identified in onion field trials in Michigan (Hausbeck et al. 2019). In our study, pyraclostrobin was included in fluxapyroxad + pyraclostrobin (FRAC 7/11). Both azoxystrobin and pyraclostrobin are classified as strobilurin fungicides. Exclusive use of strobilurin fungicides is discouraged due to the high risk of fungal pathogens developing resistance (FRAC 2022). Based on results from our study, alternating applications of azoxystrobin with chlorothalonil represents good disease management for purple spot disease.

Fluxapyroxad + pyraclostrobin (FRAC 7/11) and pydiflumetofen + fludioxonil (7/12) fungicides have a FRAC 7 fungicide in common and are at medium to high risk of resistance development (FRAC 2022). Insensitivity to fluxapyroxad has been detected in *S. vesicarium* isolates from onion, although most isolates were sensitive (Hay et al. 2019). The fludioxonil in the premix pydiflumetofen + fludioxonil (FRAC 7/12) is classified as a phenylpyrrole and is at a low to medium risk for resistance development (FRAC 2022). However, resistance to fludioxonil has been identified in *Stemphylium solani* isolates (Wu et al. 2015).

The registration of high efficacy fungicides for asparagus foliar applications could benefit Michigan growers by providing effective disease control while requiring fewer applications compared to the calendar-based program. Pydiflumetofen + fludioxonil and fluxapyroxad + pyraclostrobin were effective at all application timings. When these fungicides were used with TOMCAST 20 DSV, control was similar to the 10-day treatment, with 25-50% fewer applications in 2022 and 2023. Michigan asparagus growers are interested in reducing fungicide use and cost in their production fields. When utilizing high efficacy fungicides, sprays can be applied using higher TOMCAST thresholds resulting in fewer applications while maintaining disease control.

Future Work

Michigan asparagus growers rely on university research and funding to provide updates to purple spot management on asparagus fern. We evaluated labeled and unlabeled fungicides in order to determine registration targets. Each year, fungicides were evaluated for purple spot control in field plots under high disease pressure. We were able to identify several fungicides that suppressed disease during the application interval, as well as fungicides that provided extended protection after last application. This information is useful for updating management recommendations, but the variability in fungicide efficacy between years can be explored further. Future work might include determining population diversity of *Stemphylium vesicarium* in a given field, as well as the larger asparagus production region. In addition, the use of sequencing and fungicide assays could track possible azoxystrobin-resistance populations, and ultimately combat the spread of resistant isolates.

Additionally, this study identified that untested labeled products, azoxystrobin, and unlabeled products, pydiflumetofen + fludioxonil and fluxapyroxad + pyraclostrobin, could be applied under TOMCAST. Specifically, key products could be applied at higher DSV thresholds and still see effective control. TOMCAST was developed for an annual cropping system, while asparagus remains a perennial system. The disease forecaster does not take into account previous year's disease levels and potential inoculum. One future study could look into quantifying present inoculum and modifying the forecaster to account for high inoculum levels.

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