

**EVALUATION OF FOLIAR FUNGICIDE PROGRAMS IN MID-ATLANTIC
SOFT-RED WINTER WHEAT**

by

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fulfillment of the requirements for the degree of Master of Science in Plant and Soil
Sciences

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ABSTRACT

Foliar fungicides are commonly used by growers to manage fungal diseases of the foliage and head in mid-Atlantic soft-red winter wheat (SRWW). Fungicide applications between flag leaf emergence (Feekes growth stage [FGS] 8) and heading (FGS 10.5) have been considered the standard application timing. However, there has been a shift towards two-pass programs and late applications at beginning anthesis (FGS 10.5.1), but these programs have not been thoroughly evaluated for foliar disease control, test weight, yield, and economic benefit in the mid-Atlantic region. Experiments were conducted in Delaware, Maryland, Pennsylvania, and Virginia in 2015 and 2016 to evaluate commercially available fungicides with applications at FGS 8, FGS 10.5.1, and programs with an early application at green-up (FGS 5) followed by applications at either FGS 8 or FGS 10.5.1. All fungicide programs reduced foliar disease severity on the flag leaf and resulted in higher test weight and yield compared to the untreated check. Two-pass programs (FGS 5 + FGS 8 or FGS 5 + FGS 10.5.1) did not result in significantly lower disease severity compared to single applications at FGS 8 or FGS 10.5.1. Grain yield was highest within the FGS 5 + FGS 10.5.1 timing, and while significant, increases were small when compared to other tested application timings. The probability of profitability ranged from 0.49 to 0.56 for programs with a single application at FGS 8 compared to 0.53 for a single application of Prosaro® at FGS 10.5.1, indicating similar profitability between program timings. Two-pass programs with an early application at FGS 5 followed by FGS 8 or FGS 10.5.1 resulted in a similar probability of profitability compared to single application programs, ranging from 0.48-0.57 (FGS 5 FB FGS 8) and 0.52-0.59 (FGS 5 FB FGS 10.5.1). These findings lay the groundwork for larger scale future fungicide studies,

which could be used to make a fungicide application decision-making tool for managing foliar disease in mid-Atlantic SRWW production.

INTRODUCTION

Wheat (*Triticum* spp.) is one of the most important grain crops in the world. It is grown on more land area than any other commercial crop, ranking fourth in production behind sugarcane (*Saccharum officinarum* L.), maize or corn (*Zea mays* L.), and rice (*Oryza sativa* L.) (FOASTAT 2017). Global wheat production is estimated at 744.5 million tonnes (27.4 billion bushels), with wheat for direct human consumption at 499 million tonnes (FOA 2017). Utilization of wheat for livestock feed is estimated at 145 million tonnes, an increase of 6% in the past year (FOA 2017). The leading producers of wheat in the world are European Union (20% of world production), China (17.5%), India (12.9%), Russia (10.9%), and the United States (6.4%) (USDA-FAS 2017). The United States is the third largest exporter of wheat (14.7%), behind Russia (18.1%) and the European Union (15.8%) (USDA-FAS 2017). Within the United States, wheat ranks third in planted acreage, production, and gross farm receipts behind corn and soybean [*Glycine max* (L.) Merr.] (USDA-ERS 2017). Wheat is grown on nearly 17.8 million hectares (ha) in the United States, with an estimated value of over \$10 billion (USDA-NASS February 2017, September 2016). In the mid-Atlantic states of Delaware, Maryland, Pennsylvania, and Virginia, SRWW is planted on 336 thousand ha [830,000 ac] and is valued at over \$232 million (USDA-NASS February 2017, September 2016). SRWW fits well into mid-Atlantic cropping systems because it can be double-cropped with soybeans (Kratovich et al. 2004) and with processing vegetable crops such as lima beans (*Phaseolus lunatus* L.). SRWW is an important part of the agricultural economy in the mid-Atlantic, as the grain is used

to supply feed for the poultry industry on the Delmarva peninsula and the flour-mill industry in Pennsylvania, Maryland, and Virginia (USDA-NASS May 2017).

The majority of wheat grown in the United States is *Triticum aestivum* L. [tribe Triticeae of the family Poaceae (grasses)] and is categorized either as winter or spring types. Winter wheat, which is planted in the fall and harvested the following summer, represents 70-80% of total U.S. wheat production (USDA-ERS 2017). In comparison, spring types are grown and harvested in the same calendar year. Wheat is further divided into five major classes including hard-red winter (HRWW), hard-red spring (HRSW), soft-red winter (SRWW), white (WW), and durum (*Triticum durum* Desf.) (DW) wheat (USDA-ERS 2017). HRWW, which is used to make bread flour, makes up 40% of wheat production and is primarily grown in the Great Plains (USDA-ERS 2017). HRSW, used for specialty bread and blending with lower protein wheat, accounts for 20% of production and is primarily grown in the north-central states such as North Dakota, Montana, Minnesota, and South Dakota. SRWW is primarily grown in states east of the Mississippi River. SRWW accounts for 15-20% of wheat production, and unlike HRWW and HRSW, is used to make flour for cakes, cookies, and crackers. WW, which is grown in areas along the Pacific coast, Michigan, and New York, accounts for 10-15% percent and is used for noodles, crackers, cereals, and white crusted breads. DW only accounts for 3-5% of production, grown in North Dakota and Montana, and is used in pasta production.

Wheat Growth and Production

Winter wheat growth can be divided into five general periods: tillering, stem extension, heading, flowering, and ripening (grain fill) (Large 1954). While several

scales have been developed to describe individual wheat growth stages, the Feekes growth stage (FGS) scale is most commonly used in the United States (**Fig. 1**) (Large 1954, Zadoks et al. 1974). Wheat is typically planted in early to mid-October in the mid-Atlantic states of Delaware, Maryland, Pennsylvania, and Virginia (Kratovichil 2007). After primary seedling growth (FGS 1), plants begin to produce tillers, which will eventually function as individual plants. Under appropriate conditions, wheat plants will produce two tillers in the fall, which contribute more to overall yield than spring tillers (Herbek and Lee 2009). During the tillering stage, winter wheat enters a dormancy period, necessary for overwintering through cold temperatures. The length of this period is influenced by temperature and photoperiod (Slafer and Rawson 1995). The physiological process of vernalization occurs while dormant and prevents the plant from switching over to reproductive growth under unfavorable environmental conditions (Amasino 2004). In the spring, tillering resumes with the production of a total of two to three tillers in addition to the main stem under normal planting populations (Herbek and Lee 2009). During this period (FGS 3), nitrogen and sulfur fertilizers are applied to stimulate early season growth. The application of fertilizers at two points in wheat growth, or split applications, are recommended for greater fertilizer use efficiency and higher yields, with the first application occurring around FGS 3 (Shober et al. 2017). The second application occurs three to four weeks later just before stem elongation at “green-up” (FGS 5) (Shober et al. 2017). Stem extension occurs after jointing (FGS 6), with the flag leaf emerging at (FGS 8), and ends when the plant reaches boot (when the head has not yet emerged, but the top portion of the stem is swollen) (FGS 10). This is an important time for yield since the flag leaf is the last leaf to emerge and will intercept more sunlight than any other leaf.

In fact, the health of the photosynthetic tissues emerging after FGS 8 is critical for wheat yield, as they contribute approximately 95% of the carbohydrates for grain fill (Lupton 1972). Damage to the flag leaf from diseases, insects, and defoliation can limit potential yield (Bhathal et al. 2003, Herbek and Lee 2009). The final growth stages include heading (FGS 10.5), flowering (FGS 10.5.1), and grain fill (FGS 11), whereas flowering is the dividing line between when yield potential is being developed (vegetative stages) and when yield is realized (grain-fill). Stresses that impact the plant during grain fill, such as drought, nutrient deficiencies, or diseases, can limit kernel size and weight, impacting yield and grain quality (Everts et al. 2001, Herbek and Lee 2009).

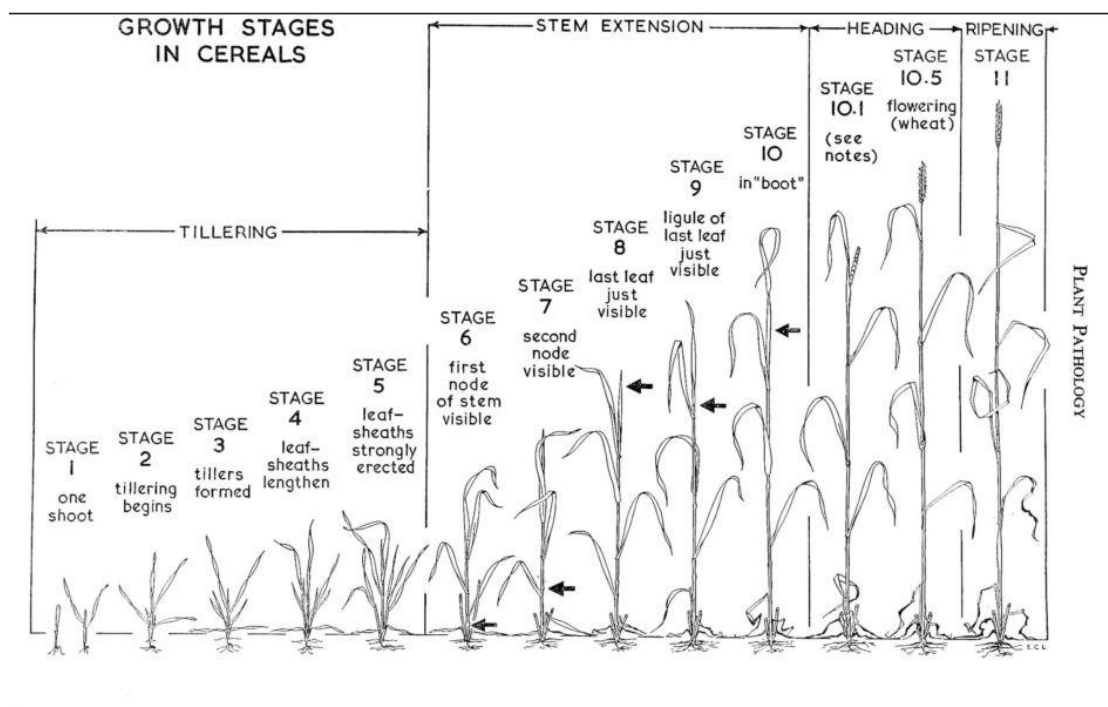


Figure 1 The Feekes growth scale of wheat. Large, E.C. 1954. Growth Stages in Cereal: Illustration of the Feekes scale. Plant Pathology 3:128-129

Foliar Fungal Diseases in mid-Atlantic SRWW

A disease is defined as “any malfunctioning of host cells and tissues that results from continuous irritation by a pathogenic agent or environmental factor and leads to development of symptoms” (Agrios 1997). In wheat, there are several disease inciting agents, or pathogens, that can infect tissues and cause diseases. The focus of this work is on fungal diseases of the foliage and the head because these are the most prevalent diseases encountered in grower fields.

Several fungal diseases of the foliage and head may impact yield and grain quality of mid-Atlantic SRWW. To generalize, fungal pathogens parasitize plant tissues, and ultimately interfere with photosynthesis and water uptake, thereby limiting carbohydrate production for plant growth (Agrios 1997, Robert et al. 2004).

Fungi are heterotrophic organisms requiring carbon sourced from other organisms such as plants or animals as they are unable to synthesize their own food. One method used by fungal pathogens obtain nutrition from plants is with the use of appressoria and haustoria, which are specialized growth structures used to enter plant tissues and extract nutrients (Szabo and Bushnell 2001). This strategy is commonly utilized by fungi classified as obligate biotrophs or those organisms that require a living host to feed and reproduce (Agrios 1997). Examples of obligate pathogens in the mid-Atlantic include powdery mildew (*Blumeria graminis* (DC.) Speer. F sp. *tritici* emend. E.J. Marchal), stripe rust (*Puccinia striiformis* f. *tritici* Erikss), and leaf rust (*Puccinia triticina* Erikss.). Alternatively, some fungal pathogens utilize biological compounds, such as enzymes and toxins, to destroy plant cellular components before utilizing the non-living substrate for nutrition. This group of fungal pathogens commonly are commonly referred to as non-obligate necrotrophs, which do not require a living host to feed and reproduce, and obtain nutrition from dead plant tissues (Oliver and Hewitt 2014). In addition, some fungal pathogens are classified as hemibiotrophs and may obtain nutrition from either living or dead plant tissues, often feeding first on living tissues prior to dead tissue. Some of the most common non-obligate pathogens in the mid-Atlantic belong to the foliar disease called leaf blotch complex (LBC).

Leaf Blotch Complex

In the mid-Atlantic, the leaf blotch complex (LBC), including the residue-borne foliar diseases Stagonospora nodorum blotch (*Parastagonospora nodorum* (Berk.) Quaedvlieg, Verkley & Crous) (SNB), Septoria tritici blotch (*Zymoseptoria tritici* (Desm.) (STB) Quaedvlieg & Crous), and tan spot (*Pyrenophora tritici-repentis* (Died.) Drechsler), is the most common foliar disease encountered in grower fields. A

major reason for this is the recent shift towards no-till and conservation tillage in the region (Mehra et al. 2015, Schuh 1990). Without tillage, infected residue remains on the soil surface providing local inoculum for fall or spring infections (Holmes and Colhoun 1975, Milus and Chalkley 1997). In addition to similar overwintering habits on infected residue, all three pathogens causing LBC are ascomycetes, a group of fungi which produce their sexual spores, or ascospores, within specialized reproductive structures called ascocarps (Bergstrom 2010, McMullen 2010, Shaner 2010). Ascocarps within the LBC group are called pseudothecia, which produce ascospores that are typically responsible for primary infections in late fall or early spring (Cowger and Silva-Rojas 2006, Shaner and Buechley 1995). Alternatively, pathogens within LBC may also produce conidia, or asexual spores, called pycnidiospores. Pycnidiospores are housed in specialized structures called pycnidia (**Fig. 2**). The exception is *P. tritici-repentis* (tan spot), which produces conidia on conidiophores, or structures used to elevate conidia off the leaf surface (Wegulo 2011). Conidia may also serve as primary inoculum in some cases but generally function as secondary inoculum. All three pathogens are polycyclic; producing several secondary spore generations which are spread locally via rain splash, creating a vertical gradient up the canopy (Eyal 1999). However, the latent period of LBC (10-20 days) is longer than that of the wind-blown diseases (e.g., powdery mildew, rusts) and may not reach the upper canopy until late in the growing season (Zearfoss et al. 2011). Also, extended periods of continuous free moisture (6-48 hours) are required for LBC development. Foliar symptoms of LBC begin as small flecks and expand into gray to tan lesions with dark centers surrounded by yellow borders that may coalesce as they age (**Fig. 2**) (Bergstrom 2010, Shaner 2010, Wegulo 2011). SNB, STB, and tan spot

produce similar symptoms on wheat foliage, and an examination of morphological structures under a microscope is often needed to distinguish one from another.

There are some minor differences between individual pathogens within LBC. For example, *P. nodorum* (SNB) and *P. tritici-repentis* (tan spot) prefer warmer temperatures 20-27°C (Bergstrom 2010, Wegulo 2011) while *Z. tritici* (STB) prefers cooler temperatures 10-20°C. *Z. tritici* may survive in a vegetative state in wheat stubble as mycelia and the period for infection is slightly longer (48-72 hours) (Shaner 2010). In addition to infections caused by primary and secondary inoculum on residue, SNB and tan spot may be transmitted by seed, though this is of lesser importance since most commercial wheat seed is now treated with a fungicide. LBC can cause reductions in grain quality and yield. (Eyal 1999). Yield losses of 30-50% have been reported in HRWW (Shabeer and Bockus 1988, Wegulo et al. 2009) and 12% in SRWW (Mehra et al. 2015). However, yield impacts of LBC in mid-Atlantic SRWW are not well established. Some evidence indicates that, in many cases, these diseases do not reach these tissues until later in the growing season, potentially limiting their overall yield impact (Grybauskas and Reed 2011, Kleczewski 2017a, b).



Figure 2 Typical LBC symptoms on wheat foliage (left) and close-up of lesion with arrow pointing to pycnidia (right). Photos by P. Sylvester.

Stagonospora Glume Blotch and Fusarium Head Blight (Head Diseases)

In addition to the common foliar diseases of winter wheat in the Mid-Atlantic region, the fungal head diseases *Stagonospora glume blotch* (*P. nodorum*) and *Fusarium head blight* (FHB) (*Fusarium graminearum* Schwabe) have increased in recent years. This increase is a result of greater amounts of residue left on the surface from conservation tillage practices (Freije and Wise 2015, Mehra et al. 2015).

Symptoms of glume blotch include purple-brown or grayish-brown streaks or lesions starting at the tips of the glumes on the spikelet (**Fig. 3**) (Bergstrom 2010). Pycnidia are diagnostic of glume blotch, which have an appearance of small brown bumps within the lesions (Francki 2013). Glume blotch is caused by the same pathogen that causes SNB on the foliage, *P. nodorum*. As with SNB on the foliage, rainy and warm conditions favor glume blotch infections. Infections occur after 12-18

hours of continuous free moisture and pycnidiospores are rain-splashed from the foliage to the head (Bergstrom 2010, Francki 2013). Glume blotch, as part of SNB, has been reported to reduce yields by 50% and test weight by 6% (Mehra et al. 2015, Milus and Chalkley 1997, Zearfoss et al. 2011).

Much like the other residue-borne foliar diseases, *Fusarium* head blight has been on the increase in recent years. *F. graminearum* survives well on decaying small grain residues and may also infect corn as *Gibberella zeae* (Schwein.) Petch, causing *Gibberella* ear rot (Markell and Francl 2003, Parry et al. 1995). Spores produced in late spring are windblown or water-splashed onto the head, causing infections during anthesis when anthers are protruding from the spikelets (McMullen et al. 2012). Wet weather (relative humidity >90%) and temperatures between 15-30°C during flowering increase the risk of FHB (McMullen et al. 2012). Symptoms of FHB include pre-mature bleaching of portions of the head. In addition, superficial pink or orange colored spores may be present along the spikelet (**Fig. 3**) (Dill-Macky 2010). FHB is a serious disease, and economic losses in the billions of dollars due to reductions in yield and quality are due to recent FHB epidemics (McMullen et al. 2012). Severe local outbreaks, such as the one in 2003, resulted in over \$8 million in losses to Maryland growers (Cowger and Sutton 2005). While the focus of this thesis is not FHB management, some of the same management practices overlap for foliar and head diseases. In addition to significant reductions of grain quality and yield (McMullen et al. 2012, Salgado et al. 2015), *F. graminearum* may produce mycotoxins, which are toxic to both livestock and humans (Payros et al. 2016, Schamle and Munkvold 2009).



Figure 3 Glume blotch (left) and FHB (right). Photos by P. Sylvester.

Powdery Mildew

Powdery mildew damages wheat by colonizing leaf tissues, which reduces photosynthesis and can increase respiration and transpiration rates (Stromberg 2010). Epidemics of powdery mildew are common in the mid-Atlantic (Cowger et al. 2016a), which can reduce both yield and grain quality (Green et al. 2014). Early season epidemics may reduce tillers, thereby reducing yield (Bowen et al. 1991). *B. graminis* overwinters as chasmothecia on wheat residue (**Fig. 4**) (Cowger et al. 2016a). Ascospores from chasmothecia serve as primary inoculum and are carried by wind in

the fall leading to potential fall or early winter infections (Cowger et al. 2016a, Stromberg 2010). Conidia, which are mostly responsible for spring infections, can germinate without water on the leaves as long as the relative humidity is significantly high (>85%) due to the high moisture content of the spores (Stromberg 2010). Ascospores or conidia can directly penetrate upper epidermal cells and absorb nutrients using haustoria. Powdery mildew is a cool season disease, with optimal development between 15-22°C (Stromberg 2010). Warm temperatures later in the growing season can result in an unfavorable environment for *B. graminis* development, limiting the spread of powdery mildew from the lower canopy to upper tissues. In susceptible varieties and under optimal environmental conditions, yield losses of 34 to 40% have been reported (Niewoehner and Leath 1998, Stromberg 2010). However, yield loss due to this disease in the mid-Atlantic is unclear, as outbreaks are sporadic, and the disease is rarely detected in the upper canopy.



Figure 4 Powdery mildew on wheat leaves (left) and close-up of mycelium with arrow pointing to chasmothecia. Photos by P. Sylvester.

Leaf Rust and Stripe Rust

Rusts are basidiomycetes, which are a group of fungi producing sexual spores on club-shaped structures called basidia, and multiple other spore stages that can include teliospores, spermatia (pycniospores), aeciospores, and urediniospores. (Agrios 1997, Zhao et al. 2016). Urediniospores can be part of a secondary reproductive cycle, which involves the repeated production of spores several times during the growing season. Rusts can have complex life-cycles involving alternate hosts, which are other plant species that can host the pycnial and aecial spore stages, but in North American urediniospores are considered the most important as they serve as primary inoculum and can be transported long distances by wind (Chen 2010, Kolmer 2010, Zhao et al. 2016). Urediniospore germ tubes penetrate leaf tissue with an appressorium or enter through stomata directly. Rusts have short spore generation times (7-10 days), which can lead to severe epidemics in a short amount of time given optimal conditions, especially on susceptible varieties (Chen 2010, Kolmer 2010). The two rusts found in mid-Atlantic SRWW are leaf rust and stripe rust.

As the name implies, stripe rust can be identified by the characteristic yellow to orange uredinia in a line on the upper leaf surface (**Fig. 5**), although it may infect the awns and glumes as well. Stripe rust has a complex lifecycle with five separate stages including the aecial and pycnial stages occurring on barberry (*Berberis* sp), which serves as the alternate host, and uredinial and telial stages occurring on wheat, with the basidial state occurring between wheat and barberry (Zhao et al. 2016). Of the five stages, the uredinial stage in which urediniospores, or asexual spores, are produced, is repeating and is the most important for infections of wheat. Compared to leaf rust, stripe rust prefers slightly cooler temperatures 10-17°C but does not survive

below -5°C. Conversely, extended periods of temperatures above 32°C stop sporulation whereas temperatures over 38°C are lethal (Sharma-Poudyal et al. 2014). Only a light dew or rain showers are needed for spore germination (Chen 2010). Therefore, conditions in the mid-Atlantic states are unfavorable for both over-summering and overwintering (Sharma-Poudyal et al. 2014). Stripe rust can be particularly damaging when infections begin very early on highly susceptible varieties, causing yield reductions of over 90% (Chen 2005, 2014). However, outbreaks in the mid-Atlantic are inconsistent, and the extent of yield loss depends on the growth stage when infections occur.

Leaf rust is one of the most widely distributed diseases of wheat (Kolmer 2010). Like stripe rust, leaf rust has five separate stages, although the alternate host is different (*Thalictrum* spp.) (Huerta-Espino et al. 2011, Zhao et al. 2016). Leaf rust produces orange-red urediniospores contained in uredinia, which are scattered on the leaf rather than any discernable pattern (**Fig. 5**). *P. triticina* (leaf rust) prefers warmer temperatures between 20-25°C and only needs six hours for spore germination (Kolmer 2010). While infections are dependent on spores from the southern US, its preference for warm temperatures coincides with later wheat development during grain fill, which may impact grain quality and yield. Leaf rust can reduce grain yield by 50% (Huerta-Espino et al. 2011), with losses of 32% reported in the mid-Atlantic (Green et al. 2014).



Figure 5 Stripe rust (left) and leaf rust (right). Photos by P. Sylvester.

Foliar Disease Control Strategies in Wheat

Integrated Disease Management (IDM) is often recommended for control or suppression of foliar and head diseases in wheat. IDM involves the adoption of multiple practices such as crop rotation, tillage to bury residue, host resistance, and fungicide applications to limit multiple aspects of pathogen biology and epidemiology (Cowger et al. 2016b, Jorgensen and Olsen 2007, Salgado et al. 2014). Crop rotation is the practice of planting different crops in alternating sequences so that the same crop is not grown year after year. This practice has been shown to increase yields in fields where a corn-soybean rotation is implemented (Pedersen and Lauer 2003, Porter et al.

1997). A corn-wheat-soybean rotation is often used in the mid-Atlantic region, meaning wheat is planted in the same field every two years. If crops are not rotated, or crops are rotated that host the same disease, rotational effects are minimized. For example, *F. graminearum*, which causes FHB, can infect corn. Consequently, when producers plant wheat following corn, corn residue serves as a local inoculum source (Freije and Wise 2015).

Tillage is the use of an implement, such as a moldboard plow, to bury residue, thereby enhancing residue decomposition, limiting food source for non-obligate pathogens that cause diseases such as LBC and FHB, and limiting sporulation from fungal structures on the soil surface. Tillage can decrease disease severity in wheat (Carignano et al. 2008, Jorgensen and Olsen 2007, Simon et al. 2011). However, many farmers have adopted conservation practices or committed to NRCS programs in our region that do not allow tillage in grain crops and therefore the burial of residue is not an option. A recent survey of fields in Delaware has shown no-till and conservation tillage is popular (DNREC, unpublished), with over 85% of the acres utilizing some sort of conservation tillage, and there is no reason to suspect this will change in the near future. Thus, many wheat producers in the region grow wheat in fields with significant quantities of crop residue on the soil surface, which may result in greater amounts of initial inoculum for some fungal diseases.

Host resistance, or the practice of choosing disease-resistant varieties to grow, can be a highly effective and economic disease management practice (Chen 2010, Martens et al. 2014, Ransom and McMullen 2008, Willyerd et al. 2012). In wheat, host resistance is considered one of the most efficient means of managing diseases such as powdery mildew, leaf rust, stripe rust, and FHB (Chen 2014, Green et al.

2014, Willyerd et al. 2012). The two types of resistance to disease are quantitative and qualitative (Agrios 1997). Quantitative, or incomplete, resistance depends on many genes that work together and lead to a general reduction in disease. Conversely, qualitative, or complete resistance, depends on one or a few genes that specifically function to detect pathogens and rapidly implement defense strategies. Resistance in wheat is a complex subject beyond the scope of this thesis. However, it is important to note that commercially available varieties may not contain resistance to all foliar and head diseases that may be present in a field. For example, a variety may contain resistance to powdery mildew, but not leaf rust (Green et al. 2014). Growers have little to no indication as to which foliar disease(s) may threaten production in a given year, making disease based variety selection difficult. Furthermore, even though producers realize the importance of resistance in disease management, variety selection often starts with yield and quality characteristics, and resistance to common diseases is the third most important criteria for selection (Jorgensen et al. 2017). One reason for this is the notion of a “yield-drag” or lowered yields with disease-resistant varieties (Brown 2002). Yield drag occurs when, in the absence of disease, yield may be reduced relative to a variety without the resistance. It does not mean growers plant susceptible varieties, and in fact, most varieties are produced to have resistance to common diseases in the region to improve average yield, however, is not priority.

The aforementioned disease management practices often do not completely prevent diseases from occurring at some level. Growers also need tools that allow for intervention during the growing season if fungal diseases do occur on the foliage or heads. For this reason, fungicides are one of the most popular tools used by growers for foliar disease management (Kelley 2001, Milus 1994), in particular with the

release of new products with better performance, higher grain prices, and reduced fungicide costs.

Fungicides are chemicals used to suppress or control growth of fungal pathogens that may infect and cause damage to plants. (Mueller et al. 2013). Foliar fungicides are applied to the above-ground portions of the plants, usually with a ground sprayer or through aerial application. In short, they work by stopping the infection process used by pathogen to cause disease (Oliver and Hewitt 2014). Fungicides may be classified as multi-site, meaning they work on several metabolic processes within fungal cells, or single-site, which are active at one point or function within metabolic pathways of fungi (Mueller et al. 2013). Single site fungicides tend to be systemic, meaning they can move within the plant after application, while non-systemic tend to be multi-site fungicides and do not enter the plant. Systemic fungicides provide both protectant and curative properties when applied early in the infection cycle. Conversely, non-systemic fungicides tend to only have protectant properties and must be reapplied often to be effective (Mueller et al. 2013).

Fungicides are often described by their mode of action, or the method by which they inhibit key biochemical functions within the plant (Oliver and Hewitt 2014). They may be further divided in target site, groups or class name, and chemical group (FRAC 2017). Modern fungicides with active ingredients in the demethylation inhibitor [DMI, FRAC code 3 (FRAC 2017)], quinone outside inhibitor (QoI, FRAC code 11), and/or succinate dehydrogenase inhibitor (SDHI, FRAC code 7) classes of fungicides are highly effective against many foliar diseases in SRWW (NCERA184 2017). This is partly due to the mobility of modern fungicides within the plant (locally systemic or translaminar), which provide protection from new infections (Oliver and

Hewitt 2014). For example, DMI fungicides are locally systemic and can move within a leaf, but not necessarily from one leaf to another or from one part of the plant to another (Mueller et al. 2013). QoI and SDHI fungicides are also locally systemic or translaminar and may move upward through the xylem or be redistributed to other leaves through a vapor phase (Bartlett et al. 2002, Mueller et al. 2013). DMI, SDHI, and QoI fungicides also contain some curative activity against early infections or may also prevent spore germination (Bartlett et al. 2002). In general, fungicides within a similar mode of action have similar spectra of activity, but some differences in curative control, potency, or duration of control after application may occur. Fungicides are most effective when applied to tissues that are strongly involved in the generation of yield prior to significant infection of these tissues by fungal pathogens.

Foliar Fungicides used in SRWW

DMI (triazoles)

The DMIs contain the triazoles, which are considered the cornerstone class of fungicides for foliar disease management in small grains (Oliver and Hewitt 2014). They are classified as systemic, protectant, curative, and eradicants (Oliver and Hewitt 2014) and have a broad activity spectrum and utility against many major ascomycete and basidiomycete pathogens (Hewitt 1998). DMI fungicides inhibit the C-14 demethylase enzyme which has a role in ergosterol production, necessary for cell wall growth, and eventually causes abnormal fungal growth and death (Mueller et al. 2013). However, DMI fungicides have no activity on spore germination since spores contain enough sterol to germinate (Mueller et al. 2013). Triazoles have been used in wheat production since the 1970's, with the most recent release in 2004 of the active

ingredient prothioconazole (Oliver and Hewitt 2014). This was important because prothioconazole is one of the few triazoles considered to be effective at reducing FHB (Paul et al. 2010). In a meta-analysis of select triazoles in 100 uniform fungicide studies across 11 years, Paul et al. (2008) reported that the fungicide Prosaro[®] (prothioconazole + tebuconazole) was one of the most effective products for reducing FHB severity. Preliminary fungicide efficacy trials in the mid-Atlantic have demonstrated good to excellent efficacy with Prosaro[®] on foliar diseases as well (Grybauskas and Reed 2011, Kleczewski 2014c, 2017a, b, Phipps et al. 2012, Rideout et al. 2009). Other commonly used triazole fungicides include Tilt[®] (propiconazole), Folicur[®] (tebuconazole), and Caramba[®] (metaconazole) (Hunger and Marburger 2017, Mehl and Kleczewski 2017).

QoI (strobilurins)

QoI's contain the strobilurins, which were discovered in a group of wood-rotting fungi belonging to the basidiomycetes (Bartlett et al. 2002). Strobilurins have been highly successful, with a broad spectrum of activity against basidiomycetes, ascomycetes, and oomycetes pathogens (Oliver and Hewitt 2014). Strobilurins act at the quinone outer binding site of the cytochrome bc1 complex (Mueller et al. 2013), inhibiting fungal mitochondrial respiration which stops energy producing resulting in death of the fungus (Bartlett et al. 2002). Strobilurins are potent inhibitors of spore germination making them highly effective when applied before infection or in the very early stages of development (Clough and Godfrey 1998, Mueller et al. 2013). In addition, the strobilurins have been shown to alter developmental and physiological changes in plants such as reduced loss of chlorophyll resulting in delayed leaf

senescence due to inhibition of ethylene formation and may increase water use efficiency through reduced stomatal aperture (Grossmann et al. 1999, Grossmann and Retzlaff 1997). These physiological effects or “plant health” benefits have been marketed to increase yield in the absence of disease leading to an increase in prophylactic applications (Chen et al. 2015, Weisz et al. 2011, Willyerd et al. 2015). However, results from field experiments are inconclusive (Swoboda and Pedersen 2009) and impacts to yield may not be enough to offset the cost of application (Henry et al. 2011, Orlowski et al. 2016, Weisz et al. 2011). Examples of products containing strobilurins used in wheat fungicide programs include (only the strobilurin component listed): Priaxor[®], Nexicor[®], and TwinLine[®] (pyraclostrobin); Quilt Xcel[®] and Trivapro[®] (azoxystrobin); Stratego YLD[®] and Absolute Maxx[®] (trifloxystrobin); and Approach Prima[®] (picoxystrobin) (Mehl and Kleczewski 2017). Some differences exist within the strobilurins fungicides (Bartlett et al. 2002). For example, pyraclostrobin is locally systemic whereas azoxystrobin and picoxystrobin have a greater degree of systemic movement within the plant (Bartlett et al. 2002).

SDHI (carboxamide)

One of the fastest growing segments in the fungicide industry has been the inclusion of SDHI fungicides, specifically those within the carboxamide group (NCERA184 2017). Similar to the strobilurins, the succinate dehydrogenase inhibitors (SDHI) work on the respiration chain, though on a separate enzyme (Avenot and Michailides 2010). Several new molecules with efficacy and spectra similar (no oomycetes to date) to the strobilurins have been released in the last ten years (Sierotzki and Scalliet 2013). Examples of commercially available SDHI fungicides

used in wheat include (only the SDHI component listed) Priaxor[®] (fluxapyroxad) and Trivapro[®] (benzovindiflupyr) (Mehl and Kleczewski 2017).

The three classes above have been highly-effective against major foliar wheat diseases, but are also at medium to high risk for fungal resistance. Fungal resistance to fungicides occurs when there is a reduction in sensitivity and pathogens are no longer suppressed or controlled with a fungicide that once proved to be efficacious (FRAC 2017). This occurs because fungicide are exerting selection pressure on a population, which kills the susceptible population, but not potential resistance (mutant) types (Jorgensen et al. 2017). Furthermore, the fungicide modes of action used in wheat target single-sites within specific biochemical processes within fungi, and are at a greater risk of developing fungicide resistance. (Oliver and Hewitt 2014). Resistance issues are especially problematic when targeting pathogens with high fecundity, which produce lots of spores quickly, such as powdery mildew (Oliver and Hewitt 2014). Examples of QoI and DMI resistant LBC pathogens have been documented in Northern France (Cheval et al. 2017) and China, Denmark, Sweden, and Switzerland (Pereira et al. 2017). Recently, a tebuconazole resistant field isolate of *F. graminearum* was found in New York (Spolti et al. 2014). Unlike vegetable crops with a wide range of available fungicide classes and rotational programs, fungicides for use in wheat are almost exclusively limited to the three classes described above. In an effort to reduce resistance issues, most commercial products now come in pre-mixtures containing a combination of DMI, QoI, and/or SDHI fungicides (van den Bosch et al. 2014). However, applying the same fungicides in multiple applications put significant selection pressure on fungal populations (van den Berg et al. 2016).

This highlights the importance of application timing for control of foliar disease to prevent yield loss.

Foliar Fungicide Application Timing

The scheduling of a fungicide application is often based on plant growth stage. There are several reasons for this including label restrictions, ease of scheduling, and lack of reliable disease thresholds (Paveley et al. 1997). While models for disease forecasting have been developed for FHB management (<http://www.wheatcab.psu.edu/>), they are lacking or being slowly developed for other foliar diseases such as STB and SNB (Jorgensen et al. 2017, Mehra et al. 2017, Zearfoss et al. 2011). Therefore, growth stage based applications remain widely used in wheat production.

Standard fungicide applications for control of foliar diseases in wheat have historically occurred between flag leaf emergence (FGS 8) and heading (FGS 10.5) (Edwards and Hunger 2011, Mourtzinis et al. 2017, Willyerd et al. 2015). This timing was selected because it protects the flag leaf shortly after emergence. However, due to the frequency of FHB outbreaks, many growers have shifted away from FGS 8-10.5 applications and towards a single fungicide application at FGS 10.5.1. To be effective against FHB, fungicides must be applied in a relatively short period around flowering, between FGS 10.5.1 and six days following flowering (D'Angelo et al. 2014, Freije and Wise 2015, Willyerd et al. 2012). However, FGS 10.5.1 applications have not been thoroughly evaluated for foliar disease control and potential to return a profit in mid-Atlantic production settings.

Two-Pass Programs

Recently, fungicide applications are occurring early in the season at FGS 5 as insurance against the early onset of foliar diseases (Willyerd et al. 2015). In general, reduced rates of fungicides are used, and growers will tank mix with fertilizer to lower application costs. The use of half rates of fungicides is controversial (Jorgensen et al. 2017), and fungicides applied at FGS 5 do not protect the flag leaf and head. Therefore, they are combined with an application at FGS 8 or FGS 10.5.1. Preliminary efficacy trials with early season applications using split rates have shown disease suppression and yield increases in some scenarios (Rideout and Waldenmaier 2011). However, efficacy trials often use susceptible varieties which tend to overestimate yield increases compared to many commercial varieties with some tolerance to common foliar disease. Furthermore, these two-pass fungicide application programs have not been adequately assessed under grower conditions in mid-Atlantic wheat production systems. In addition, although there has been some research addressing sequential applications of fungicides for foliar diseases of wheat in other parts of the United States (Wegulo et al. 2009, Willyerd et al. 2015) and Canada (Caldwell et al. 2017, Fernandez et al. 2014), to our knowledge, the use of a FGS 10.5.1 fungicide application in sequential fungicides programs has not been thoroughly evaluated in the mid-Atlantic region.

Profitability of Fungicide Programs

Even though fungicides may suppress or control disease, thereby protecting yield and grain quality, fungicide applications represent an additional expense to the grower. Growers select fungicide programs, consisting of a product and timing, based

on economics rather than disease control or yield response alone. In other words, growers often want to know if a fungicide program will deliver a yield increase high enough to offset the cost of the fungicide and associated application fee. However, yield response and subsequent profitability are variable. Past research has shown environmental conditions which influence the development of disease can impact profitability and in general, conditions that favor moderate to severe disease development increase the potential profitability of a fungicide program (Edwards et al. 2012, Wegulo et al. 2011). An evaluation of 42 fungicide trials in Virginia and North Carolina showed routine fungicide applications in no-disease environments had a low probability (<50%) of profitability, whereas fungicide applications in the presence of foliar disease had a greater than 50% of profit (Weisz et al. 2011). In mid-West SRWW, fungicide use increased yields 7.4-16.8% when leaf rust, powdery mildew, and FHB were present (Mourtzinis et al. 2017). In addition to disease pressure being as a factor in profitability, the use of genetic resistance also influences whether a fungicide application will be profitable. In Oklahoma, HRRW sprayed with Quilt® or Stratego® at FGS 9 or 10 increased yields 11% in resistant or intermediate varieties and 20% in susceptible varieties compared to the untreated check (Thompson et al. 2014). In North Dakota, susceptible varieties were found to be the most responsive to fungicide applications when disease pressure is moderate (Ransom and McMullen 2008). Grain prices and fungicide costs also influence profitability. Wiik and Rosenqvist (2010) found that doubling or tripling grain prices had the biggest impact on profitability from fungicide programs, and to a lesser degree, the cost of the fungicide. One extreme case from Texas showed notable returns when grain prices are

high $\$0.25 \text{ kg}^{-1}$ ($\$6.80 \text{ bu}$) and fungicide application programs costs are low $\$17.30 \text{ ha}^{-1}$ ($\$7.00/\text{ac}$) (Lopez et al. 2015).

Project Focus

To date, two-pass (FGS 5 FB FGS 8 or FGS 5 FB FGS 10.5.1) and FGS 10.5.1 applications for foliar disease have not been adequately assessed, or compared to the standard flag leaf fungicide application at FGS 8 under mid-Atlantic conditions, yet many producers consider their use mandatory for producing high yielding wheat. Producers in the region routinely question researchers and extension agents such as myself as to which fungicides, timings, or programs are the “the best” and if “it pays” to apply a fungicide. The main goal of my Master’s thesis is to provide some answers to these questions in the region through replicated studies and statistics.

Previous studies have been conducted in other wheat growing regions of the United States or used susceptible varieties which may over-estimate the yield response from a fungicide application. This area presents unique foliar disease management challenges, given the characteristic moderate temperatures and high humidity experienced during the growing season. Other considerations such as crop rotations and varieties are specific to the mid-Atlantic. This research will address this knowledge gap and provide growers in the mid-Atlantic with pertinent information to make informed decisions regarding profitable fungicide use in SRWW production.

Research Goals

The goals of this research are to 1) evaluate the effectiveness of commonly used fungicide programs for managing foliar diseases; 2) determine if two-pass

fungicide programs are more efficacious than a single fungicide application at FGS 8 or FGS 10.5.1 for management of fungal diseases of the foliage; 3) determine the impact of fungicide applications at FGS 10.5.1 for foliar disease control, grain quality, and yield; and 4) assess the profitability of commonly used growth-stage based fungicides programs for managing foliar diseases of SRWW in the mid-Atlantic region of the United States. To address these questions, we tested thirteen fungicide programs, consisting of five different fungicides applied at specific growth stages, on SRWW at ten different environments in Delaware, Maryland, Pennsylvania, and Virginia.

The research contained within this thesis has been accepted for publication or is under review in the following peer-reviewed journals: Chapter 1- Crop Protection (*accepted for publication; Vol. 103, January 2018, pages 103-110*) and Chapter 2- Plant Disease (*under review*). Chapters are presented as individual publications. Chapter 1 focuses solely on fungicide efficacy within Delaware and Maryland, whereas Chapter 2 examines fungicide profitability through the use of meta-analysis on replicated studies in Delaware, Maryland, Pennsylvania, and Virginia.

Chapter 1

EVALUATION OF FOLIAR FUNGICIDE PROGRAMS ON FOLIAR DISEASE, GLUME BLOTCH, NDVI, TEST WEIGHT, AND YIELD

Accepted for publication in Crop Protection (22 September 2017)

Sylvester, P. N., and Kleczewski, N. M. 2018. Evaluation of foliar fungicide programs in mid-Atlantic winter wheat production systems. *Crop Protection* 103:103-110.

Abstract

Foliar fungicides are commonly used to manage foliar fungal diseases of soft-red winter wheat (SRWW) grown in the mid-Atlantic region, but data on the overall performance and utility of various products and application timings on yield and quality is lacking. Eight replicated experiments were conducted in Delaware and Maryland in 2015 and 2016 to evaluate the effects of 13 fungicide programs, consisting of five commercially-available fungicides applied at flag leaf emergence [Feekes growth stage (FGS) 8], anthesis (FGS 10.5.1), or in two-pass programs with the first application at green-up (FGS 5) followed by applications at either FGS 8 or FGS 10.5.1, for utility on naturally occurring foliar diseases on the flag leaf and head, yield, and test weight compared to an untreated check. All fungicide programs reduced disease severity on the flag leaf and resulted in higher test weight and yield compared to the untreated check. Foliar disease on the flag leaf and glume blotch were best managed with FGS 10.5.1 applications. Two-pass programs (FGS 5 + FGS 8 or FGS 5 + FGS 10.5.1) did not result in significantly lower disease severity compared to single applications at FGS 8 or FGS 10.5.1. Yield was highest within the FGS 5 + FGS 10.5.1 timing, and while significant, increases were small, ranging from 111 to 198 kg ha⁻¹. Within a given application timing, Priaxor® (FGS 8), Quilt Xcel® (FGS 5 + FGS

8), and Quilt Xcel[®] (FGS 5) + Prosaro[®] (FGS 10.5.1) provided the greatest yields. This information will help guide Integrated Disease Management (IDM) systems in the mid-Atlantic region and assist growers in avoiding unnecessary fungicide applications in SRWW.

Introduction

In the United States, wheat (*Triticum aestivum* L.) is grown on nearly 17.8 million ha and valued at over \$9 billion (NASS, February 2017, September 2016). In Delaware and Maryland, soft-red winter wheat (SRWW) is an important rotational crop planted in the fall after grain corn, soybean, or high-value processing vegetable crops, and is grown on 174 thousand ha with an average yield of 4,300 kg ha⁻¹ valued at over \$78 million (NASS February 2017, September 2016). SRWW is an important part of the agricultural economy in the mid-Atlantic, as it is used to supply the large flour-mill industry in the region, particularly in Pennsylvania (NASS May 2017).

The health of the photosynthetic tissues including the head, flag leaf, flag leaf sheath, and sheath above the flag-leaf are critical for wheat yield, as they contribute approximately 95% of the carbohydrates for grain fill (Lupton 1972). Diseases affecting the foliage and head of wheat can reduce photosynthetic area and grain fill; impacting both yield and test weight (Milus 1994, Milus and Chalkley 1997). In the mid-Atlantic, leaf blotch complex (LBC), including the residue-borne diseases *Stagonospora nodorum* blotch (*Parastagonospora nodorum* (Berk.) Quaedvlieg, Verkley & Crous), *Septoria tritici* blotch (*Zymoseptoria tritici* (Desm.) Quaedvlieg & Crous), and tan spot (*Pyrenophora tritici-repentis* (Died.) Drechsler), is the most common foliar disease encountered in grower fields. A major reason for this is the recent shift towards no-till and conservation tillage in the region (Mehra et al. 2015,

Schuh 1990). LBC may result in yield reductions between 20-48% when they reach the flag leaf or above (Bergstrom 2010, McMullen 2010, Wegulo et al. 2009). However, yield impacts of LBC in the mid-Atlantic are not well established, and evidence suggests that these diseases do not reach these tissues until later in the growing season, potentially limiting their overall yield impact (Grybauskas and Reed 2011, Kleczewski 2017a, b). Other foliar diseases such as powdery mildew (*Blumeria graminis* (DC.) Speer.), leaf rust (*Puccinia triticina* Erikss.), and stripe rust (*Puccinia striiformis* Westend.) may occasionally impact yield and grain quality in the mid-Atlantic (Bowen et al., 1991, Cowger et al. 2016a, Green et al. 2014). Fungal diseases affecting wheat heads include Stagonospora glume blotch (*Parastagonospora nodorum*) and Fusarium head blight (FHB) (*Fusarium graminearum* Schwabe). In addition to causing significant yield losses, the pathogen that causes FHB infections also produces mycotoxins, which are toxic to livestock and humans (Payros et al. 2016).

Fungicides are one component of Integrated Disease Management (IDM) used by growers to protect the flag leaf and head from fungal diseases (Kelley, 2001). Traditionally, fungicides are applied between flag leaf emergence (FGS 8) and heading (FGS 10) (Willyerd et al. 2015). However, threats to regional wheat production by FHB and glume blotch have forced growers to re-evaluate fungicide application timings. The use of a fungicide application for FHB management, which needs to occur within 5-6 days after the start of FGS 10.5.1, has become more common (D'Angelo et al. 2014, Wegulo et al. 2011). Although several studies have examined the impact of FGS 10.5.1 applications for FHB control in manipulated experimental settings, none have evaluated the utility of this timing for overall control

of foliar disease and yield in typical, mid-Atlantic production setting. In addition, many producers include a fungicide early in the season at greenup (FGS 5) as insurance against the early onset of foliar diseases. Fungicide applications at FGS 5 will not provide protection of the flag leaf and head and therefore, are combined with an application at FGS 8 or FGS 10.5.1. These sequential fungicide application programs have not been adequately assessed for their utility and yield compared to standard, FGS 8 applications in mid-Atlantic wheat production systems. In addition, although there has been some research addressing sequential applications of fungicides for foliar diseases of wheat in other parts of the United States (Wegulo et al. 2009, Willyerd et al. 2015), to our knowledge, the use of a FGS 10.5.1 fungicide application in sequential fungicides programs has not been thoroughly evaluated in the mid-Atlantic region.

Growers have many choices when it comes to selecting a fungicide product. However, the majority of fungicides used in small grain production contain active ingredients belonging to the triazole (Fungicide Resistance Action Committee (FRAC) group 3), strobilurin (FRAC group 11), SDHI (FRAC group 7) classes, or combinations thereof. In the mid-Atlantic states of Virginia and North Carolina, Weisz et al. (2011) analyzed fungicides programs containing active ingredients belonging to the triazole or strobilurin class and found the yield response to a fungicide to be highly variable, ranging from 1680 kg ha⁻¹ to -540 kg ha⁻¹, with a mean response of 310 kg ha⁻¹. Our data will contribute to this research by conducting a planned experiment, using a commercially available, moderately resistant variety, with commonly encountered fungicides used in the mid-Atlantic at specific timings. A better understanding of how fungicide timing in relation to the product used is essential in

promoting wheat production while potentially avoiding unneeded application costs and environmental impact.

The goals of this project were to 1) evaluate the utility of commonly used fungicides for managing foliar diseases in the mid-Atlantic, 2) determine if sequential fungicide programs are more efficacious than a single fungicide application at FGS 8 or FGS 10.5.1 for management of fungal diseases of the foliage and the head, and 3) determine the impact of fungicide applications at FGS 10.5.1 for foliar disease control, grain quality, and yield. To address these questions, we conducted a replicated field study across eight sites and two years.

Materials and Methods

Trials were conducted at four sites in 2015 and 2016 as described in **Table 1**. The experimental design was a randomized complete block (RCB) with six replications. The SRWW variety ‘Growmark FS815’ was planted at a rate of 4.4×10^6 seeds ha⁻¹ with no-till drills. FS815 was selected because it represents a commercially available, high yielding variety planted throughout the region (University of Delaware 2012-2014, University of Maryland 2012-2014). The variety is characterized by medium maturity, with average test weight and height, and moderately resistant to leaf rust, powdery mildew, and LBC (Kleczewski 2013, 2014d). Plots were similar in size though varied with equipment (**Table 1**). Untreated border rows between adjacent plots and at plot ends were used at all sites. Fields with typical crop rotations of the region were selected to provide a broad range of residue and conditions (**Table 1**). Standard nutrient management and pest management practices were followed for each state (Coale 2010, Curran et al. 2016, Shober et al. 2017). In addition to rainfall, irrigation was used at three sites in 2015 (5.1 cm at GT15, 7.2 cm at FT15, and 14.4

cm at HB15) and two sites in 2016 (3.6 cm at HB16, 3.8 cm at GT16) ensuring some disease.

Fungicide Programs

Thirteen fungicide programs, consisting of five fungicides and three timings, were evaluated according to **Table 2**. The fungicides tested were propiconazole (Tilt[®], Syngenta Crop Protection, Greensboro, NC), azoxystrobin + propiconazole (Quilt Xcel[®], Syngenta Crop Protection, Greensboro, NC), fluxapyroxad + pyraclostrobin (Priaxor[®], BASF Corporation, Research Triangle Park, NC), prothioconazole + trifloxystrobin (Stratego[®] YLD, Bayer CropScience, Research Triangle Park, NC), and prothioconazole + tebuconazole (Prosaro[®] 421SC, Bayer Crop Science, Research Triangle Park, NC). The fungicides tested represented commonly used products in the region and differed in initial cost and mode of action. Fungicide application timings tested included Feekes Growth Stage (FGS) 8/9 (flag leaf emergence), FGS 10.5.1 (flowering), and split applications at FGS 5 (leaf sheaths strongly erect) followed by either FGS 8 or FGS 10.5.1 (**Table 2**). FGS 5 applications are used because growers believe they may reduce yield losses due to early season disease development; however, these programs have not been adequately tested in this region. FGS 8 applications are used to protect the flag leaf from foliar diseases but provide limited protection of the glumes, sheath, or flowering head. The use of FGS 10.5.1 applications are the newest fungicide application timing used in the region. This timing enables suppression of Fusarium head blight (FHB) and glume blotch, and also can protect the flag leaves, sheath, and glumes from other late-season foliar diseases (Kleczewski 2014a, b, c, 2017a, b).

All fungicide treatments included 0.125% of a nonionic surfactant (Induce[®], Helena Chm. Company, Collierville, TN). Treatments were applied using a CO₂ pressurized backpack sprayer (R&D Sprayers, Opelousas, LA) and offset handheld boom equipped with three XR8002 flat fan nozzles (TeeJet Technologies, Wheaton, IL) spaced 50.8 cm apart. Treatments were made at a spray pressure of 234 kPa to deliver 187 liters ha⁻¹ of spray solution.

Flag Leaf Severity

In both years, flag leaf severity (percent diseased leaf area) on the flag leaf of ten arbitrarily selected tillers were estimated before plant senescence between late milk (FGS 11.1) and soft dough (FGS 11.2). The total amount of disease from all sources was used to determine the percent of affected leaf tissue. If possible, a subsample of leaves from the untreated check plots were collected and observed under a compound microscope to estimate the approximate disease composition for each site. Extremely low levels of barley yellow dwarf virus was present at WY16 and FT16 but were not included in foliar disease ratings since average incidence and severity was estimated to be less than 1%.

Glume Blotch Ratings

No GB ratings were recorded in 2015 because GB was not detected in plots. In 2016, glume blotch was rated at FT16, GT16, HB16, and WY16 at late milk stage (FGS 11.1). Briefly, the spikes of ten arbitrarily selected tillers per plot were assessed for incidence by counting the number of spikes with glume blotch symptoms and for severity as the average percentage of symptomatic spikelets on symptomatic spikes. The Glume blotch index (GBI) was calculated as the product of incidence and severity

divided by 100 [$GBI = (incidence * severity) / 100$]. Similar methods have been used to evaluate FHB (Cowger et al. 2016b, D'Angelo et al. 2014, Paul et al. 2008, Salgado et al. 2015).

NDVI

In both years, NDVI (Normalized Difference Vegetation Index) was recorded between FGS 11.1 and FGS 11.2 at all sites to estimate plant biomass. A GreenSeeker[®] handheld optical crop sensor (Trimble Navigation Limited, Westminster, CO) was held approximately 60 cm above the crop canopy, and plots were continuously scanned while walking along the plot at a constant pace (per instructions provided by the company). The crop sensor emits red and near-infrared light to measure the amount of crop reflectance, essentially providing a quantitative measurement of biomass. A representative mean value was recorded once the observation was completed for each plot. NDVI was recorded the same day as disease severity ratings.

Test Weight and Yield

In both years, plots were harvested with a Massey Ferguson 8XP research plot combine (Kincaid Equipment Manufacturing, Haven, KS) equipped with a Harvest Master HM400 or HM800 GrainGage (Juniper Systems, Inc., Logan, UT). Yields were adjusted to 13.5% moisture and converted to kilograms per hectare based on a bushel weight of 25.87 kg per bushel. Test weight was converted to kilograms per cubic meter.

Data Analysis

Treatments were first analyzed as collapsed timings, hereafter referred to as timings, and then further analyzed as individual programs, hereafter referred to as programs. Data from all experiments were pooled and analyzed. Site, block nested within site, and program or timing interaction with site were treated as random effects, whereas, either program or timing were treated as fixed effects. Foliar disease severity data was analyzed using PROC GLIMMIX (SAS[®], Version 9.4, SAS Institute Inc., Cary, NC). The response distribution was specified as beta with a logit link function. Results are presented as least square means. All other data met assumptions of normality and data were analyzed using a linear mixed model. Means were separated following significant F-tests using Fisher's LSD ($\alpha=0.05$). Spearman rank correlation was used to test associations between foliar disease severity, GBI, NDVI, test weight, and yield.

Results

Effects of Fungicide Programs on Disease Severity (%) on the Flag Leaf

Leaf blotch complex (LBC), leaf rust, and powdery mildew were the most prevalent foliar diseases during this two-year study. In 2015, only LBC was detected on flag leaves. Mean foliar disease severity in the untreated checks was 5% (GT15), 7% (FT15), and 13% (HB15). LBC was the most prevalent disease on flag leaves in 2016; however, leaf rust and powdery mildew were detected at low levels. Mean foliar disease severity in the untreated checks was 32% (WY16), 41% (HB16), 79% (GT16), and 99% (FT16). Foliar disease severity was significantly reduced at all timings when compared to the untreated checks ($P < 0.0001$, $F_{4, 24} 34.11$) (**Fig. 6A**). Fungicides applied at FGS 8 reduced foliar disease by 58% compared to the untreated checks

while the FGS 10.5.1 timing reduced foliar disease by 91% (**Fig. 6A**). FGS 5 FB FGS8 and FGS 5 FB FGS 10.5.1 timings provided foliar disease control similar to FGS8 and FGS 10.5.1 timings. All tested programs significantly reduced foliar disease on the flag leaf relative to untreated checks. Of all the tested programs, QSPLT5+F provided the greatest amount of foliar disease control, reducing leaf disease 92% compared to the untreated checks, whereas TSOLO8 provided the lowest amount of control, only reducing foliar disease by 49% (**Table 3**). No significant differences were detected when comparing individual FGS 8 or FGS 10.5.1 programs to corresponding timings containing an application at FGS 5. Within the FGS 8 timing, QSOLO8 and XSOLO8 resulted in the lowest amounts of foliar disease. Within the FGS 5 FB FGS 8 timing, QSPLT5+8 resulted in the lowest amounts of foliar disease.

Glume Blotch Index

Mean GBI in the untreated checks was 86 (FT16), 58 (GT16), 66 (HB16), and 61 (WY16). All fungicide timings significantly reduced GBI when compared to the untreated checks ($P < 0.0001$, $F_{4,13.09} 45.1$) (**Fig. 6B**). Applications at FGS 10.5.1 timing resulted in the lowest GBI, nearly 48% less than the untreated checks and 40% less than the FGS 8 timing. The addition of an early application at FGS 5 to the FGS 8 and FGS 10.5.1 timings did not significantly reduce GBI when compared to the untreated check. Programs containing Prosaro® applied at FGS 10.5.1 resulted in lowest GBI when compared to FGS 8 programs (**Table 3**). All Prosaro® programs resulted in a similar reduction of GBI. Programs within the FGS 8 timings resulted in similar reductions and were not significantly different from each other. Within the FGS 5 FB FGS 8 timing, QSPLT5+8 resulted in significantly lower GBI than XSPLT5+8 but not SSPLT5+8 or TSPLT5+8. SSPLT5+8 resulted in a similar reduction of GBI compared

to TSPLT5+8 and SSPLT5+8. Disease severity was strongly correlated ($\rho=0.63$) to GBI (**Table 4**).

NDVI

Mean NDVI in the untreated checks was highest at FT15 (0.48), HB15 (0.47), and HB16 (0.46) and lowest at WY16 (0.37), FT16 (0.32), and GT15 (0.28). All fungicide application timings resulted in significantly higher NDVI values between FGS 11.1 and 11.2 compared to the untreated check ($P < 0.0001$, $F_{4,23.2}$ 25.84) (**Fig. 6C**). Applications at FGS 10.5.1 resulted in significantly higher NDVI values compared to applications at FGS 8, but not at FGS 5 FB FGS 8. Early applications at FGS 5 followed by an application at FGS 8 or FGS 10.5.1 did not significantly increase NDVI values compared to solo applications at FGS 8 and FGS 10.5.1. When timings were evaluated by program, those with a Prosaro[®] application at 10.5.1 resulted in similar NDVI values compared to the untreated checks. Within the FGS 8 timing, QSOLO8, XSOLO8, and SSOLO8 resulted in similar values and were significantly higher than TSOLO8. In the FGS 5 FB FGS 8 timing, QSPLT5+8 resulted in a significantly higher NDVI values compared to XSPLT5+8, SSPLT5+8, and TSPLT5+8. NDVI readings were not significantly different between XSPLT5+8, SSPLT5+8, and TSPLT5+8.

Test Weight

Mean test weight in the untreated checks was highest at GT15 (699 kg/mg³) followed by WY16 (665 kg/mg³) and HB16 (651 kg/mg³) while FT15 (644 kg/mg³), GT16 (591 kg/mg³), and FT16 (547 kg/mg³) had the lowest. All timings significantly increased test weight compared to the untreated check ($P < 0.0001$, $F_{4,22.1}$ 14.45) (**Fig.**

6D). The FGS 10.5.1 timing increased test weight 2% when compared to FGS 8 and 4% compared to the untreated checks. The addition of an early application at FGS 5 did not improve test weight compared to the solo applications at FGS 8 and FGS 10.5.1 timings. When timings were further assessed by program, all applications with Prosaro[®] applied at FGS 10.5.1 resulted in similar test weight (**Table 3**). Within the FGS 8 timing, QSOLO8 resulted in significantly greater test weight than TSOLO8. All programs with the FGS5 FB FGS8 timing increased test weight equally. Test weight was strongly correlated to disease severity ($\rho=-0.64$) (**Table 4**).

Yield

Minimum, mean, and maximum grain yields in the untreated checks across all seven environments were 2,508, 4,561, 5,713 kg ha⁻¹, respectively. All timings significantly increased yield compared to the untreated checks ($P < 0.0001$, $F_{4,10.95}$ 42.90) (**Fig. 6E**). Fungicides applied at FGS 5 FB FGS 10.5.1 resulted in significantly higher yield (5,227 kg ha⁻¹) compared to the untreated checks (4,561 kg ha⁻¹). Yields were not significantly different between the FGS 8 and FGS 10.5.1 timing. The addition of FGS 5 to the FGS 8 timing did not significantly increase yield. When timings were further assessed by program, QSPLT5+F resulted in the greatest yields (5,329 kg ha⁻¹), whereas yields were lowest in TSOLO8 (4,900 kg ha⁻¹) (**Table 3**). QSPLT5+F yielded significantly more than TSPLT5+F but not XSPLT5+F or SSPLT5+F. Within the FGS 8 timing, XSOLO8 yielded significantly more than TSOLO8, but not QSOLO8 or SSOLO8. QSOLO8 yielded significantly more than TSOLO8, but not SSOLO8. Within the FGS FB FGS 8 timing, QSPLT5+8 yielded significantly more than XSPLT5+8, SSPLT5+8, and TSPLT5+8. XSPLT5+8,

SSPLT5+8, and TSPLT5+8 did not result in significantly different yields from each other. Yield was strongly correlated to disease severity ($\rho=-0.77$) (Table 4).

Discussion

To our knowledge, this was the first comprehensive study to evaluate the impact of fungicide programs, consisting of applications at FGS 10.5.1 and FGS 8 or in sequential applications at FGS 5 FB FGS 8 and FGS 5 FB FGS 10.5.1, on flag leaf disease severity, glume blotch, test weight, and yield in the Chesapeake Bay region of the mid-Atlantic. In addition, this was the first study to examine the response of fungicide timings for a wide range of fungicide products currently used in wheat production. Results from our study showed fungicides increased yields by 556 kg ha⁻¹ compared to the untreated check, which was similar to Weisz et al. (2011), who showed average yield increases of 440 and 557 kg ha⁻¹ using strobilurin and triazole fungicides. Programs with a fungicide application at FGS 10.5.1 consistently resulted in the lowest disease severity on the flag leaf, lowest GBI, and highest test weight when compared to the traditional applications at FGS 8 and the untreated checks suggesting that applications made at flowering may be just as effective as those targeting the flag leaf. Fungicides applied at FGS 5 followed by either FGS 10.5.1 or FGS 8 did not significantly reduce disease severity on the flag leaf, lower GBI, or increase test weight when compared to solo applications at FGS 8 or FGS 10.5.1. However, they did result in a small, though significant, impact on yield when applied in conjunction with an application at FGS 10.5.1.

This study was conducted using a wheat variety used in the region which contained average resistance to many commonly encountered fungal pathogens encountered in the mid-Atlantic. The environments encountered throughout the course

of this study varied greatly, from an extremely dry 2015 to an exceptionally wet 2016. Thus, we believe that the results from this study provide an excellent average approximation of the utility and yield response of wheat grown in this region, similar to other studies conducted in Nebraska (Wegulo et al. 2009). The goal of this study was to examine the overall effectiveness and yield impact of fungicide products and application timings in situations more likely encountered by a grower.

Although several diseases were detected on the flag leaf in this study, LBC was the most prevalent disease encountered, occurring at all sites in both years. In 2016, morphological structures observed under a compound microscope revealed *Stagonospora nodorum* blotch (SNB) (*P. nodorum*) was by far the most common of the three LBC pathogens. This result supports observations by the authors and other agronomic professionals in the region, who have seen an increase in LBC with the increase in conservation tillage in the region. Recent research from North Carolina indicated that only 10% residue ground cover is needed to result in the development of SNB epidemics (Mehra et al. 2015). It follows that this residue-borne disease complex would frequently be encountered in a region where approximately 80% of acres utilize conservation tillage with residue levels greater than 15% (DNREC, unpublished).

The time course of infection and disease progression of LBC and SNB, in particular, may explain why FGS 10.5.1 applications were more efficacious than FGS 8 applications for disease control. In the mid-Atlantic, and specifically, in the region surrounding the Chesapeake Bay where this study was conducted, production conditions typically consist of cool, humid conditions until after flag leaves emerge. SNB infections begin in the residue and spores are rain-splashed from the base of the crop to the upper leaves (Eyal 1999). Prolonged, warm and humid conditions are

required for spore germination, and subsequent symptom development (Shaner and Buechley 1995), and disease development is slow, often taking nearly two weeks for spores to be produced on new lesions under favorable conditions. A lack of favorable temperatures early in the growing season and sufficient leaf wetness within the canopy until after full canopy closure would reduce disease development, and delay disease development on the flag leaf until after head emergence (FGS 10.3), which occurs approximately 7 to 10 days after FGS 8. Residual fungicide activity typically extends roughly 14 days after fungicide application, with reduced efficacy for an additional 5 to 7 days. If the development of SNB was absent or limited to regions of the lower canopy at FGS 8, it is likely that the residual control of the fungicide was not sufficient to prevent movement of the disease onto the flag leaf and above during later periods of grain fill. Fungicides applied at FGS 10.5.1 were likely applied prior to LBC or leaf rust development on the flag leaf in most instances, and protected the flag leaf, as well as the glumes, thereby reducing both foliar disease and glume blotch related yield losses. Observations of disease development recorded over time in 2016 indicated that in all fields, LBC or leaf rust was not observable on the flag leaf in untreated controls until FGS 11.1 (data not shown). Furthermore, glume blotch does not move onto the head until after flowering is complete and past research in the region has shown applications made after heading are most efficacious (Orth and Grybauskas 1994). Fungicidal activity from the FGS 8 applications has limited capacity for translocation and applications before head emergence will not translocate active ingredients to developing heads or flowers. In fact, our data showed only one of the four programs within the FGS 8 timing reduced glume blotch to levels low enough to be considered significant from the untreated check. The FGS 10.5.1 timing

protected the glumes into late grain fill and were effective in reducing glume blotch. This result does not mean that growers in the mid-Atlantic should completely remove the FGS 8 application as an option for their wheat production systems; in fact, this timing could still be efficacious in instances when foliar diseases, are detected early in the season and variety, and environmental factors are favorable for disease development. This may be particularly true for cool-season diseases with rapid generation times such as stripe rust, which caused significant yield losses in susceptible varieties in Delaware and Maryland wheat fields in 2008, 2016, and 2017.

The addition of an early-season fungicide application at FGS 5 has become more common in wheat production in the region and is viewed as cheap “insurance” against early season foliar diseases. This study showed that overall, the additional fungicide application did not provide any additional benefit in terms of reducing disease on the flag leaf or improving test weights. Other studies have shown similar results in different growing environments (Wegulo et al. 2009, Willyerd et al. 2015). In the Chesapeake Bay region of the mid-Atlantic, powdery mildew is the most frequently encountered early season disease. Powdery mildew requires significant amounts of humidity to develop, and in the mid-Atlantic, generally occurs in where fields have excessive vegetative growth due to the use of excessive early season nitrogen applications or use of poultry manure. The production of lush growth results in rapid canopy closure and development, and ultimately, increased levels of powdery mildew (Grybauskas et al. 1988). However, the development of powdery mildew typically is restricted to the lower canopy due to increases in temperature as the crop develops in addition to reduced humidity in the upper portions of the canopy. Powdery mildew was detected earlier in the season but did not persist through flag leaf

emergence in all but one site. This could partially explain the relative lack of a substantial yield response to early applications. Although this yield increase was statistically significant, other factors, such as product and application cost, grain price, and overall yield, are more likely to be more important in determining if this application timing is worthwhile for mid-Atlantic wheat production. Lastly, LBC was not detected on lower canopies in untreated controls until FGS 9 in 3 of 7 environments. Therefore, the potential benefit in terms of reducing disease development and spread of LBC to the upper canopy was minimal with an FGS 5 application, as residual control of disease was not likely sufficient to protect lower tissues from LBC when disease development began.

Growers have many options regarding fungicide products. Products vary in price but typically are comprised of solo QoI or DMI modes of action, or premixes containing combinations of QoI, DMI, and SDHI. In this study, we evaluated five commonly used fungicides in three combinations and found that the application of any fungicide, regardless of timing and product, reduced disease on the flag leaf, increased yields, and improved test weights when compared to untreated controls. Within the FGS 8 and FGS 5 FB FGS 8 timing, some products showed a slight, though significant, decrease in disease severity on the flag leaf and corresponding increase in yield (**Table 3**). However, additional research is needed that examines the utility of different products and timings for profitability, as a product that appears less efficacious may be more profitable in the long run. Overall, growers and crop consultants have flexibility in selecting products and that economic factors are more likely to impact fungicide selection and program selection for foliar disease control.

Summary and Conclusions

Application of fungicides, regardless of product or application timing, can significantly and consistently reduce disease of the flag leaf and increase yield and test weight compared to untreated controls, in mid-Atlantic wheat production systems. As such, fungicides are a useful tool for maximizing regional wheat yields, but should not subvert the use or promotion of sound integrated disease management programs. Although many growers utilize a growth stage-based fungicide program for wheat production, minimizing potential disease potential by careful variety selection and scouting may reduce potential fungicide inputs and unnecessary economic and environmental impacts.

Table 1 Description of sites in Delaware and Maryland used to evaluate the impact of foliar fungicide programs on foliar disease, glume blotch, NDVI, test weight, and yield.

Abb.	Site	Coordinates	Irrigation	Soil Type	Previous Crop	Planting Date	Plot Size (m)	Row Spacing (m)	Harvest Date
<i>2015</i>									
FT15	Felton, Delaware	39.006°N, 75.569°W	Yes	Sandy loam	Corn	29-Oct-14	1.4x7	0.18	1-Jul-15
GT15	Georgetown, Delaware	38.637°N, 75.453°W	Yes	Loamy sand	Corn	8-Oct-14	1.4x7	0.18	23-Jun-15
HB15	Harbeson, Delaware	38.679°N, 75.246°W	Yes	Loamy sand	Corn	27-Oct-14	1.5x7	0.19	25-Jun-15
WY15*	Queenstown, Maryland	38.916°N, 76.140°W	No	Silt loam	Corn	20-Oct-14	1.5x7	0.19	25-Jun-15
<i>2016</i>									
FT16	Felton, Delaware	39.006°N, 75.569°W	No	Sandy loam	Corn	15-Oct-15	1.4x7	0.18	30-Jun-16
GT16	Georgetown, Delaware	38.637°N, 75.453°W	Yes	Loamy sand	Wheat	9-Oct-15	1.4x7	0.18	1-Jul-16
HB16	Harbeson, Delaware	38.679°N, 75.246°W	Yes	Loamy sand	Corn	24-Oct-15	1.5x7	0.19	7-Jul-16
WY16	Queenstown, Maryland	38.916°N, 76.140°W	No	Silt loam	Corn	13-Oct-15	1.5x7	0.19	27-Jun-16

*Data were not included due to feeding damage from cereal leaf beetle

Table 2 Description of fungicides programs evaluated for their effects on flag leaf severity, glume blotch, NDVI, grain yield, and test weight in soft-red winter wheat in Delaware and Maryland in 2015 and 2016.

Fungicide(s) ¹	Fungicide Active Ingredient(s)	Total Active Ingredients (g ha ⁻¹) ²	Timing (FGS) ³	Product Rate (l ha ⁻¹) ⁴	Program ⁵
-	Untreated Control	-	-	-	CK
Tilt	propiconazole 41.8%	126	8	0.29	TSOLO8
Tilt FB Tilt	propiconazole 41.8%	63,126	5+8	0.15,0.29	TSPLT5+8
Tilt FB Prosaro	propiconazole 41.8% fb prothioconazole 19% & tebuconazole 19%	63,100,100	5+10.51	0.15,0.48	TSPLT5+F ⁶
Quilt Xcel	azoxystrobin 13.5% & propiconazole 11.7%	94,108	8	0.77	QSOLO8
Quilt Xcel FB Quilt Xcel	azoxystrobin 13.5% & propiconazole 11.7%	63,72,94,108	5+8	0.51,0.77	QSPLT5+8
Quilt Xcel FB Prosaro	azoxystrobin 13.5% & propiconazole 11.7% fb prothioconazole 19% & tebuconazole 19%	63,72,100,100	5+10.51	0.51,0.48	QSPLT5+F ⁶
Priaxor	fluxapyroxad 14.33% & pyraclostrobin 28.58%	97,49	8	0.29	XSOLO8
Priaxor FB Priaxor	fluxapyroxad 14.33% & pyraclostrobin 28.58%	49,24,97,49	5+8	0.15,0.29	XSPLT5+8
Priaxor FB Prosaro	fluxapyroxad 14.33% & pyraclostrobin 28.58% fb prothioconazole 19% & tebuconazole 19%	49,24,100,100	5+10.51	0.15,0.48	XSPLT5+F ⁶
Stratego YLD	prothioconazole 10.8% & trifloxystrobin 32.3%	37,110	8	0.29	SSOLO8
Stratego YLD FB Stratego YLD	prothioconazole 10.8% & trifloxystrobin 32.3%	18,55,37,110	5+8	0.15,0.29	SSPLT5+8
Stratego YLD FB Prosaro	prothioconazole 10.8% & trifloxystrobin 32.3% fb prothioconazole 19% & tebuconazole 19%	18,55,100,100	5+10.51	0.15,0.48	SSPLT5+F ⁶
Prosaro	prothioconazole 19% & tebuconazole 19%	100,100	10.51	0.48	PSOLOF ⁶

¹Fungicides with FB=followed by indicate a sequential application

²Total active ingredient listed in order of product as found in the fungicide(s) column

³FGS=Feekes growth stage

⁴Product rate listed in order of product as found in the fungicide(s) column

⁵Program code to be used in following sections when describing fungicide programs

⁶Misapplication at WY16 resulted in 13.8% less product for all FGS 10.5.1 applications.

Table 3 Results of foliar disease severity, glume blotch index (GBI), NDVI, test weight, and yield from seven field experiments to evaluate commonly used fungicide programs in Delaware and Maryland.

Program ¹	Disease Severity (%) ²	GBI ³	NDVI ⁴	Test Weight (kg/m ³)	Yield (kg ha ⁻¹)
TSOLO8	20.1 B ⁵	64 AB	0.44 G	648 D	4900 G
TSPLT5+8	19.3 BC	62 ABC	0.45 FG	651 CD	4994 FG
TSPLT5+F	3.4 F	37 D	0.48 ABCD	667 A	5143 BCDE
QSOLO8	13.3 DE	57 BC	0.47 CDE	656 BC	5077 DEF
QSPLT5+8	9.2 E	55 C	0.47 ABCD	655 CD	5251 AB
QSPLT5+F	3.3 F	36 D	0.49 A	670 A	5330 A
XSOLO8	14.2 CDE	61 ABC	0.46 DEF	656 CD	5127 BCDE
XSPLT5+8	15.8 BCD	64 AB	0.46 EF	652 CD	5111 CDEF
XSPLT5+F	3.4 F	35 D	0.49 AB	666 A	5237 ABC
SSOLO8	18.4 BC	60 ABC	0.45 EFG	651 CD	5013 EFG
SSPLT5+8	18.7 BC	58 BC	0.45 EFG	653 CD	5105 DEF
SSPLT5+F	3.6 F	38 D	0.48 ABC	667 A	5203 ABCD
PSOLOF	3.7 F	35 D	0.47 BCD	663 AB	5035 EF
CK	39.2 A	68 A	0.40 H	634 E	4561 H

¹Detailed descriptions of fungicide programs are lists in Table 1.

²Disease severities were estimated using the total amount of foliar disease on the flag leaf of ten randomly selected plants per plot between FGS 11.1 and 11.2 (late milk to early soft dough) at each site

³Glume blotch index (GBI) is calculated by taking the product of disease incidence and severity divided by 100.

⁴NDVI is calculated as (NIR-Red)/(NIR+Red), where NIR is the fraction of emitted near-infrared radiation returned from the sensed area (reflectance) and Red is the fraction of emitted red radiation returned from the sensed area (reflectance) (Solie et al., 2012).

⁵Means followed by the same letter within a column are not significantly different according to Fisher's protected least significant difference test at $P \leq 0.05$.

Table 4 Spearman's correlations (ρ)¹ for disease severity on the flag leaf (N=588) x GBI (N=336), NDVI (588), test weight (N=585), and yield (N=585).

	Disease Severity (%)	GBI	NDVI	Test Weight (kg/m ³)	Yield (kg ha ⁻¹)
Disease Severity (%)	1.00	-	-	-	-
GBI	0.63	1.00	-	-	-
NDVI	-0.35	-0.31	1.00	-	-
Test Weight (kg/m ³)	-0.64	-0.42	ns	1.00	-
Yield (kg ha ⁻¹)	-0.77	-0.46	0.48	0.55	1.00

¹All correlations were significant at $P \leq 0.0001$ except for NDVI x test weight (ns).

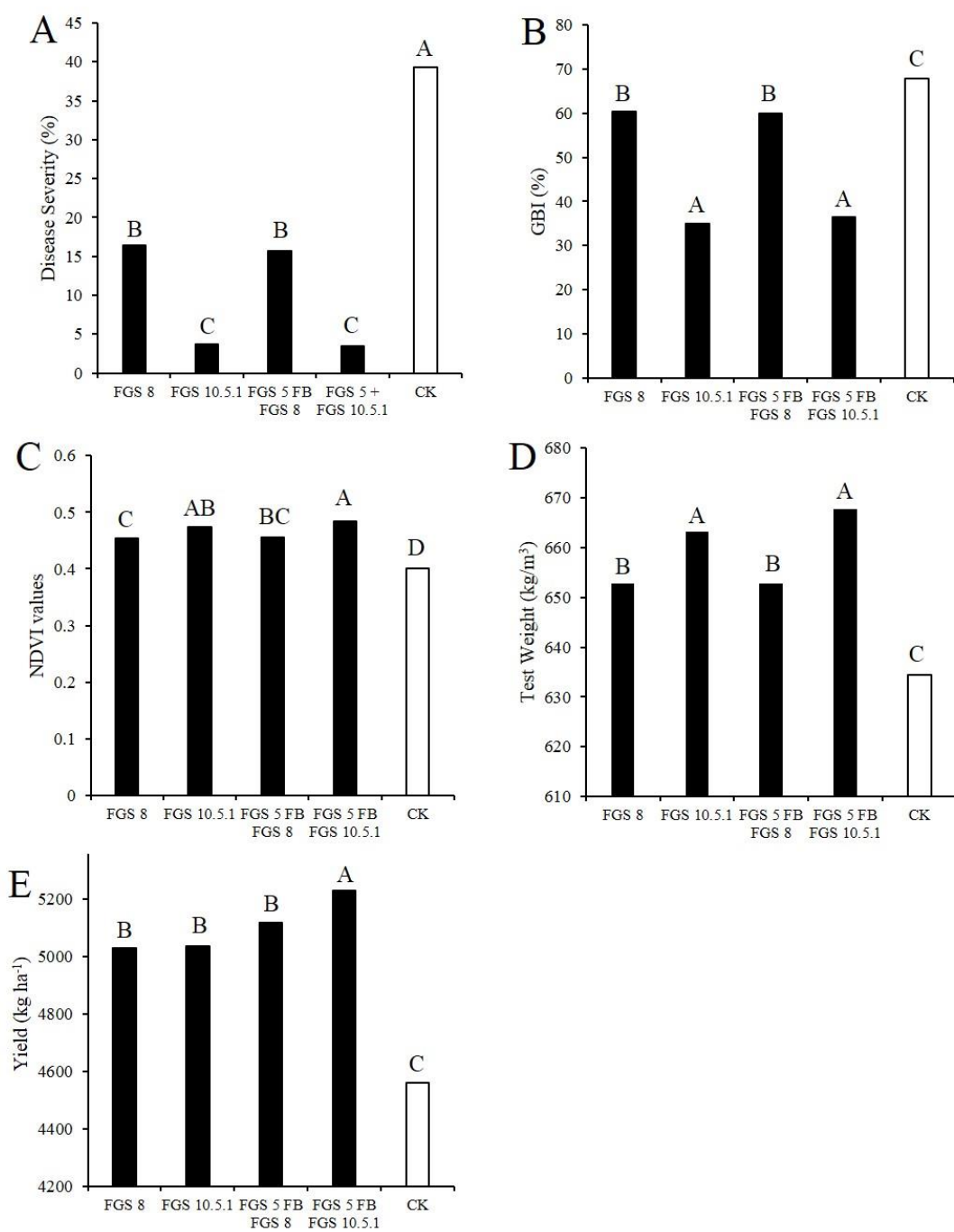


Figure 6 Mean values of fungicide timing impact on A disease severity (%) on the flag leaf at FGS 11.1-11.2, B glume blotch index (GBI) at FGS 11.1, C NDVI, D test weight, and E grain yield for fungicide program timings from seven field experiments conducted from 2015-2016 in Delaware and Maryland. FGS=Feekes growth stage and FB=followed by. Means with the same letter are not statistically different from each other at $P \leq 0.05$.

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Chapter 2

EVALUATING THE PROFITABILITY OF FOLIAR FUNGICIDE PROGRAMS IN MID-ATLANTIC SOFT-RED WINTER WHEAT PRODUCTION

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Abstract

In the mid-Atlantic, fungicide applied between flag leaf emergence (Feekes growth stage [FGS] 8) and heading (FGS 10.5) were considered the standard application timing in soft-red winter wheat (SRWW). However, there has been a shift towards two-pass programs and late applications at beginning anthesis (FGS 10.5.1), but these programs have not been thoroughly evaluated for disease control on the flag leaf, yield and grain quality response, and potential profitability. Ten experiments were conducted in Delaware, Maryland, Pennsylvania, and Virginia in 2015 and 2016 to evaluate fungicide programs with applications at flag leaf emergence (FGS 8), beginning anthesis (FGS 10.5.1), and programs with an early application at green-up (FGS 5) followed by applications at either FGS 8 or FGS 10.5.1. Programs tested included the fungicides 41.8% propiconazole (Tilt[®]); 13.5 % azoxystrobin and 11.7% propiconazole (Quilt Xcel[®]); 14.3% fluxapyroxad and 28.58% pyraclostrobin (Priaxor[®]); or 10.8 % prothioconazole and 32.3% trifloxystrobin (Stratego YLD[®]); and 19% prothioconazole and 19% tebuconazole (Prosaro[®]). Foliar diseases were assessed and analyzed using a generalized linear mixed model to estimate the likelihood of foliar disease reaching or exceeding a certain level on the flag leaf. Based on estimated probabilities, fungicide programs including an application at FGS

10.5.1 resulted in the highest probability of no disease on the flag leaf (0.29-0.40) compared to other program timings (≤ 0.11). Yield and test weight data were collected, and multi-treatment random effects meta-analysis was used to estimate the mean yield and test weight increases ($\bar{D}$) for each fungicide program relative to the untreated check. Mean yield $\bar{D}$ was significantly different from zero ($P \leq 0.016$) for all programs, with values ranging from 253.65 to 634.16 kg ha⁻¹. Mean test weight ($\bar{D}$) was significantly different from zero ($P \leq 0.004$) for all programs, with values ranging from 11.54 to 30.61 kg/mg³. Using a grain price of \$0.18 kg⁻¹ (\$5 bu⁻¹), and regional fungicide price data, the probability of profitability ranged from 0.49 to 0.56 for programs with a single application at FGS 8 compared to 0.53 for a single application of Prosaro[®] at FGS 10.5.1, indicating similar profitability between program timings. Two-pass programs with an early application at FGS 5 followed by FGS 8 or FGS 10.5.1 resulted in similar probability of profitability compared to single application programs, ranging from 0.48-0.57 (FGS 5 FB FGS 8) and 0.52-0.59 (FGS 5 FB FGS 10.5.1). These findings lay the ground work for larger scale future fungicide studies, which could be used to make a fungicide application decision making tool for managing foliar disease in mid-Atlantic SRWW production.

Introduction

In the mid-Atlantic states of Delaware, Maryland, Pennsylvania and Virginia, soft-red winter wheat (*Triticum aestivum* L.) (SRWW) is harvested from over 263 thousand hectares (ha), with an average yield of 4,237 kg ha⁻¹ and an annual value of over \$232 million (NASS February 2017, September 2016). SRWW is an important part of the agricultural economy in the mid-Atlantic, supplying feed for the poultry industry on the Delmarva Peninsula and grain for the large flour mill industry in Pennsylvania, Maryland, and Virginia (NASS May 2017). Wheat production in this area is negatively impacted by several fungal diseases affecting the foliage and head (Kleczewski 2014a, 2017a, Weisz et al. 2011). These diseases include the residue-borne leaf blotch complex (LBC) of *Stagonospora nodorum* blotch (*Parastagonospora nodorum* (Berk.) Quaedvlieg, Verkley & Crous), *Septoria tritici* blotch (*Zymoseptoria tritici* (Desm.) Quaedvlieg & Crous), and tan spot (*Pyrenophora tritici-repentis* (Died.) Drechsler). Other foliar diseases encountered less frequently in the region include powdery mildew (*Blumeria graminis* (DC.) Speer.), leaf rust (*Puccinia triticina* Erikss.), and stripe rust (*Puccinia striiformis* Westend.) (Bowen et al. 1991, Cowger et al. 2016a, Green et al. 2014). Lastly, *Fusarium* head blight [(*Fusarium graminearum* Schwabe)(FHB)], and *Stagonospora glume* blotch (*Parastagonospora nodorum* (Berk.) Quaedvlieg, Verkley & Crous) diseases that affect the heads and glumes (Milus and Chalkley 1997, Salgado et al. 2015), are also part of the disease complex in the region. These diseases have the potential to significantly reduce grain yields and test weight in the mid-Atlantic in years that are favorable for disease development (Kleczewski 2017a, b, Phipps et al. 2012, Sylvester and Kleczewski 2018).

Infection of the flag leaf and head has the greatest impact on yield because the majority of carbohydrates necessary for grain fill are produced by the flag leaf (45%), flag leaf sheath (25%), and head (25%) (Lupton 1972), whereas only 5% is derived from other portions of the plant canopy. Fungicides are used as a tool, along with variety selection and cultural practices, to minimize yield loss from diseases. However, many growers in the region do not utilize disease thresholds to determine if a fungicide application is needed, and instead, they apply fungicides on a crop developmental stage-based program (Chen et al. 2015). There are several reasons for utilizing such a program, including ease of scheduling, increased availability and reduced cost of fungicides, lack of thresholds for common diseases in the region, increased focus on grain quality, and the perceived notion of protecting an investment. Historically, fungicide applications in the region have been made between flag leaf emergence [Feekes growth stage (FGS) 8] and heading (FGS 10.1) (Large 1954). However, there has been a shift away from FGS 8 fungicide programs to applications within five days of the start of flowering (FGS 10.5.1). This timing is the most effective for managing FHB (D'Angelo et al. 2014) and recent studies from the region indicate that it may be as effective as FGS 8 applications for managing common foliar diseases (Sylvester and Kleczewski 2018). Another trend is the inclusion of a reduced-rate fungicide with the application of nitrogen prior to jointing (FGS 6) to minimize early season disease development without the added cost of a separate application (Wegulo et al. 2012, Willyerd et al. 2015). A recent study examining fungicide programs for impact on foliar disease and yield in Delaware and Maryland indicates that programs using the two-pass approach may result in a small (198 and 192 kg ha⁻¹), though significant, yield increase when compared to single applications at FGS 8 or

FGS 10.5.1 (Sylvester and Kleczewski 2018) . However, such a small increase may not be sufficient to offset application costs.

In addition to the wide range of timings available for applying fungicides to wheat, growers have access to a multitude of products. The cost of these products varies greatly, which impacts the net profitability to the grower. For example, in 2015, and 2016, we requested current prices for each of the five fungicides used in this study from regional chemical suppliers in the mid-Atlantic and calculated the amount of yield needed to offset the price differential relative to an untreated control (assuming an average ground application cost of \$19.24 ha⁻¹ and a grain price of \$0.18 kg⁻¹), would range from 155 kg ha⁻¹ with the low cost product, to more than double (350 kg ha⁻¹) with the more expensive product. Thus, a low cost, less efficacious product could potentially result in similar or increased potential net profitability to a grower, depending on the situation. Similarly, multiple pass programs include an additional chemical cost, despite reducing the overall application cost by including a fungicide with an early season nitrogen application.

Fungicide economics have been previously assessed in other wheat classes and growing regions of the United States. In northeast Texas SRWW, Lopez et al. (2015) found tebuconazole sprayed at FGS 10 produced notable returns (\$107.70 ha⁻¹) in one year and net loss in the other (-3.53 ha⁻¹). In Nebraska hard red winter wheat, Wegulo et al. (2011) found profits were highest when environmental conditions favor moderate to severe disease development though low wheat prices may still result in net losses by using a fungicide. Thompson et al. (2014) found hard red winter wheat varietal selection in Oklahoma may also influence profitability when using fungicides, especially on susceptible varieties in high disease environments. In the Great Lakes

region of the US, Willyerd et al. (2015) tested Prosaro[®] (tebuconazole+prothioconazole) and Headline[®] (pyraclostrobin) at FGS 5, FGS 8, or FGS 10 as well as two-pass programs for control of LBC in SRWW. Using a multivariate random-effects meta-analysis, the authors were able to generate data as to the likelihood that a given fungicide program would result in a yield gain large enough to offset application costs across three levels of grain price scenarios. Their work indicated that fungicides applied at FGS 8 or FGS 10 provided roughly the same chance of resulting in a positive yield response when comparing to two-pass systems. However, results were limited to two fungicide products, did not utilize the commonly used FGS 10.5.1 application program, and did not represent the mid-Atlantic region, which is characterized by moderate temperatures, high humidity, and diverse cropping systems. Weisz et al. (2011) analyzed 42 fungicide trials conducted from 1994-2010 in the mid-Atlantic states of Virginia and North Carolina, and found a low probability (≤ 0.50) of profitability in no disease environments, compared to a higher probability (≥ 0.50) when disease was recorded. However, the authors state the wheat cultivars used in fungicide trials are often susceptible to at least one foliar disease, which can often inflate the yield response to fungicides. Our work contributes to (Weisz et al. 2011) by conducting a planned experiment, across four mid-Atlantic states, using the same fungicide programs at each site on a moderately resistant variety, in order to gain a better understanding of the impact of fungicide programs on grain yield, test weight, and profitability under typical field conditions which a grower might experience.

Growers are often interested in the potential yield response from, and economics of, a fungicide application, which is essentially asking about the mean yield difference compared to an untreated check (estimated effect size) and whether

such a difference is high enough to offset application cost. Therefore, the goal of this research was to assess the profitability of commonly used fungicide programs in SRWW in the mid-Atlantic region of the United States. To accomplish this goal, we chose fungicides with active ingredients belonging to the demethylation inhibitors (DMI, FRAC code 3 (FRAC 2017)), quinone outside inhibitors (QoI, FRAC code 11), and succinate dehydrogenase inhibitors (SDHI, FRAC code 7) classes or combinations thereof. Fungicides were applied in single applications at FGS 8, FGS 10.5.1, or in two-pass programs with an application at FGS 5 followed by (FB) a second at FGS 8 or FGS 10.5.1 to a moderately resistant, commercially available variety. Experiments were conducted under ten different environments in Delaware, Maryland, Pennsylvania, and Virginia to examine the potential range of grain yield and test weight benefits from fungicide programs. We then used meta-analysis to obtain estimated effect sizes (mean grain yield differences) for each fungicide program and probabilities of yield response in future applications. Finally, a cost-benefit analysis was conducted to determine the potential profitability of each fungicide program estimated over a range of fungicide application costs under low, average, and high wheat grain prices. This information could lay the groundwork for creating a tool which assists growers in the fungicide decision making process for managing foliar diseases in mid-Atlantic winter wheat.

Materials and Methods

Experimental design & plot establishment

Ten trials were conducted over two years, four in 2015 and six in 2016, in the mid-Atlantic states of Delaware, Maryland, Pennsylvania, and Virginia (**Table 5**). The

experimental design was a randomized complete block (RCB) with six replications, except for PA16 and VA16 that had five and four replications, respectively. Soft red winter wheat (SRWW) variety ‘Growmark FS815’ was sown at a rate of 4.4×10^6 seeds ha⁻¹ with no-till drills. FS 815 was selected because it represents a commercially available, high yielding variety planted throughout the region (Delaware 2012-2014, Maryland 2012-2014). The variety is characterized as medium maturity, with average test weight and height, and moderately susceptible to foliar diseases common to the region (Kleczewski 2013, 2014d). Plot dimensions and row spacing were similar, though varied slightly with equipment (**Table 5**). Untreated border rows between adjacent plots and at plot ends were used at most sites. Sites were selected to provide a range of cropping systems and environmental conditions (**Table 5**). Standard nutrient and pest management practices were followed for each state (Coale 2010, Curran et al. 2016, Herbert and Flessner 2016, Maguire and Heckendorn 2015, Roth et al. 2016, Shober et al. 2017). When available, irrigation was applied as needed (**Table 5**)

Fungicide programs

Thirteen fungicide programs, consisting of demethylation inhibitor, Quinone outside inhibitor, and succinate dehydrogenase inhibitor fungicides applied either individually or sequentially at one or more of three growth stages (timings) (**Table 6**). The fungicides tested were propiconazole (Tilt[®], Syngenta Crop Protection, Greensboro, NC), azoxystrobin + propiconazole (Quilt Xcel[®], Syngenta Crop Protection, Greensboro, NC), fluxapyroxad + pyraclostrobin (Priaxor[®], BASF Corporation, Research Triangle Park, NC), prothioconazole + trifloxystrobin (Stratego[®] YLD, Bayer CropScience, Research Triangle Park, NC), and

prothioconazole + tebuconazole (Prosaro[®] 421SC, Bayer Crop Science, Research Triangle Park, NC). These fungicides differed in initial cost and mode of action, and represented commonly used products in the region. The application timings tested included FGS 8/9 (flag leaf emergence), FGS 10.5.1 (beginning flower) and two-pass applications, with the first at FGS 5 (leaf sheaths strongly upright, commonly referred to as green-up) followed by the second at either FGS 8 or FGS 10.5.1. FGS 5 applications are touted as preventing yield losses due to early season disease development; however, these programs have not been adequately tested in the mid-Atlantic region. FGS 8 applications are aimed at protecting the flag leaf from foliar diseases but are less effective against diseases of the spike and late-season foliar diseases. FGS 10.5.1 applications are becoming more common and are the newest fungicide application timing used in the region. This timing is used primarily to manage *Fusarium* head blight (FHB) and *Stagonospora* glume blotch, but also protects the flag leaves and spikes from other late season diseases (Kleczewski 2014a, b, c).

All fungicide treatments included 0.125% of a nonionic surfactant (Induce[®], Helena Chm. Company, Collierville, TN). At Delaware and Maryland sites, treatments were applied using a CO₂ pressurized backpack sprayer (R&D Sprayers, Opelousas, LA) and offset handheld boom equipped with three XR8002 flat fan nozzles (TeeJet Technologies, Wheaton, IL) spaced 50.8 cm apart. Treatments were made at a spray pressure of 234 kPa to deliver 187 liters ha⁻¹ of spray solution. For the Virginia study site, treatments were applied with a tractor-mounted sprayer (LeeAgra, Lubbock, TX) using eight 8002 VS nozzles spaced 46cm apart at a rate of 186 liters ha⁻¹ and a pressure of 262 kPa. For the Pennsylvania site, treatments were applied with a tractor-mounted custom built plot sprayer by research staff at The Pennsylvania State

University. Four AITTJ6011002 Teejet nozzles were spaced 48cm apart on the boom and calibrated to apply at a rate of 187 liters ha⁻¹ at a pressure of 276 kPA.

Data collection and analysis

Flag leaf disease assessment, yield, and test weight

Total disease severity was estimated as percent flag leaf area affected by one or more members of the leaf blotch complex (*Stagonospora nodorum* blotch, *Septoria tritici* blotch, and tan spot), leaf rust, powdery mildew, and/or stripe rust. In 2015, only LBC were detected and rated on the flag leaf at all sites. In 2016, a combination of foliar diseases were detected, with LBC being the most prevalent followed by leaf rust, powdery mildew, and stripe rust, and estimated as total disease severity on the flag leaf rather than rating each disease separately. A subsample of leaves from the untreated control plots was occasionally collected and observed under a compound microscope to estimate the approximate disease composition for each site. Foliar disease estimates were recorded on ten randomly selected leaves between FGS 11.1 and 11.2 depending on the site. *Fusarium* head blight developed at low levels at two of the ten sites and glume blotch only developed in one year of the study and therefore, data were omitted from this analysis.

Plots were harvested with research combines when grain moisture approached 13.5%. Delaware and Maryland plots were harvested with a Massey Ferguson 8XP research plot combine (Kincaid Equipment Manufacturing, Haven, KS) equipped with a Harvest Master HM400 or HM800 GrainGage (Juniper Systems, Inc., Logan, UT) coupled to a field computer (Allegro CX and Mirus, Juniper Systems, Inc., Logan, UT) that immediately measured grain yield (bu/A), test weight (pounds per bushel),

and moisture. Virginia plots were harvested with a Wintersteiger Elite plot combine (Wintersteiger, Salt Lake City, UT), bagged, and later weighed on an Ohaus DS10 scale (OHAUS, Parsippany, NJ) and moisture measured on a Dickey John GAC 2000 (DICKEY-John, Auburn, IL). Pennsylvania plots were harvested with a Wintersteiger Nurserymaster Elite, bagged, and later weighed on an Adam CPWplus compact scale (Adam Equipment, Inc, Oxford, CT) and grain moisture measured with a John Deere SW08120 moisture tester (Deere & Company, Moline, IL). Yield data were adjusted to 13.5% moisture and converted to kilograms per hectare based on a bushel weight of 25.87 kg/bushel, which is less than the industry standard of 27 kg/bushel, but more representative of SRWW grown in the region based on 87 site-years of regional variety performance trials (data not shown). Test weight was converted to kilograms per cubic meter.

Fungicide program effects on yield and test weight

Following Willyerd et al. (2015), PROC MIXED was used to determine the effects of fungicide program on yield and test weight. Each environment and response was analyzed separately by fitting a linear mixed model with fixed effect of fungicide program and block as a random effect. The *lsmeans* statement in MIXED was used to estimate the expected least square mean yield and test weight for each program. The estimated values were then used in a multi-treatment random-effects meta-analysis across all studies in order to estimate the overall mean yield and test weight difference between fungicide program and the control ($\bar{D}$), along with their 95% confidence interval and the between-study variance ($\hat{\sigma}^2$). The meta-analytical model was fitted to the data in PROC MIXED of SAS using maximum likelihood as the parameter estimation method, as described previously (Paul and Madden 2015, Paul et al. 2011).

Fungicide program effect on the risk of foliar disease on the flag leaf

Significant contributions to yield come from the flag leaf, but foliar diseases may compromise the health of the flag leaf, especially late in the season during grain fill. Foliar fungicides are a management tool used minimize the impact of these diseases, however, they vary in effectiveness, depending on the product used and application timing. To gain a better understanding of how these fungicide programs performed in terms of disease control, foliar disease severity data (each of the 10 observations from each plot for a total of 7,980 observations across all sites) were compressed into a four-class scale: category 1: no disease on the flag leaf, category 2: 1-5% disease severity on flag leaf, category 3: 5-15% disease severity on the flag leaf, and category 4: >15% disease severity on the flag leaf. Following Willyerd et al. (2015), a generalized linear mixed model (GLMM) was used to estimate the odds or likelihood of a fungicide program resulting in a certain level of foliar disease on the flag leaf. The proportional odds model was fitted to the data pooled across the ten environments using the GLIMMIX procedure of SAS to estimate the odds of disease severity being assigned to one of the four categories previously described, given a fungicide program. Proportional odds models were fitted to the cumulative logit link function (η) of foliar disease class, with the distribution as multinomial. The model can be written as:

$$\eta_{0jkm} = \log \left(\frac{\pi_{0jkm}}{1-\pi_{0jkm}} \right) = \theta_0 + \beta_j + \varphi_m + b(\varphi)_{km} \quad (\text{eq. 1a})$$

$$\eta_{1jkm} = \log \left(\frac{\pi_{0jkm} + \pi_{1jkm}}{1-(\pi_{0jkm} + \pi_{1jkm})} \right) = \theta_1 + \beta_j + \varphi_m + b(\varphi)_{km} \quad (\text{eq. 1b})$$

$$\eta_{2jkm} = \log \left(\frac{\pi_{0jkm} + \pi_{1jkm} + \pi_{2jkm}}{1-(\pi_{0jkm} + \pi_{1jkm} + \pi_{2jkm})} \right) = \theta_2 + \beta_j + \varphi_m + b(\varphi)_{km} \quad (\text{eq. 1c})$$

where $\log(\bullet)$ is the natural log link function, $\pi_{\bullet jkm}$ is the probability of disease severity falling into a certain severity category (reaching or exceeding a certain level of severity on the flag leaf) for the j th treatment in the k th block and m th

environment. β_j is the fixed effect of the j th treatment on η , φ_m is the random effect of the m th environment, $b(\varphi)_{km}$ is the random effect of the k th block within the m th environment, and $\theta_{\bullet}$ is an intercept term for each equation (the transition between the classes). The probability of severity class 0 (disease restricted to below the flag leaf) is π_{0jkm} , π_{1jkm} is the probability of disease reaching the flag leaf, but below 5% severity, π_{2jkm} is the probability of disease on the flag leaf between 5-15% severity, and the probability of disease on the flag above 15% severity, π_{3jkm} , was estimated as $1 - \pi_{0jkm} - \pi_{1jkm} - \pi_{2jkm}$. The *estimate* statement in GLIMMIX was then used along with the *ilink* option to estimate probability values (Willyerd et al. 2015).

Projected yield response to different fungicide programs

The potential for fungicide programs to increase yield under certain conditions has been well documented. However, growers are also interested in their return on investment; mainly what is the likelihood of a specific fungicide program being profitable and which ones are the most likely to be profitable. The estimated expected effect size and estimated between-study variance for each fungicide program ($\bar{D}$ and $\hat{\sigma}_D^2$, respectively) from the meta-analysis were used to estimate the probability of yield responses in new randomly selected studies (done in a manner similar to the studies in this investigation) being above some critical level (D_c) needed to offset application cost at a given grain price (Willyerd et al. 2015). As a way of assessing the cost-benefit of the fungicide programs evaluated in this study, probabilities were estimated for each program for a range of D_c as $\rho = \Phi((\bar{D} - D_c) / \hat{\sigma}_D)$ (Willyerd et al. 2015), whereas $\Phi(\bullet)$ is the cumulative standard-normal function and $\hat{\sigma}_D$ is the estimated between-study standard deviation for the difference ($\sqrt{\hat{\sigma}_D^2}$). Probabilities were

estimated for grain prices of \$0.11 kg⁻¹ (\$3.00 bu⁻¹), \$0.18 kg⁻¹ (\$5.00 bu⁻¹), and \$0.26 kg⁻¹ (\$7.00 bu⁻¹).

Results

Fungicide program effect on yield

Minimum, mean, and maximum grain yield across all ten environments were 2,508, 4,973, and 7,211 kg ha⁻¹ (39.2, 77.8, and 112.8 bushels/acre), respectively. Across all fungicide programs, mean yields were highest at FT15 (5,947 kg ha⁻¹) and PA16 (5,699 kg ha⁻¹) and lowest in FT16 (3,829 kg ha⁻¹) and VA16 (4,037 kg ha⁻¹). The overall mean effect size ($\bar{D}$) was significantly different from zero ($P \leq 0.01$) for all fungicide programs (**Table 7**). The program with the highest $\bar{D}$ was QSPLT5+F (634 kg ha⁻¹), followed by QSPLT5+8 (570 kg ha⁻¹), XSPLT5+F (542 kg ha⁻¹), TSPLT5+F (520 kg ha⁻¹), and SSPLT5+F (482 kg ha⁻¹). When assessing the effect of program timing on grain yield, the overall mean effect size ($\bar{D}$) was significantly different ($P \leq 0.01$) from zero for all timing comparisons, except FGS 8 vs FGS 10.5.1 ($P \geq 0.838$) and FGS 10.5.1 vs FGS 5 FB FGS 8, which were not significant ($P \geq 0.838$ and $P \geq 0.11$, respectively). FGS 5 FB FGS 10.5.1 resulted in a mean effect size ($\bar{D}$) that was 183 kg ha⁻¹ higher than FGS 8, 171 kg ha⁻¹ higher than FGS 10.5.1, and 94 kg ha⁻¹ higher than FGS 5 FB FGS 8. FGS 5 FB FGS 8 resulted in a mean effect size ($\bar{D}$) that was 88 kg ha⁻¹ higher than FGS 8.

Fungicide program effect on test weight

Across all fungicide programs, test weights were highest at PA16 (749 kg/m³), GT15 (703 kg/m³), and HB16 (675 kg/m³) and lowest at GT16 (630 kg/m³), FT16 (593 kg/m³), and VA16 (590 kg/m³). The overall mean effect size ($\bar{D}$) was

significantly different from zero ($P \leq 0.004$) for all fungicide programs (**Table 8**). The program with the highest $\bar{D}$ was QSPLT5+F (30.6 kg/mg³), followed by TSPLT5+F (28 kg/mg³), XSPLT5+F (27.6 kg/mg³), SSPLT5+F (27.6 kg/mg³), and PSOLOF (24.8 kg/mg³). When assessing the effect of program timing on test weight, the overall mean effect size ($\bar{D}$) was significantly different ($P \leq 0.009$) for all comparisons between pairs of timings except FGS 8 versus FGS 5 FB FGS 8, which was not significant ($P \geq 0.808$). FGS 5 FB FGS 10.5.1 resulted in a mean effect size ($\bar{D}$) that was 13 kg/mg³ higher than FGS 5 FB FGS 8, 13 kg/mg³ higher than FGS 8, and 4 kg/mg³ higher than FGS 10.5.1. FGS 10.5.1 resulted in a mean effect size ($\bar{D}$) that was 10 kg/mg³ higher than FGS 5 FB FGS 8 and 9 kg/mg³ higher than FGS 8.

Fungicide program effect on the risk of foliar disease on the flag leaf

Only diseases of the leaf blotch complex (*Stagonospora nodorum* blotch, *Septoria tritici* blotch, and tan spot) were detected on the flag leaf in 2015. In 2016, LBC was the most commonly encountered foliar disease on the flag leaf and, across sites, averaged 74% of the total disease on the flag leaf, followed by leaf rust (21%), powdery mildew (4%), and stripe rust (<1%). Across all treatments, mean percent flag leaf area infected between late milk and soft dough varied across sites and years and was greatest at FT16 (47.4%), GT16 (23%), and HB16 (10%) and lowest at WY15 (0.4%), FT15 (1.1%), and GT15 (1.3%). Minimum, mean, and maximum disease severity on the flag leaf across all ten environments were <1%, 10%, and 99%. Over 60% of the 7980 total individual observations (individual flag leaves) were grouped in either category 1: no foliar disease on the flag leaf (**Fig. 7A**) or category 2: 1-5% disease severity on the flag leaf (**Fig. 7B**). Untreated checks had the greatest

probability (0.65) of falling into category 4: $\geq 15\%$ disease severity on the flag leaf. (**Fig. 7D**).

Fungicide programs including an application at FGS 10.5.1 resulted in the highest probability (0.29-0.40) of falling into category 1, while all other programs had ≤ 0.11 probability of falling into this category (**Fig. 7A**). The probabilities of category 2 ranged from 0.38 to 0.66 (**Fig. 7B**). Within this category, slight differences existed between products though, on average, no one program provided a significant increase or decrease in probabilities based on timings. Fungicide programs including an FGS 10.5.1 application, in general, had lower probabilities (0.05-0.09) of falling into category 3 compared to programs with an application at FGS 8 (0.24-0.52) (**Fig. 7C**). Fungicide programs including an application at FGS 5 FB FGS 8 or FGS 10.5.1 applications did not substantially increase or reduce the chances of foliar disease reaching the flag leaf or exceeding a certain level on the flag leaf. For example, TSOLO8 had a 0.49 probability of severity being in category 3, whereas, the corresponding probability for TSPLT5+8 was 0.45.

Projected yield response to different fungicide programs

As part of the primary meta-analysis, fungicide programs were grouped together based on timing in order to make specific comparisons (**Fig. 8-10**) due to the high number of treatments and relatively similar yield response. All of the fungicide programs had more than a 0.60 probability of resulting in a yield increase in a new random study, given similar conditions to those observed in this study (**Fig. 8a, 9a, 10a**). For all programs, probability decreased as the projected yield response increased from 0-1500 kg ha⁻¹. For example, the fungicide program QSOLO8 had a 0.64 probability of a yield increase of 7.5 kg ha⁻¹ but only a 0.11 probability of 1,500 kg ha⁻¹

¹. The probability of obtaining a yield increase high enough to offset fungicide application costs (breakeven) decreased as application costs increased and increased as grain price increased from \$0.11 kg⁻¹ (\$3.00 bu⁻¹) to 0.26 kg⁻¹ (\$7.00 bu⁻¹) (**Fig. 8-10, B-D**). Using the fungicide price data we collected from local agribusinesses, the probability of profitability for programs were similar for all programs with and application at FGS 8, ranging from 0.49 to 0.56, compared to a single application at FGS 10.5.1 timing (0.53) using a wheat price of \$0.18 kg⁻¹ (**Fig. 8C**). Programs with an application at FGS 5 FB FGS 8 applications did not increase the probability of profitability, on average, when compared to single applications at FGS 8 (**Fig. 9C**). For example, the probability increased from 0.54 to 0.57 for TSOLO8 and TSPLT5+8, 0.54 to 0.55 for QSOLO8 and QSPLT5+8, but decreased from 0.49 to 0.48 for XSOLO8 and XSPLT5+8 and from 0.56 to 0.52 for SSOLO8 and SSPLT5+8 (**Fig. 9 C**). Programs with an application at FGS 5 FB FGS 10.5.1 applications did increase the chance of profitability compared to single applications at FGS 10.5.1; however, this increase was small, only amounting to a 1% increase at \$0.11 kg⁻¹, 3% at \$0.18 kg⁻¹, and 5% at \$0.26 kg⁻¹ grain prices (**Fig. 10 B-D**).

Discussion

This is the first study to use meta-analysis to describe the potential profitability of multiple fungicides and fungicide timings in SRWW grown in the mid-Atlantic states of Delaware, Maryland, Pennsylvania, and Virginia. This work adds to previous research conducted in the Midwest (Willyerd et al. 2015) and mid-Atlantic (Weisz et al. 2011), by assessing a wider range of fungicide programs for potential profitability and foliar disease control. Fungicide applications at FGS 10.5.1 are becoming increasingly popular for foliar disease control in mid-Atlantic SRWW. Recent threats

from Fusarium head blight have elevated grower awareness of management practices, which include planting a moderately resistant variety and applying FHB specific fungicides at FGS 10.5.1 if risk levels are high (Willyerd et al. 2012). Using a multivariate random-effects meta-analysis, Paul et al. (2008) found the triazole fungicides Prosaro[®], Caramba[®], and Proline[®] had the greatest efficacy against FHB when applied at anthesis (FGS 10.5.1), and a subsequent study showed that these fungicides were just as effective against FHB when applied within six days after the start of FGS 10.5.1 (D'Angelo et al. 2014). Our data indicate that Prosaro[®] applied at FGS 10.5.1 can provide just as good control of foliar diseases compared to programs with an application at FGS 8. The observed results were due to the fact that foliar disease did not develop until after anthesis (FGS 10.5.1).

Although several foliar diseases were encountered in this study, LBC was the most frequently observed disease across all environments. Diseases causing LBC are residue-borne and require prolonged periods of leaf wetness and temperatures warmer than those typical of the pre-FGS 8 period to produce spores and infect the leaves (Bergstrom 2010, McMullen 2010, Shaner 2010). Thus, environmental conditions in the region typically are not favorable for the development of this disease complex until after FGS 8, when canopies have closed and therefore can hold moisture for longer periods of time (Kleczewski 2014d, 2017a, b). This, coupled with relatively slow spore production times that result in new infections, may explain the similar effectiveness between FGS 8 and FGS 10.5.1 fungicide applications observed in this study. Development of LBC prior to FGS 8 would require persistent, wet conditions and moderate temperatures, which infrequently occur in the region during early wheat development in March and April. Our results are consistent with field observations

and single-season fungicide efficacy trials conducted in the region in recent years (Kleczewski 2014b, c, 2017a, b). Subtle differences between fungicide programs with FGS 8 and FGS 10.5.1 applications on flag leaf disease severity did not result in a significant difference in yield response between the two timings when compared to the untreated check (**Table 7**). For example, PSOLOF had a yield response of 374 kg ha⁻¹, which was higher than SSOLO8 (329 kg ha⁻¹) and TSOLO8 (254 kg ha⁻¹) but not QSOLO8 (405 kg ha⁻¹) or XSOLO8 (460 kg ha⁻¹) (**Table 7**). Using fungicide price data provided by local agribusinesses, our results showed that both FGS 10.5.1 and FGS 8 applications resulted in similar probability of profitability (**Fig. 8**). Thus, our data indicate that Prosaro applied at FGS 10.5.1 did not result in a lower grain yield response or likelihood of profitability compared to fungicide programs with an application at FGS 8.

The use of the FGS 10.5.1 application may provide additional economic benefits that were beyond the scope of our objectives. Diseases affecting the head, such as glume blotch and FHB, can reduce grain quality, resulting in dockage (Cowger et al. 2016b). The use of the FGS 10.5.1 program has been shown to provide significantly better glume blotch control compared the FGS 8 timing in mid-Atlantic SRRW (Sylvester and Kleczewski 2018). Locally, in 2017, grain with a test weight below 746 kg/mg³ was subject to dockage that decreased grain prices by 1-11% as test weight decreased to 682 kg/mg³, at which point loads were subject to rejection. In addition, mycotoxins such as deoxynivalenol (DON) produced by *Fusarium graminearum*, can result in dockage or rejection of the grain if levels exceed 2 ppm (Cowger et al. 2016b, Ransom and McMullen 2008). It has been suggested that the United States reduce the allowable amount of DON in wheat destined for human

consumption to match Brazilian and European standards (Belluco et al. 2017, Pinotti et al. 2016), placing additional importance on minimizing mycotoxin contamination of SRWW grain. Research conducted across multiple states and years in the Midwest showed that Prosaro[®] applied at or within six days after FGS 10.5.1 was the most effective timing to suppress FHB and DON (D'Angelo et al. 2014). In a two-year study conducted in Ohio, Salgado et al. (2014) found that this timing, when integrated with additional management strategies such as host resistance and modifications to harvesting equipment, reduced DON by 32-50% resulting in lower price discounts and an economic benefit of \$31-272 ha⁻¹. However, the same management strategies without Prosaro[®] at FGS 10.5.1 only reduced DON by 4.3-38.7%. Furthermore, test weight and DON levels directly dictate marketing options and if grain can be sold to the potentially more lucrative flour mill market for human consumption or on the often less profitable animal feed market (Cowger et al. 2016b). Coupled with effective spike disease management and mycotoxin management, FGS 10.5.1 are also effective against late-season diseases such as rusts (Salgado et al. 2017). While we did encounter leaf rust in our study, it does not overwinter in the region, and therefore disease development is dependent on the arrival of spores from warmer southern regions. This, coupled with relatively high-temperature optima (Kolmer 2010), often results in leaf rust developing in the canopy late in the growing season. Recently, the region has suffered from outbreaks of stripe rust (*P. striiformis*), which, similar to the leaf rust pathogen, enters the region from warmer, southern areas. However, unlike leaf rust, stripe rust epidemics can develop rapidly under cool, wet conditions often encountered during earlier phases of crop growth in the mid-Atlantic. Fortunately, variety selection and regional disease monitoring can be used to effectively determine

the need for a fungicide application during a particular growing season. The additional advantages associated with the FGS 10.5.1 timing would likely make it a more profitable decision when compared to the FGS 8 timing.

Our data indicate that the use of two pass programs provides little to no benefit in relation to disease suppression or profitability. Programs with an FGS 5 application followed by either FGS 8 or FGS 10.5.1 applications improved yield somewhat when compared to FGS 8 or FGS 10.5.1 single fungicide programs (**Table 7**). Programs with an early application at FGS 5 FB FGS 8 or FGS 10.5.1 applications may have provided some suppression of disease in the lower canopy, though this would not have been captured in the flag leaf severity ratings. A less diseased lower canopy (leaves below the flag) may have resulted in slightly higher yields (**Fig. 8-10**), which would support the notion that these tissues only supply roughly 5% of photosynthates for grain fill (Lupton 1972). Indeed, our data indicates an average yield increase of 3% when comparing two pass programs to their solo FGS 8 or FGS 10.5.1 counterpart programs. However, the additional cost associated with the extra fungicide application prevented any sizeable increases in the probability of profitability (**Fig. 9 and 10**) under all price scenarios. These data support those of Willyerd et al. (2015), which also showed no significant benefit combining FGS 5 and FGS 8 or FGS 10 applications in the Great Lakes Region. In addition to the lack of economic benefit with the FGS 5 timing, resistance issues are of concern given the limited number of fungicide modes of action for use in wheat. Recently, there has been an increase in the number of premix fungicides containing two or more different fungicide modes of action. This is problematic, as only fungicides belonging to the DMI class are currently recommended for application to the grain head since products with a QoI

mode of action have the potential to increase DON in grain (Madden et al. 2014). Examples of DMI resistance in the United States have been recently described in *Fusarium graminearum* (Spolti et al. 2014) and reduced DMI sensitivity in *Parastagonospora nodorum* has been observed in Europe and China (Pereira et al. 2017). Furthermore, several examples of rusts and powdery mildew developing resistance to DMI fungicides have been documented in other pathosystems (Colcol et al. 2012, Keinath 2015, Lebeda et al. 2010, Schmitz et al. 2014). Consequently, it is important that concepts of Integrated Disease Management be emphasized to wheat producers and the agronomic industry in order to reduce fungicide inputs and increase profitability through effective fungicide application.

In this study, we assessed the effectiveness and profitability of numerous fungicide programs across multiple states in the mid-Atlantic region over a two year period. Although we realize the results are limited to the conditions encountered in this study, we believe that our data provide an excellent representation of the average or likely fungicide response in this region and other regions as our findings are consistent with those reported elsewhere (Weisz et al. 2011, Willyerd et al. 2015). Environmental conditions varied widely during the course of this study, ranging from hot and dry for the region (mean temp and rainfall of 18.3°C and 20 cm, respectively) to wet and cool (mean temp and rainfall of 16.8°C and 35 cm, respectively) (**Table 5**). The five-year average temperature and rainfall for this time period are 17.6°C and 29.5 cm, respectively (DEOS 2017). Thus, our findings, although limited in terms of the number of site-years, represents a fairly wide spectrum of environmental, epidemiological, and production conditions. In addition, we utilized a high yielding variety grown in the region, but which contained average resistance to LBC, leaf rust,

and powdery mildew (Kleczewski 2013, 2014d). Therefore, the disease and yield responses reported herein represents a realistic, average response to fungicides in the region. Our research supports that of Weisz et al. (2011), whereas the probability of a fungicide program resulting in breakeven or net profit can exceed 0.50 when foliar disease is present. However, we recognize growth stage-based fungicide applications should not be solely relied upon for managing fungal diseases of the foliage and head. Significant economic losses can be avoided by implementing an integrated disease management program targeting diseases through selecting resistant varieties, scouting fields to assess disease pressure, and utilize disease tracking or forecasting tools.

Summary and Conclusions

Based on our results, we recommend single fungicide applications at either FGS 8 or FGS 10.5.1, rather than two-pass programs with applications at FGS 5 FB FGS 8 or FGS 10.5.1, would be the recommended timing for managing common foliar diseases in mid-Atlantic SRWW, though crop advisors and growers should also take into account disease pressure, grain price, and fungicide cost before making a fungicide application decision. The framework presented in this study and that of Willyerd et al. (2015) provide powerful and useful starting points for the development of larger scale studies involving multiple wheat growing environments, varieties, and classes. Data from such studies could be used to develop tools for use by wheat producers that enable profitability and informed fungicide use.

Table 5 Description of sites used to evaluate the profitability of foliar fungicides programs in mid-Atlantic soft-red winter wheat production.

Abb.	Site	Coordinates	Rainfall and [Irrigation] ¹ (cm)	Soil Type	Previous Crop	Planting Date	Plot Size (m)	Row Spacing (m)	Harvest Date
2015									
FT15	Felton, Delaware	39.006°N, 75.569°W	29,[7.2]	Sandy loam	Corn	29-Oct-14	1.4x7	0.18	1-Jul-15
GT15	Georgetown, Delaware	38.637°N, 75.453°W	18,[5.1]	Loamy sand	Corn	8-Oct-14	1.4x7	0.18	23-Jun-15
HB15	Harbeson, Delaware	38.679°N, 75.246°W	15,[14.4]	Loamy sand	Corn	27-Oct-14	1.5x7	0.19	25-Jun-15
WY15	Queenstown, Maryland	38.916°N, 76.140°W	18	Silt loam	Corn	20-Oct-14	1.5x7	0.19	25-Jun-15
2016									
FT16	Felton, Delaware	39.006°N, 75.569°W	31	Sandy loam	Corn	15-Oct-15	1.4x7	0.18	30-Jun-16
GT16	Georgetown, Delaware	38.637°N, 75.453°W	38,[3.8] ²	Loamy sand	Wheat	9-Oct-15	1.4x7	0.18	1-Jul-16
HB16	Harbeson, Delaware	38.679°N, 75.246°W	33,[3.6]	Loamy sand	Corn	24-Oct-15	1.5x7	0.19	7-Jul-16
WY16	Queenstown, Maryland	38.916°N, 76.140°W	32	Silt loam	Corn	13-Oct-15	1.5x7	0.19	27-Jun-16
PA16	Manheim, Pennsylvania	40.118°N, 76.427°W	41	Silt loam	Soybean	15-Oct-15	1.5x6	0.19	12/13-Jul-16
VA16	Suffolk, Virginia	36.683°N, 76.766°W	35	Loamy fine sand	Peanut	25-Nov-15	1.2x6	0.17	20-Jun-16

¹FT15, GT 15, HB 15, GT16, and HB16 were the only sites with irrigation. Total irrigation amounts follow rainfall total in brackets [x] where applicable.

²Estimated total irrigation due to rain gauge malfunction

Table 6 Description of fungicides programs evaluated for their effects on foliar diseases, grain yield and, test weight in soft red winter wheat in Delaware, Maryland, Virginia, and Pennsylvania in 2015 and 2016.

Program ¹	Fungicide(s) ²	Fungicide Active Ingredient(s)	Total Active Ingredients (g ha ⁻¹) ³	Timing (FGS) ⁴	Product Rate (l ha ⁻¹) ⁵
CK	-	Untreated Control	-	-	-
TSOLO8	Tilt	propiconazole 41.8%	126	8	0.29
TSPLT5+8	Tilt FB Tilt	propiconazole 41.8%	63,126	5+8	0.15,0.29
TSPLT5+F ⁶	Tilt FB Prosaro	propiconazole 41.8% fb prothioconazole 19% and tebuconazole 19%	63,100,100	5+10.5.1	0.15,0.48
QSOLO8	Quilt Xcel	azoxystrobin 13.5% and propiconazole 11.7%	94,108	8	0.77
QSPLT5+8	Quilt Xcel FB Quilt Xcel	azoxystrobin 13.5% and propiconazole 11.7%	63,72,94,108	5+8	0.51,0.77
QSPLT5+F ⁶	Quilt Xcel FB Prosaro	azoxystrobin 13.5% and propiconazole 11.7% fb prothioconazole 19% and tebuconazole 19%	63,72,100,100	5+10.5.1	0.51,0.48
XSOLO8	Priaxor	fluxapyroxad 14.33% and pyraclostrobin 28.58%	97,49	8	0.29
XSPLT5+8	Priaxor FB Prixaor	fluxapyroxad 14.33% and pyraclostrobin 28.58%	49,24,97,49	5+8	0.15,0.29
XSPLT5+F ⁶	Priaxor FB Prosaro	fluxapyroxad 14.33% and pyraclostrobin 28.58% fb prothioconazole 19% and tebuconazole 19%	49,24,100,100	5+10.5.1	0.15,0.48
SSOLO8	Stratego YLD	prothioconazole 10.8% and trifloxystrobin 32.3%	37,110	8	0.29
SSPLT5+8	Stratego YLD FB Stratego YLD	prothioconazole 10.8% and trifloxystrobin 32.3%	18,55,37,110	5+8	0.15,0.29
SSPLT5+F ⁶	Stratego YLD FB Prosaro	prothioconazole 10.8% and trifloxystrobin 32.3% fb prothioconazole 19% and tebuconazole 19%	18,55,100,100	5+10.5.1	0.15,0.48
PSOLOF ⁶	Prosaro	prothioconazole 19% and tebuconazole 19%	100,100	10.5.1	0.48

¹Program code to be used in following sections when describing fungicide programs

²Fungicides with FB=followed by; indicating a sequential application

³Total active ingredient listed in order of product as found in the fungicide(s) column

⁴FGS=Feekes growth stage

⁵Product rate listed in order of product as found in the fungicide(s) column

⁶Misapplication at WY16 resulted in 13.8% less product for all FGS 10.5.1 applications.

Table 7 Mean difference (effect size) and corresponding statistics from random-effects meta-analysis of the effect of fungicide programs on grain yield in soft red winter wheat from field experiments conducted in Delaware, Maryland, Virginia, and Pennsylvania in 2015 and 2016^a

Contrast ^b	$\bar{D}$	$se(\bar{D})$	P	CI_L	CI_U
TSOLO8 versus CK	253.65	104.85	0.016	48.12	459.19
TSPLT5+8 versus CK	331.51	96.26	<0.001	142.83	520.20
TSPLT5+F versus CK	520.54	100.92	<0.001	322.73	718.36
QSOLO8 versus CK	405.03	112.66	<0.001	184.20	625.86
QSPLT5+8 versus CK	569.53	154.43	<0.001	266.81	872.25
QSPLT5+F versus CK	634.16	143.34	<0.001	353.18	915.14
SSOLO8 versus CK	329.49	98.92	<0.001	135.58	523.39
SSPLT5+8 versus CK	419.85	103.49	<0.001	217.00	622.70
SSPLT5+F versus CK	482.42	129.66	<0.001	228.26	736.57
XSOLO8 versus CK	460.19	107.74	<0.001	248.99	671.38
XSPLT5+8 versus CK	481.21	100.46	<0.001	284.29	678.13
XSPLT5+F versus CK	542.40	122.99	<0.001	301.32	783.49
PSOLOF versus CK	373.69	111.82	<0.001	154.49	592.89
FGS8 versus FGS5 FB FGS8	-88.44	36.35	0.015	-159.70	-17.18
FGS8 versus FGS5 FB FGS10.5.1	-182.79	38.47	<0.001	-258.20	-107.38
FGS8 versus FGS10.5.1	-11.60	56.64	0.838	-122.63	99.42
FGS10.51 versus FGS5 FB FGS8	-76.84	48.01	0.110	-170.95	17.28
FGS10.51 versus FGS5 FB FGS10.5.1	-171.19	52.40	0.001	-273.91	-68.47
FGS5 FB FGS8 versus FGS5 FB FGS10.5.1	-94.36	32.83	0.004	-158.70	-30.01

^a $\bar{D}$ = effect size as mean grain yield difference for each fungicide program relative to the untreated check and for comparisons between selected pairs of application timings, averages across programs (below the broken line); $se(\bar{D})$ = standard error of $\bar{D}$; lower (CI_L) and upper (CI_U) limits of the 95% confidence interval around $\bar{D}$; and P = probability value (significance level) for the effect of treatment on yield.

^bDescription of treatments found in **Table 5** of the materials and methods section.

Table 8 Mean difference (effect size) and corresponding statistics from random-effects meta-analysis of the effect of fungicide programs on grain test weight in soft red winter wheat from field experiments conducted in Delaware, Maryland, Virginia, and Pennsylvania in 2015 and 2016a

Contrast ^b	$\bar{D}$	$se(\bar{D})$	<i>P</i>	<i>CI_L</i>	<i>CI_U</i>
TSOLO8 versus CK	11.54	3.98	0.004	3.74	19.33
TSPLT5+8 versus CK	13.83	4.64	0.003	4.74	22.93
TSPLT5+F versus CK	28.32	7.39	<0.001	13.83	42.81
QSOLO8 versus CK	18.55	4.92	<0.001	8.91	28.18
QSPLT5+8 versus CK	16.21	5.68	0.004	5.09	27.34
QSPLT5+F versus CK	30.61	7.71	<0.001	15.50	45.72
SSOLO8 versus CK	13.99	4.04	<0.001	6.08	21.91
SSPLT5+8 versus CK	15.77	4.34	<0.001	7.27	24.27
SSPLT5+F versus CK	27.60	7.37	<0.001	13.15	42.06
XSOLO8 versus CK	17.61	4.70	<0.001	8.40	26.82
XSPLT5+8 versus CK	14.66	4.42	<0.001	6.00	23.32
XSPLT5+F versus CK	27.65	6.43	<0.001	15.05	40.24
PSOLOF versus CK	24.77	6.49	<0.001	12.04	37.50
FGS8 versus FGS5 FB FGS8	0.30	1.25	0.808	-2.14	2.75
FGS8 versus FGS5 FB FGS10.5.1	-13.12	3.06	<0.001	-19.12	-7.13
FGS8 versus FGS10.5.1	-9.35	2.49	<0.001	-14.24	-4.46
FGS10.51 versus FGS5 FB FGS8	9.65	2.46	0.009	4.84	14.46
FGS10.51 versus FGS5 FB FGS10.5.1	-3.78	1.44	<0.001	-6.59	-0.96
FGS5 FB FGS8 versus FGS5 FB FGS10.5.1	-13.43	3.07	<0.001	-19.45	-7.40

^a $\bar{D}$ =effect size as mean grain test weight difference for each fungicide program relative to the untreated check and for comparisons between selected pairs of application timings, averages across programs (below the broken line); $se(\bar{D})$ =standard error of $\bar{D}$; lower (*CI_L*) and upper (*CI_U*) limits of the 95% confidence interval around $\bar{D}$; and *P*=probability value (significance level) for the effect of treatment on yield.

^bDescription of treatments found in **Table 6** of the materials and methods section.

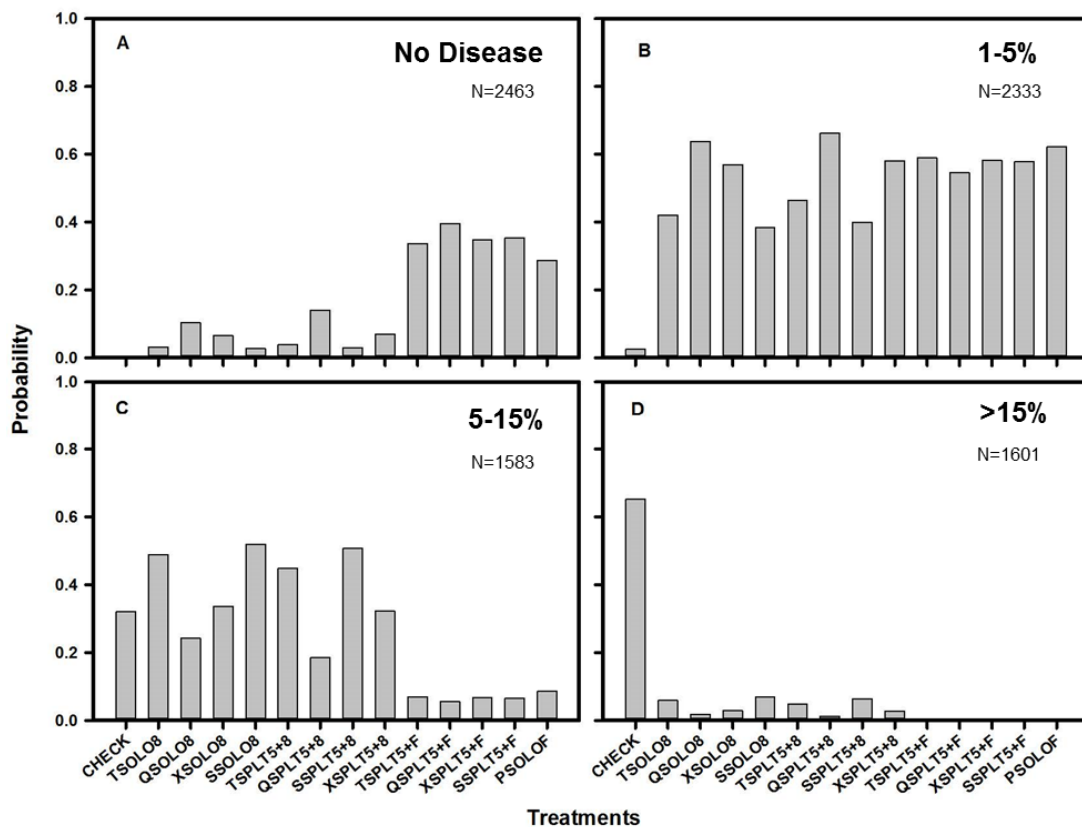


Figure 7 Probability of wheat foliar disease severity reaching one of four new categories, which include (A) category 1: no foliar disease on the flag leaf, (B) category 2: 1-5% disease severity on the flag leaf, (C) category 3: 5-15% disease severity on the flag leaf, and (D) category 4: >15% disease severity on the flag leaf according to assessments taken between FGS 11.1 to 11.2. Estimates were based on individual observations from field experiments conducted in four mid-Atlantic states from 2015-2016 and entered into a generalized linear mixed model (GLMM) to generate the likelihood of disease severity being placed in a one of the four categories given a fungicide program. Fungicide programs are described in detail in **Table 6** of the materials and methods section.

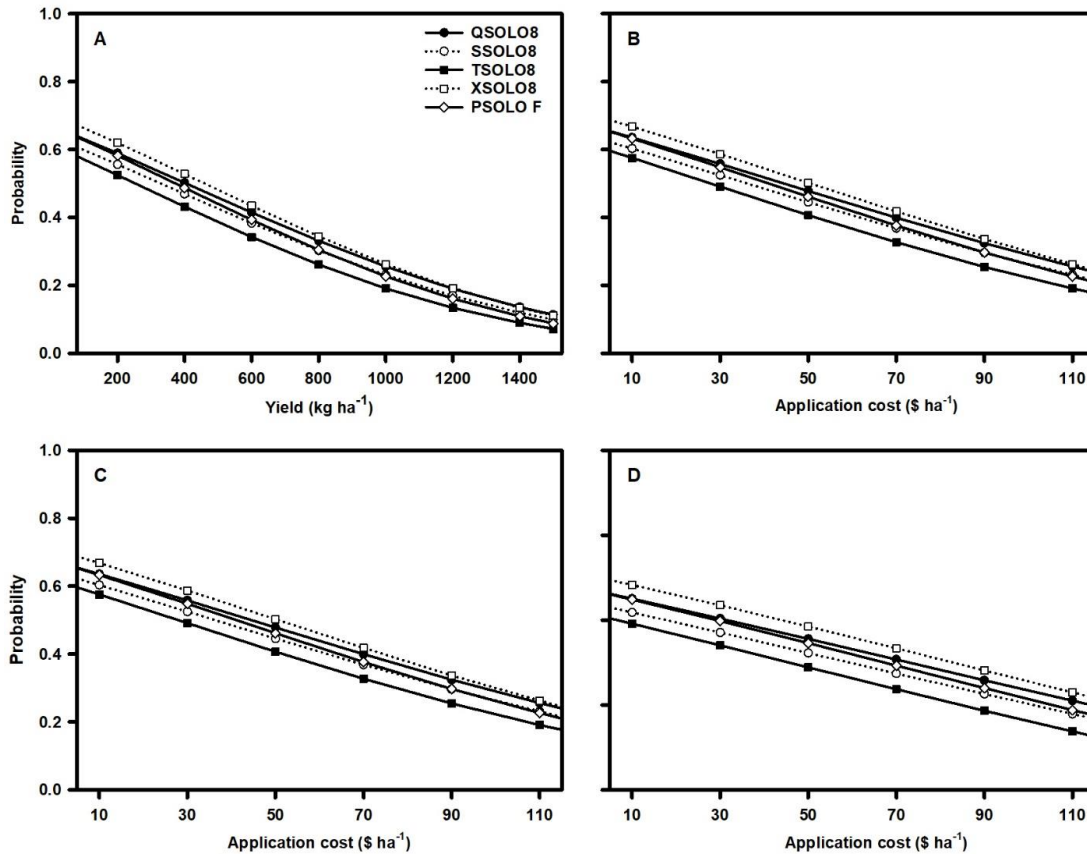


Figure 8 Estimated probability of FGS 8 & FGS 10.5.1 programs resulting in **A**, yield increases of 1 to 1400 kg ha⁻¹ relative to the untreated check; and **B-D** profitability of break-even at grain prices of \$0.11 (\$3.00), \$0.18 (\$5.00), and \$0.26 (\$7.00) kg⁻¹ (bu⁻¹), respectively for a range of application costs. Estimates were based on mean effect sizes and between-study variances from a random-effects meta-analysis from field experiments conducted in the mid-Atlantic states from 2015-2016 to evaluate the effects of fungicides programs for foliar disease control on wheat grain yield. Fungicide programs are described in **Table 6** of the materials and methods section.

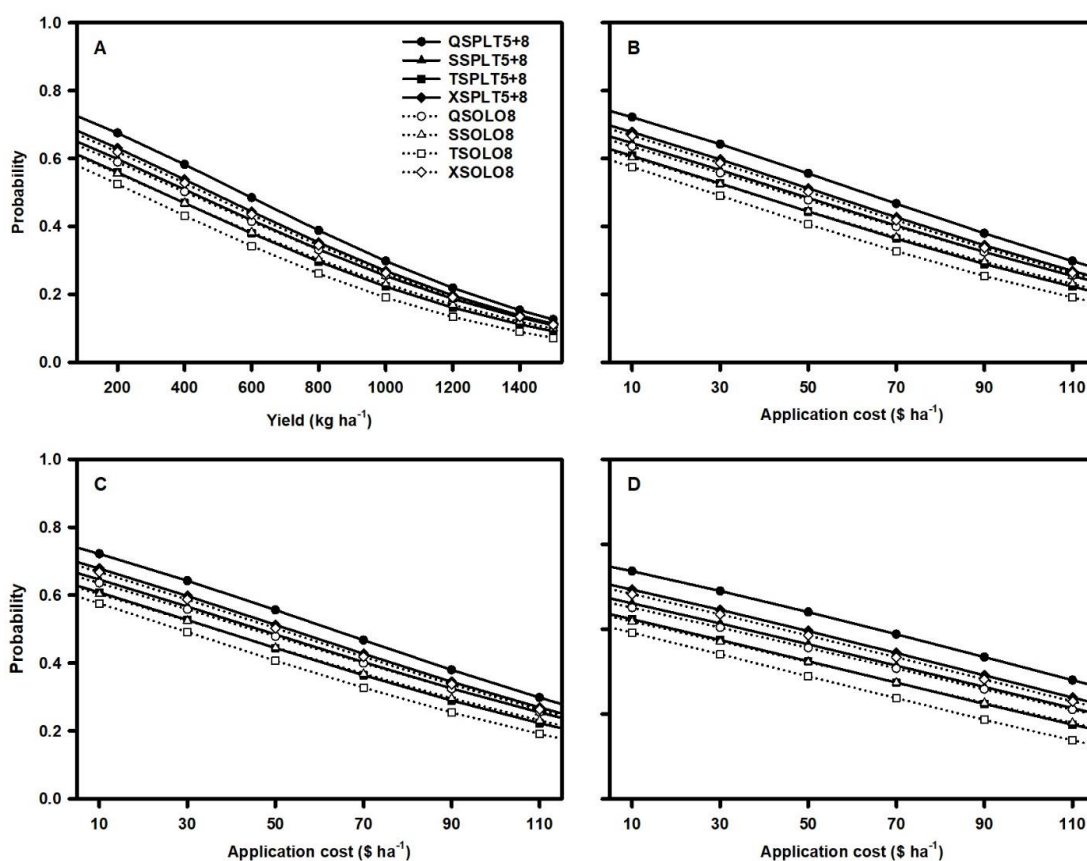


Figure 9 Estimated probability of FGS 8 & FGS 5 FB FGS 8 programs resulting in **A**, yield increases of 1 to 1400 kg ha⁻¹ relative to the untreated check; and **B-D** profitability of break-even at grain prices of \$0.11 (\$3.00), \$0.18 (\$5.00), and \$0.26 (\$7.00) kg⁻¹ (bu⁻¹), respectively for a range of application costs. Estimates were based on mean effect sizes and between-study variances from a random-effects meta-analysis from field experiments conducted in the mid-Atlantic states from 2015-2016 to evaluate the effects of fungicides programs for foliar disease control on wheat grain yield. Fungicide programs are described in **Table 6** of the materials and methods section.

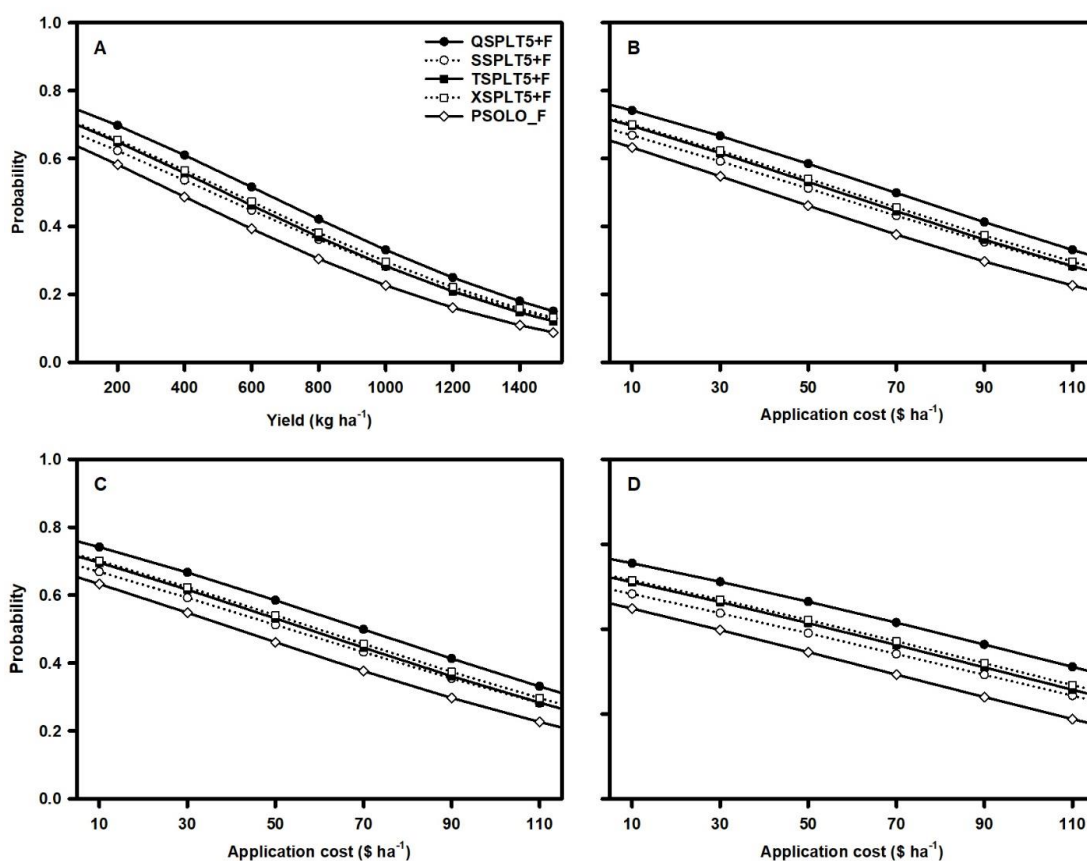


Figure 10 Estimated probability of FGS 10.5.1 & FGS 5 FB FGS 10.5.1 programs resulting in **A**, yield increases of 1 to 1400 kg ha⁻¹ relative to the untreated check; and **B-D** profitability of break-even at grain prices of \$0.11 (\$3.00), \$0.18 (\$5.00), and \$0.26 (\$7.00) kg⁻¹ (bu⁻¹), respectively for a range of application costs. Estimates were based on mean effect sizes and between-study variances from a random-effects meta-analysis from field experiments conducted in the mid-Atlantic states from 2015-2016 to evaluate the effects of fungicides programs for foliar disease control on wheat grain yield. Fungicide programs are described in **Table 6** of the materials and methods section.

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Chapter 3

PROJECT SUMMARY

Findings from this research contribute to the existing body of knowledge on fungicide use in wheat and can be used to support future research exploring fungicide utility and economics. My observations indicate LBC was the most commonly occurring foliar disease in wheat, supporting observations by others in the region. The impacts of foliar fungicides on yield and test weight were, therefore, most heavily influenced by this disease complex. Consequently, growers should consider adopting integrated disease management practices that reduce LBC, such as selecting high yielding, resistant varieties, and planting wheat behind a non-host crop such as soybeans if possible. These results offer potential other avenues of study, for example, we understand little of the population structure of the LBC pathogen complex in the region and the relative fungicide sensitivity of these pathogens. Growers have been using fungicides in wheat for many years, and many of these pathogens are exposed to these same modes of action in other rotational crops, especially corn. It is possible that producers in the region may see some fungicide resistance development in this pathogen group in the future. The sales of premix fungicides, which contain at least two different fungicide modes of action, have recently increased as a strategy to delay fungicide resistance. If a pathogen has already developed reduced sensitivity to a particular mode of action, these premixes, in essence, are acting as single mode of action fungicides. Thus, continued use could result in eventual failure of the fungicide and loss of disease control with these products.

My work shows that fungicides can be effective for foliar disease management and yield in mid-Atlantic SRWW, and was the first study to evaluate multiple timings

and fungicide products in a comprehensive manner. My data show that fungicide use can be profitable in mid-Atlantic wheat production, but application timing appears more important rather than product selection. Therefore, growers could select cheaper products applied between FGS 8 – 10.5.1 and still see an economic benefit, as opposed to choosing more expensive, premium products. Furthermore, generic fungicides containing mixed modes of actions are entering the marketplace and may be lower in price than name brand products, which could influence profitability. My work also indicates that fungicides applied at FGS 10.5.1 can be just as effective for managing foliar diseases affecting the flag leaf as applications at FGS 8. This result indicates that growers could make a single fungicide application at FGS 10.5.1 and control both foliar and head diseases in a profitable manner. One important factor to note is that only DMI fungicides are recommended for application at FGS 10.5.1, which could result in fungicide resistance development in diseases of the head and foliage. There are at least two non DMI fungicides that will be released for FHB management in the near future. If these fungicides are as efficacious for foliar diseases as those tested in this study, they will allow growers to rotate or tank mix different fungicide modes of action and minimize fungicide resistance development in wheat. In addition, my results show that there was minimal economic benefit of applying fungicides early in the growing season at FGS 5. This result supports other non-replicated studies in the region, and may enable growers to reduce fungicide applications during the season and maximize profitability.

I used a novel statistical technique to generate probabilities of profitability for different fungicide programs across different production scenarios in the mid-Atlantic. Essentially, this work can begin to answer the questions growers often ask me, “Does

it pay to apply a fungicide?” Based on these data, I can now provide estimates of the potential profitability of different fungicide programs for growers. It is important to note that the scope of this work is limited to the conditions experienced in the ten site-years. However, the goal of my work was to begin to answer these questions for growers and researchers in the region. My platform serves as a starting point which lays the foundation for future research. For example, the fungicides used in this study, in addition to new commercial fungicides entering the market, should be tested on more varieties, with varying levels of resistance to common foliar diseases. If collected properly and assessed over many years, data from such research could be used to develop a profitability tool for growers. This tool could be made available to growers using web-based application tools, to further aid the grower in making profitable fungicide decisions. This would take significant research, funding, and effort, but would be a potentially groundbreaking tool for wheat producers.

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