SINGLE VERSUS DUAL PESTICIDE APPLICATIONS FOR INCREASING OKLAHOMA WINTER WHEAT GRAIN YIELD AND PROFITABILITY

By

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Abstract:

Foliar fungicides and insecticides can be useful tools in management decisions against fungal diseases and insect pests of winter wheat in Oklahoma, but little is known about multiple applications and tank-mixes of these pesticides. Two studies were conducted across three different locations during the 2016-2017 and 2017-2018 growing seasons, focusing on multiple fungicide treatments and fungicide + insecticide treatments at two different timings, Feekes 6 (jointing) and Feekes 9 (full flag leaf emergence). Two wheat varieties were used in each study, chosen based on susceptibility and resistance to fungal diseases. In the first study which assessed a dual fungicide application approach compared to a single application, results showed that a dual fungicide application can reduce disease levels, protect more yield potential, and provide greater marginal return than a single fungicide application. However, this management practice was highly dependent on variety and location. Due to the timing of disease occurrence in most cases during the course of the study, a single fungicide application was more often profitable than the dual application approach. The second study examined the effect of fungicide + insecticide tank-mix applications compared to each pesticide applied alone at both growth stages. Results for this study showed that a fungicide + insecticide application can provide greater yield than each pesticide applied alone. However, this result was highly dependent on the year, location, and timing when fungal diseases and/or insects were present, and it only occurred at the Feekes 6 application timing. Greater marginal return from a fungicide + insecticide application compared to each pesticide applied alone was also dependent on year and location. This greater marginal return from the fungicide + insecticide application was observed at both Feekes 6 and Feekes 9 but occurred at the Feekes 6 application timing the majority of the time. Based on the results of these two studies, scouting for fungal diseases and insects and understanding wheat variety susceptibility to fungal diseases should dictate whether multiple fungicide applications and/or fungicide + insecticide tank-mixes should be used instead of making prophylactic applications in Oklahoma.

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CHAPTER I

INTRODUCTION

Wheat (*Triticum aestivum* L.) ranks third among U.S. field crops behind corn and soybean in planted hectares, production, and gross farm receipts (USDA-NASS, 2018). In Oklahoma, winter wheat is the number one production crop. Winter wheat was planted on 1.8 million hectares across the state during 2017-2018, and 1.0 million hectares were harvested for grain during that production season (USDA-NASS, 2018). With Oklahoma producing 1.9 million Mg of grain during the last production season and the price for wheat in Oklahoma during June 2018 valued at \$0.19 kg^{-1}, this resulted in a \$361,000,000 value for the Oklahoma economy (USDA-NASS, 2018). Due to its economic importance, there is considerable focus devoted to improving winter wheat management in order to keep input costs low and to maximize economic returns. Oklahoma wheat producers face a challenging task when it comes to management practices and the timing of implementing these practices. Properly timed foliar pesticide applications play a significant role in protecting the crop from pathogens and insects in order to maintain yield potential and quality of the crop, all while attempting to maximize profitability. Therefore, this research focused on single and dual foliar fungicide and insecticide applications at two wheat growth stages, Feekes 6 (jointing) and Feekes 9 (ligule of flag leaf visible) (Large, 1954). The goal of this research is to determine whether a dual foliar pesticide application approach results in increased winter wheat grain yield and profitability compard to a single application in Oklahoma.

CHAPTER II

REVIEW OF LITERATURE

Dual-purpose Wheat Management

Dual-purpose wheat is the grazing of the crop when it is in the vegetative state and then removing the livestock at the proper time to still produce grain for harvest. Dual-purpose wheat gives livestock access to forage that is available in late fall, winter, and early spring. If grazing is appropriately managed, it can provide producers with income derived from both the harvested grain and the weight gain to growing cattle that are pastured on winter wheat (Redmon et al., 1995). However, failing to remove livestock at the first hollow stem growth stage (i.e., between Feekes 5 and 6) can result in a grain yield loss of 1 to 5% per hectare per day that it is grazed past this growth stage (Edwards and Horn, 2016).

Grazing winter wheat is a common practice across the U.S. southern Great Plains. It is also practiced in other countries such as Argentina, Australia, Morocco, Pakistan, Syria, and Uruguay (Rodríguez et al., 1990). Pinchak et al. (1996) estimated that 30-80% of the eight million hectares seeded annually to wheat in the U.S. southern Great Plains are grazed. Within the U.S. southern Great Plains, winter wheat as a dual-purpose crop is highly valued across southwestern Kansas, western Oklahoma, the Texas Panhandle, eastern New Mexico, and southeastern Colorado.

Wheat used for dual-purpose must be planted earlier, ranging from early to late September, and results in a lengthened time of exposure to the environment (Lollato et al., 2017). In a monoculture wheat cropping system, early planting can result in increased weed pressure (Epplin et al., 2000), can increase the risk of volunteer wheat that may facilitate the build-up and transfer of organisms and diseases from one wheat crop to the next (Epplin et al., 2000), and can increase the incidence of several diseases including Wheat streak mosaic (WSM), High Plains disease (HPD), barley yellow dwarf (BYD), eyespot, common root rot, and take-all root rot (Bowden, 1997).

Fungi

Diseases caused by plant pathogenic (i.e., disease-causing) organisms, including fungi, are a major source of crop damage. Fungal diseases are considered the number one cause of crop loss worldwide (McGrath, 2004), and there are approximately 20,000 species of fungi which are plant pathogenic (Jibril et al., 2016). Fungi were once considered lower plants that lacked chlorophyll, but it is now known to constitute a group of organisms distinct from plants (Bockus et al., 2010). Most true fungi exist as filamentous, branched chains of cells called hyphae (known collectively as a mycelium) 2-10 μm in diameter with cell walls that contain chitin and well-differentiated organelles (Bockus et al., 2010).

Fungi infect wheat by direct penetration of the epidermis or through wounds or natural openings. Infections are expressed as blights, wet or dry rots, deformations, mildews, smuts, spots, and rusts (Bockus et al., 2010). As part of their life cycle, most fungi produce spores, which can be the result of sexual or asexual reproduction. Sexual reproduction occurs by association of two harmonious nuclei produced by meiosis

(Schultz, 2007). For some phytopathogenic fungi, the sexual cycle happens just once amid each developing season. From these spores, ascospores, basidiospores, oospores, and zygospores can be produced only once each growing season. Asexual reproduction can create mitotic spores, mycelia fragmentation, division, and budding using mitosis. These cycles can be continuous throughout the growing season. Classifications of asexual spores are conidia (borne on edges or tips of specialized branches of hyphae), oidia (developed by division of hyphae), and sporangiospores (immotile spore born in a sporangium or case) (Schultz, 2007). Fungi cannot ingest food like animals or make their food as plants do. Fungi must grow within the substrate on which they are feeding and absorb the nutrients needed (Bockus et al., 2010). An understanding of the life cycle of any fungal pathogen allows for proper management of that pathogen. Several fungal pathogens of concern in Oklahoma include *Pyrenophora tritici- repentis* (tan spot), *Zymoseptoria tritici* (Septoria leaf blotch), *Parastagonospra nodorum* (Stagonospora glume blotch), *Cochliobolus sativus* (spot blotch), *Blumeria graminis* f. sp. *graminis* (powdery mildew), *Puccinia triticina* (leaf rust), and *Puccinia striiformis f. sp. tritici* (stripe rust).

Insects

Most insects that are present in cropping systems do not have an impact on plant growth or yield, but certain species can cause devastating damage (Bockus et al., 2010). Some of these destructive species include leaf beetles and grasshoppers. Others such as wireworms or Hessian fly may be concealed or hidden within the plant itself or the soil (Bockus et al., 2010). For many years, aphids were considered the most prominent insect pest of winter wheat (Chambers and Adams, 1986; Hasken and Poehling, 1994), and it is one of the most yield-limiting insects of winter wheat in the southern Great Plains (Royer, 2007). The two most common aphids in Oklahoma are the bird cherry-oat aphid (*Rhopalosiphum padi* L.) and the greenbug (*Schizaphis graminum* Rondani) (Ismail et al., 2003). These two aphids can limit wheat profitability significantly by transmitting a luteovirus or by direct feeding if infestations occur during early growth stages (Starks and Burton, 1977; Kieckhefer and Kantack 1986; Kieckhefer and Gellner 1992; Kieckhefer et al., 1994; Riedell and Kieckhefer 1995; Webster et al., 2000; Kindler et al., 2002). Bird cherry-oat aphid and greenbug both feed by inserting tube-like mouthparts into the vascular system of the plant and removing sap from the plant. Greenbugs also inject a toxin into the host plant that reduces shoot mass development and tillering in wheat (Burton, 1986; Burton and Burd, 1993; Riedell and Kieckhefer, 1995). Both aphid species are also capable of transmitting barley yellow dwarf virus (BYDV) when they feed (Chirumamilla, 2014). Aphids transmit this virus in a non-propagative way; the virus does not replicate in the vector but does circulate through the aphid's body (Royer et al., 2015). There are many different ways of controlling aphids, such as biological control, resistant or tolerant varieties, insecticide seed treatments, and foliar insecticides. Arnold (1981) reported that grazing reduced greenbug populations in winter wheat, and Ismail et al. (2003) also found that grazing significantly reduced aphid-days by nearly 87%.

Eriophyidea Herbaceous Mites

Wheat curl mite (*Aceria tosichella* Keifer) is an organism that is 0.25 μm long, and is best seen under 20× magnification. They infest wheat, corn, barley, oats, and foxtail millet, as well as many other grass hosts (Webb, 2018). Wheat curl mites transmit diseases known as wheat streak mosaic (WSM), High Plains disease (HPD), and Triticum mosaic (TriM). Wheat curl mites can increase rapidly on the plant when conditions are favorable, going from an egg through two nymphal stages to an adult in as little as eight to 10 days at 25℃ (Hein, 2007). In severe cases, WSMV causes yield losses of more than 80% when susceptible cultivars are infected as seedlings. Cultivars with intermediate levels of resistance, while less damaged, may still experience up to 20% yield loss (Webb, 2018).

Seed Treatments

Seed treatments can contain a combination of insecticides and fungicides to provide initial protection from soil-borne pathogens and insects that may arise after planting. For example, a fungicide seed treatment can limit soil-borne pathogens such as *Rhizoctonia solani* and *Fusarium* spp., which are the leading cause of root rot diseases of cereals worldwide (Weller et al., 1986). Systemic fungicide seed treatments are also recommended to help protect against seed-borne bunts and smuts. Depending on the type of seed treatment, chemicals may be translocated to aboveground portions of the plant and protect against foliar fungal diseases and insects (Taylor and Harman, 1990). For example, applying insecticide to the seed can assist with controlling an early infestation of wireworms below-ground and aphids above-ground.

Seed treatments can help protect against pathogens that overwintered from the previous crop, especially when planted into heavy residue. However, not all soil-borne diseases can be controlled by a fungicide seed treatment. Therefore, cultural practices are needed for control, and generally, the best practice includes rotating crops. For example, take-all, caused by soil-borne fungus, *Gaeumannomyces graminis*, is a severe root disease of wheat worldwide but cannot be controlled by a fungicide seed treatment (Hershman and Bachi, 2001). Rotating to another crop for one year can significantly reduce the potential for take-all to damage subsequent wheat crops, but two to four-year crop rotations, with corn or soybean for example, are recommended for problem fields (Hershman and Bachi, 2001). In Oklahoma, rotating to canola for one growing season can help reduce take-all and other soil-borne diseases.

Past investigation has indicated both fungicide and insecticide seed treatment successfully diminish grain yield losses. Gray et al. (1996) reported that imidacloprid seed treatment reduced BYD incidence but generally had no effect on wheat yield or test weight in New York. Imidacloprid seed treatment for hard red winter wheat in Oklahoma was found to reduce bird cherry-oat aphid (*Rhopalosiphum padi* L.) populations and prevalence of BYD (Royer et al., 2005). The results also showed aphid abundance and incidence of BYD were reduced as insecticide rates increased. All yield components and grain yield increased as insecticide rate increased, resulting in positive economic returns. The authors also indicated producers are more likely to obtain a positive economic return when seed treatment is used in a dual-purpose planting window, which makes up 40-60% of the planting acres in Oklahoma each year (Royer et al., 2005). Another study conducted in Oklahoma evaluated winter wheat seed treatments at seven locations over three years (2008, 2011, and 2012) (DeVuyst et al., 2014). Results indicated insecticide and fungicide seed treatment increased wheat grain yield by 144 kg ha^{-1}. Overall, grain volume weight was unaffected due to seed treatment. While seed treatments in Oklahoma were shown to increase wheat grain yield, results indicated a significantly increased economic return only occurred when wheat sale prices were greater than \$294 Mg^{-1} (DeVuyst et al., 2014).

Foliar Fungicides

Planting a disease-resistant variety is an efficient way to control disease-causing organisms that may occur, but wheat varieties today typically only provide protection against a few specific diseases. In addition to using seed treatment fungicides to help protect against pathogens to save a crop from economic loss, foliar fungicide applications can also be made. There are two broad categories for describing how foliar fungicides work. A contact fungicide sticks to the plant surface leaving a protective barrier on the leaf surface after application. It does not penetrate the tissue. In contrast, systemic fungicides are compounds that are absorbed by the plant and then translocated throughout the plant, thus protecting the plant by limiting already established infections or protecting the plant from the occurrence of attacking pathogenic fungi. Foliar fungicides can also help increase the activity of plant antioxidants which can slow down the degredation of chlorophyll and leaf proteins by fungi (Zhang et al., 2010).

A properly timed foliar fungicide application can be economically profitable for a producer. A study in Europe examined single, double, and triple fungicide applications for their effect on yield and grain quality in winter wheat (Jarroudi et al., 2015). Experiments were conducted at two sites in Germany, Burmerange and Everlange, during 2006-2009, and various fungal diseases were monitored. Results showed that yields from plots treated with fungicide were higher compared to the non-treated plot at both sites, except for when fungal disease pressure was low in 2008. Results were significant when comparing fungicide treatment effects for all grain quality parameters, including thousand grain weight (TGW), test weight, grain protein content (GPC), and Zeleny sedimentation volume (ZSV) analyzed at Burmerange. Plots receiveing one, two, or three fungicide applications generally had greater TGW, GPC, and ZSV than those which did not receive fungicide, but results were mixed regarding differences among the fungicide-treated plots. At Everlange, TGW and ZSV were the only quality parameters found to be influenced by fungicide use, and the trends were similar to those at Burmerange. This study showed grain quality after a single fungicide application was similar to the grain quality from plants receiving the double or triple applications, and it also showed that a single fungicide application led to grain yield and financial returns similar to those from a double or triple fungicide application (Jarroudi et al., 2015). Another study done by Edwards et al. (2012) addressed the agronomic and economic response of hard red winter wheat to foliar fungicide applied at Feekes 9-10 in Oklahoma. The experiments were conducted at Lahoma, OK and Apache, OK from 2005-2010. Results indicated that when wheat achieved greater yields, it was due to the application of foliar fungicides, which also resulted in increased thousand-kernel weight, harvest index, and grain volume weight. For the different parameters examined, the largest benefit observed from foliar fungicide application occurred with susceptible cultivars. The yield difference between treated and non-treated susceptible cultivars was 270 kg ha^{-1} (10%) at Apache and 810 kg ha^{-1} (24%) at Lahoma. For intermediate and resistant cultivars, there was no significant effect on grain yield due to fungicide application at Apache. At Lahoma though, average grain yield for intermediate and resistant cultivars treated with a foliar fungicide was 11 and 10% greater, respectively, than the same cultivars non-treated. Response to foliar fungicide application in susceptible cultivars was anticipated, but a significant response to foliar fungicide application for intermediate and resistant cultivars at Lahoma was not as expected. This response was likely due to greater leaf rust incidence and severity at

Lahoma across all years except 2010. It was also noted that foliar fungicide applications to wheat represented a sound economic input, generating a high likelihood of positive returns when disease incidence and severity were high. An economic analysis examined three different scenarios of return based on wheat grain sale price, wheat cultivars (resistant, intermediate, and susceptible), and fungicide cost. Breakeven grain yield advantages needed from foliar fungicide use were based on $ kg^{-1} of wheat and $ ha^{-1} of fungicide cost and were calculated to be 84 kg ha^{-1}, 168 kg ha^{-1}, and 336 kg ha^{-1}. Results indicated that nine of 36 foliar fungicide price scenarios at Apache, OK and 35 out of 45 price scenarios at Lahoma had a greater than 80% likelihood that foliar fungicide use resulted in enough additional grain yield to offset the foliar fungicide cost (Edwards et al., 2012). Another study by Thompson et al. (2014) also found foliar fungicide treatment on hard red winter wheat applied at Feekes 9-10.5 in Oklahoma can be an economically sound management strategy under some conditions. Experiments were conducted in Apache, OK and Lahoma, OK during 2005-2012. Differences on average net returns between fungicide-treated and non-treated plots for resistant, intermediate, and susceptible varieties across years were -$28, -$19, and -$6 ha^{-1} at Apache, OK and $36, $36, and $116 ha^{-1} at Lahoma, OK. Despite the variable response, fungicide treatment did tend to protect producers from the downside risk of large yield losses in years of high disease incidence and severity, especially when growing wheat varieties susceptible to common foliar diseases (Thompson et al., 2014).

Foliar Insecticides

Foliar insecticides are beneficial in controlling the insects that might be present later in the growing season when the seed treatment is no longer active or when an infestation reaches economic threshold (ET). Pesticides should not be used as a substitute for good agronomic practices or as "preventative insurance" as it can cause pest resurgence issues and are rarely economically or environmentally justifiable (Royer and Giles, 2015).

A study was conducted to evaluate the effectiveness and timing of insecticidal seed treatment (thiamethoxam) and foliar insecticide (lambda-cyhalothrin) for managing wheat stem maggot [*Meromyza Americana* Fitch (Diptera: Chloropidae)] and wheat stem sawfly [*Cephus cinctus* Norton (Hymenoptera: Cephidae)] in spring wheat in North Dakota during 2008-2009 (Knodel et al., 2009). A foliar application at Feekes 3-5 and Feekes 9 reduced the number of whiteheads caused by wheat stem maggot. A combination of low rate seed treatment plus a foliar application of lambda-cyhalothrin at Feekes 3-5 also resulted in a significantly lower number of whiteheads caused by wheat steam maggot, but the different high and low rates of seed treatment alone showed to be ineffective at reducing the number of whiteheads. Peak adult emergence occurred around the timing of lambda-cyhalothrin Feekes 3-5 and at Feekes 9 potentially affecting the whitehead numbers. None of the treatments reduced the percentage of damaged stems from wheat stem sawfly. There were also no yield differences among the treatments for either wheat stem maggot or wheat stem sawfly (Knodel et al., 2009). Another study performed by Royer et al. (2011) evaluated the effect of temperature on the field efficacy of three classes of registered insecticides for greenbug control in winter wheat fields. The insecticides were selected to represent different modes of action (organophosphate, pyrethroid, and neonicotinoid) and offer systemic (imidacloprid: neonicotinoids), contact (chlorpyrifos and lambda-cyhalothrin: pyrethroid), or a combination of systemic and contact (dimethoate: organophosphate) activity. Results indicated any insecticide applied during the winter provided up to 70 to 80% control of greenbug on average as long as temperatures exceeded 13℃ during the 14 days following application with no significant rainfall occurring (Royer et al., 2011).

Objectives

Previous work examining foliar fungicide and insecticide applications has focused on a single application. Little information exists, especially for the southern Great Plains, whether multiple applications and tank-mixes of fungicide and insecticide result in increased winter wheat grain yield and positive economic returns. The purpose of this research was to examine foliar fungicide and insecticide applications focused on timings at Feekes 6 (jointing) and Feekes 9 (full flag leaf emergence) to better understand the impact that these practices have on winter wheat grain yield and profitability in Oklahoma. The first objective of this research was to determine whether a dual foliar fungicide application approach results in increased winter wheat grain yield and profitability compared to a single application. The second objective was to determine whether a fungicide + insecticide application results in increased winter wheat grain yield and profitability compared to each pesticide applied alone in Oklahoma.

CHAPTER III

SINGLE VERSUS DUAL FUNGICIDE APPLICATIONS FOR PROTECTING WINTER WHEAT GRAIN YIELD AND INCREASING PROFITABILITY

ABSTRACT

Fungicide application timing on wheat can be a significant factor in protecting the crop from foliar diseases and maintaining yield potential. The objective of this study was to assess a dual fungicide application approach compared to a single application for increasing winter wheat grain yield and profitability in Oklahoma. A randomized complete block design with treatments arranged in a 2 × 4 factorial was implemented at two locations (Apache and Stillwater, OK) during the 2016-2017 and 2017-2018 growing seasons. Treatments consisted of two winter wheat varieties (Gallagher and Bentley) and four fungicide application treatments (non-treated control, Feekes 6, Feekes 9, and Feekes 6 + 9). At Stillwater during 2016-2017 where leaf rust was present after spring greenup through stem elongation, the Feekes 6 + 9 fungicide treatment resulted in the greatest yield and highest economic return for the variety Bentley (leaf rust susceptible). No differences among the fungicide-treated plots was observed for the variety Gallagher (leaf rust resistant), but all were significantly greater than the non-treated control. The Feekes 9 fungicide treatment resulted in the highest marginal economic return though

for Gallagher. At Apache, the Feekes 6 + 9 and Feekes 9 treatments averaged across both varieties yielded 640 and 590 kg ha^{-1} greater than the non-treated control, but the greatest profitability occurred for the Feekes 9 treatment and was likely due to leaf rust which rapidly developed and increased from the end of stem elongation through grain-fill. Conditions during 2017-2018 were considerably dryer than normal which limited disease development overall and resulted in no significant fungicide treatment or interaction effects. However, a mixed result of positive marginal economic returns at both locations was found among the fungicide treatments for both varieties. These results showed that a dual fungicide application approach can be a sound management practice by reducing disease levels, protecting more yield potential, and providing greater economic return than a single fungicide application, but it was highly dependent on variety and location.

INTRODUCTION

In Oklahoma, winter wheat (*Triticum aestivum* L.) is the number one production crop. During the 2017-2018 growing season, winter wheat was planted on 1.8 million hectares across the state, and 1.0 million hectares were harvested for grain (USDA-NASS, 2018). With grain production at 1.9 million Mg during that season and the price for wheat in Oklahoma during June 2018 valued at \$0.19 kg^{-1}, this resulted in a \$361,000,000 value for the Oklahoma economy (USDA-NASS, 2018). Due to its economic importance, there is considerable focus devoted to improving winter wheat management to keep input costs low and to maximize economic returns. A significant portion of its management includes protecting the crop from fungal pathogens.

Diseases caused by plant pathogenic (i.e., disease-causing) organisms, including fungi, represent a major source of potential crop damage which can reduce yields and economic returns. Fungal diseases are considered the number one cause of crop loss worldwide (McGrath, 2004), and there are approximately 20,000 species of fungi, which are plant pathogenic (Jibril et al., 2016). Several fungal pathogens of concern in Oklahoma include *Pyrenophora tritici- repentis* (tan spot), *Zymoseptoria tritici* (Septoria leaf blotch), *Parastagonospra nodorum* (Stagonospora glume blotch), *Cochliobolus sativus* (spot blotch), *Blumeria graminis* f. sp. *graminis* (powdery mildew), *Puccinia triticina* (leaf rust), and *Puccinia striiformis* f. sp. *tritici* (stripe rust). Understanding the life cycle of any fungal pathogen allows for proper management of that pathogen.

Planting a resistant variety is an efficient way to control fungal diseases that may occur, but wheat varieties today can only provide protection against some specific diseases. A properly timed foliar fungicide application can also play a significant role in protecting the crop from fungal pathogens and in maintaining yield potential and quality of the crop. If a foliar fungicide is applied at the proper time, it can also be economically profitable for a producer. A study in Europe examined single, double, and triple fungicide applications for their effect on grain quality in winter wheat (Jarroudi et al., 2015). Experiments were conducted at two sites in Germany, Burmerange, and Everlange during 2006-2009, and monitored various fungal diseases. Results showed that yields from plots treated with fungicide were higher overall compared to the non-treated plot at both sites, except for when fungal disease pressure was low in 2008. This study also showed that a single fungicide application led to grain yield and financial returns similar to those from a double or triple fungicide application (Jarroudi et al., 2015). Edwards et al. (2012)

addressed the agronomic and economic response of hard red winter wheat to foliar fungicide applied at Feekes 9-10 (Large, 1954) in the U.S. southern Great Plains. The experiments were conducted at Lahoma, OK, and Apache, OK from 2005-2010. Results indicated that when wheat achieved greater yields, it was due to the application of foliar fungicides, which also increased thousand-kernel weight, harvest index, and grain volume weight. For the different parameters examined, the largest difference observed as a result of the foliar fungicide application occurred for the susceptible cultivars. The yield difference between treated and non-treated susceptible cultivars, for example, was 270 kg ha^{-1} (10%) at Apache and 810 kg ha^{-1} (24%) at Lahoma. For intermediate and resistant cultivars, there was no effect on grain yield due to fungicide applications at Apache. At Lahoma though, average grain yield for intermediate and resistant cultivars treated with a foliar fungicide was 11 and 10% greater, respectively, than the same cultivars non-treated. This response for intermediate and resistant cultivars at Lahoma was likely due to greater leaf rust incidence and severity at this location across all years except 2010. It was also noted that foliar fungicide applications to wheat represented a sound economic input, generating a high likelihood of positive returns when disease incidence and severity were high. An economic analysis examined three different scenarios of return based off wheat grain sale price, wheat cultivar (resistant, intermediate, and susceptible), and fungicide cost. The economic analysis found there was a greater than 80% likelihood that foliar fungicide use resulted in enough additional grain yield to offset the foliar fungicide cost in nine out of 36 price scenarios at Apache and 35 out of 45 price scenarios at Lahoma (Edwards et al., 2012). Another study by Thompson et al. (2014) also found foliar fungicide treatment on hard red winter wheat at Feekes 9-10.5 in the southern Great

Plains can be an economically sound management strategy under some conditions. Experiments conducted in Apache, OK and Lahoma, OK during 2005-2012 showed differences on average net returns between fungicide-treated plots and non-treated plots for resistant, intermediate, and susceptible varieties across years were -$28, -$19, and -$6 ha^{-1} at Apache, OK and $36, $36, and $116 ha^{-1} at Lahoma, OK. Despite the variable response, fungicide treatment did tend to protect producers from the downside risk of large yield losses in years of high disease incidence and severity, especially when growing wheat varieties susceptible to common foliar diseases (Thompson et al., 2014).

Research in the southern Great Plains has shown that foliar fungicide applications can protect against fungal pathogens and save winter wheat from economic loss, but there is little peer-reviewed information regarding the use of multiple fungicide applications on winter wheat grain yield and profitability. Therefore, the objective of this study was to determine whether a dual foliar fungicide application approach results in increased winter wheat grain yield and profitability compared to a single application in Oklahoma.

METHODOLOGY

Research trials were established at Stillwater, OK (36° 7'13.65" N, 97° 5'21.29" W) and Apache, OK (34°52'45.59" N, 98°22'34.23" W) during the 2016-2017 and 2017-2018 growing seasons. The experimental design was a randomized complete block (RCB) with four replications of treatments arranged as a 2 × 4 factorial. Treatments consisted of two winter wheat varieties and four foliar fungicide treatments. The two non-seed treated varieties were 'Bentley' and 'Gallagher.' Gallagher was chosen based on susceptibility to leaf spotting diseases and resistance to leaf rust, while Bentley was chosen based on moderate resistance to leaf spotting diseases and moderate susceptibility to leaf rust. The four foliar fungicide treatments consisted of a non-treated control, a single application at Feekes 6 (jointing), a single application at Feekes 9 (ligule of flag leaf visible), and application at Feekes 6 and 9. Plots treated with fungicide at Feekes 6 received Headline SC (pyraclostrobin) at a rate of 266 mL ha^{-1}. Plots receiving fungicide at Feekes 9 were treated with Tebucure Fungicide 3.6 (tebuconazole) at a rate of 118 mL ha^{-1}. Fungicide applications were applied with a CO_2 backpack sprayer through a 1.5 m boom calibrated to deliver 187 L ha^{-1} spray solution using TT11003 nozzles (Teejet Technologies, Glendale Heights, Illinois). Fungicide treatments were applied during the first growing season on 16 Mar. 2017 and 21 Apr. 2017 at Apache and on 21 Mar. 2017 and 19 Apr. 2017 at Stillwater. Application dates for the second growing season were 4 Apr. 2018 and 1 May 2018 for Apache and 24 Mar. 2018 and 30 Apr. 2018 for Stillwater.

Trials at Stillwater both seasons followed wheat under conventional tillage and were planted on 31 Oct. 2016 and 20 Oct. 2017 using a Hege 500 small-plot cone seeder (Wintersteiger, Salt Lake City, UT) which consisted of eight rows each spaced 15 cm apart. Trials at Apache were no-till following canola during 2016-2017 and no-till following soybean during 2017-2018 and were planted with a Great Plains no-till drill (Great Plains Ag, Salina, KS) which consisted of seven rows each spaced 19 cm apart. The planting date at this location was 10 Oct. 2016 and 19 Oct. 2017. All trials were planted to a length of 11.6 m and later shortened 9.3 m at harvest. The seeding rate was 67 kg ha^{-1}. Fertilizers and herbicides were applied according to Oklahoma State Universtity best management recommendations.

Disease ratings on all plots were collected immediately before each fungicide application as well as two weeks after each application. Disease incidence and severity ratings for each plot were scored from a 45 cm section within the middle of the plot. Data were collected on the incidence and severity of fungal diseases present at the time of each rating. Incidence was rated on a 0 to 100 % scale of plants expressing disease symptoms. Severity was rated based on symptoms expressed on a single plant using a 1 to 5 scale: 1 = ≤15% resistant, 2 = 16-39% moderately resistant, 3 = 40-64% intermediate, 4 = 65-80% moderately susceptible, and 5 = 81-100% susceptible. Disease incidence and severity numbers were combined to create an index number for each rating timing. The index number was created by multiplying the incidence and severity values and then dividing it by the product of the maximum incidence number of 100 and the maximum severity number of five. These index numbers were then used to calculate the area under the disease progress curve (AUDPC) (Madden et al., 2007).

At plant maturity, wheat seed was mechanically harvested using a Wintersteiger Delta plot combine (Wintersteiger, Salt Lake City, UT). Seed weight and moisture were collected from each plot. Harvest dates for Apache were 1 June 2017 and 8 June 2018 and 8 June 2017 and 5 June in 2018 for Stillwater. Seed samples also collected from each plot were non-destructively analyzed for protein content using a Perten Model DA7200 diode array infrared instrument (Perten Instruments, Hagersten, Sweden). Grain yield and protein content values were adjusted to 12% moisture content.

A partial budget economic analysis was conducted for the fungicide treatments at grain sale prices of \$0.11 kg^{-1}, \$0.18 kg^{-1}, and \$0.26 kg^{-1}. Treatment costs used were \$0, \$57.87, \$15.83, and \$73.70 ha^{-1} for the non-treated control, Feekes 6, Feekes 9, and

Feekes 6 +9 treatments, respectively. Treatment costs also included a \$12.35 ha^{-1} application fee for each time foliar fungicide was applied. The marginal economic return was calculated for each fungicide treatment by multiplying the yield and grain sale price and then subtracting the treatment cost. Values are reported as the difference in marginal return compared to the non-treated control.

Statistical Methods

Statistical analyses were performed in SAS v9.4 (SAS Institute Inc., Cary, NC). Analysis of variance (ANOVA) using PROC GLIMMIX was conducted for disease ratings, test weight, protein content, and grain yield. Data were analyzed separately by year and location due to the variability of disease pressure observed across years and locations. The square root transformation was used to analyze the AUDPC values. Variety, fungicide treatment, and their interaction were considered fixed effects, and replication was considered a random effect. Means were separated using Fisher's Protected LSD at the 5% significance level. The SLICE option was used to compare means of significant interactions.

FINDINGS

Weather Conditions

Monthly precipitation totals and average air temperature during the study period are presented in Table 1. Precipitation during the beginning of the 2016-2017 growing season was below the 20-year average entering the winter at both locations, while temperatures during much of that time were above normal. The rains returned during

January and continued throughout April with above average precipitation totals during that time. Extremely warm temperatures occurred in February, and this coaxed plants at both locations out of dormancy approximately two weeks earlier than normal at both locations. Temperatures remained above average until May when below average temperatures occurred during that time.

The 2017-2018 growing season was characterized by season-long drought. Above average rainfall occurred at planting in both locations, but the next significant amount of rainfall did not occur until February. Rainfall remained below average from this point throughout the rest of the season at Stillwater. The same was observed at Apache except for the above average rainfall in May; however, this precipitation in May was untimely. Temperatures at both locations were near average during the fall and were cooler than average during the end of winter. This delayed spring green-up about ten days later than normal. Temperatures remained near average during March and dropped below normal during April, resulting in the second coldest April on record. This was followed by the hottest May on record.

Fungal Diseases

Leaf rust was the primary disease present at both locations during the 2016-2017 growing season. However, leaf rust levels and timing of disease development differed between locations, which may have been partially due to the previous crop. Under no-till following canola at Apache, leaf rust levels were minimal until Feekes 8 to Feekes 9 when leaf rust levels strongly increased. Under conventional tillage following wheat at Stillwater, leaf rust was present early (i.e., prior to Feekes 6) and remained active throughout grain-fill.

The leaf rust AUDPC results from the 2016-2017 season showed a fungicide treatment × variety interaction at both Apache and Stillwater (Table 2). For the variety Bentley at Apache, all fungicide applications resulted in significantly less leaf rust compared to the non-treated control, with the Feekes 9 and Feekes 6 + 9 resulting in the lowest amounts (Figure 1). For the variety Gallagher, no difference in leaf rust AUDPC was observed among the treatments receiving fungicide, but treatments Feekes 9 and Feekes 6 + 9 had significantly less leaf rust compared to the non-treated control (Figure 1). Results at Stillwater for the variety Bentley were similar to those observed at Apache (Figure 1). For the variety Gallagher, all fungicide-treated plots had significantly less leaf rust compared to the control, but no differences were found among the fungicide-treated plots (Figure 1).

Drought conditions during the 2017-2018 growing season prompted little disease development overall at both locations. Powdery mildew was the predominant disease observed at both locations. Despite the low levels of disease development, the powdery mildew AUDPC results showed a significant fungicide treatment × variety interaction ($P < 0.01$) at Apache (Table 2). For the variety Bentley, the Feekes 6 and Feekes 6 + 9 treatments resulted in significantly lower powdery mildew levels compared to the Feekes 9 and control treatments, and no difference among fungicide treatments was found for the variety Gallagher (Figure 2). At Stillwater, there was no evidence of a fungicide treatment × variety interaction, but both main effects were significant (Table 2). For the fungicide main effect, the Feekes 6 and Feekes 6 + 9 treatments showed the lowest powdery mildew AUDPC values and were significantly different from the control (Table

3). No difference was found between the Feekes 6 and Feekes 9 treatments, and no difference was found between the Feekes 9 and control treatments (Table 3).

Test Weight

Results showed a fungicide treatment × variety interaction ($P < 0.01$) at Stillwater during 2016-2017 (Table 2). For the variety Bentley, the fungicide treatment Feekes 6 + 9 had significantly greater test weight compared to the Feekes 6 treatment, but there were no differences among the Feekes 6 + 9, Feekes 9, and control treatments (Table 4). No differences among the fungicide treatments were observed for the variety Gallagher (Table 4). At Apache during the same growing season, there was no evidence of a fungicide treatment × variety interaction, but both main effects were significant (Table 2). All plots treated with fungicide had higher test weight compared to the control, but no differences were observed among the fungicide-treated plots (Table 3).

None of the fungicide treatment main effects or interactions with variety were significant at either location during the 2017-2018 growing season (Table 2).
Bentley had significantly lower test weight than Gallagher at both locations (Table 3). Test weight in Bentley is often below average compared to other varieties in the Oklahoma small grains variety performance testing (Marburger et al., 2018).

Protein

The main effect of variety ($P < 0.01$) and the fungicide treatment × variety interaction ($P = 0.0229$) at Apache in 2016-2017 were the only significant effects observed across both locations during the two years of this study (Table 2). For the fungicide treatment × variety interaction, protein content in Bentley was significantly greater for the Feekes 6 + 9 treatment compared to the control, but no differences among the fungicide-treated plots were found (Table 5). However, Gallagher showed the opposite results. The non-treated control had significantly greater protein content compared to the Feekes 6 + 9 treatment, and no differences among the fungicide-treated plots were found (Table 5). The inconsistencies in the results for these two varieties may be due to their leaf rust resistance (Gallagher) and susceptibility (Bentley) and to the timing in which leaf rust development rapidly increased at this site.

Grain Yield

A fungicide treatment × variety interaction ($P < 0.01$) was found at Stillwater during the 2016-2017 growing season (Table 2). For the variety Bentley, all of the fungicide treated plots yielded significantly greater than the control by an average of 1,250 kg ha^{-1} (Table 4). Of the fungicide treated-plots, the Feekes 6 + 9 fungicide treatment was the highest yielding at 3,190 kg ha^{-1} and was 570 kg ha^{-1} greater than the Feekes 6 treatment. The Feekes 6 treatment was also was significantly greater than the Feekes 9 treatment by 330 kg ha^{-1}. No differences among the fungicide-treated plots were observed for the variety Gallagher, but all were significantly greater than the non-treated control by an average of 970 kg ha^{-1} (Table 4). At Apache during the same growing season, there was no evidence of a fungicide treatment × variety, but both main effects were significant (Table 2). Due to the later onset of leaf rust at this location, there was significantly higher yield for the Feekes 6 + 9 and Feekes 9 treatments compared to the Feekes 6 and control treatments, but no difference was observed between the Feekes 6 + 9 and Feekes 9 treatments. The yield difference compared to the control was 640 and 590 kg ha^{-1} for the Feekes 6 + 9 and Feekes 9 treatments, respectively.

None of the fungicide treatment main effects or interactions with variety were significant at either location during the 2017-2018 growing season (Table 2). The variety main effect at Apache was the only significant effect observed during that season with Bentley having a greater yield than Gallagher (Table 3).

Economics

Marginal economic return ($\$$ ha^{-1}) using a partial budget analysis was examined under multiple scenarios using wheat market sale prices at $0.11 kg^{-1}, $0.18 kg^{-1}, and $0.26 kg^{-1} (Table 6). Fungicide treatment cost, which was comprised of product and application costs, are also included in Table 6. During the 2016-2017 growing season which had the highest disease levels during the study period, positive marginal economic returns at the three different grain sale prices were dependent on the fungicide treatment for both varieties at Apache (Table 6). Negative returns were found for both varieties at all three grain sale prices with the Feekes 6 fungicide treatment. For the variety Bentley, positive returns were found at all three grain sale prices for the Feekes 9 and Feekes 6 + 9 fungicide treatments, and at each sale price, the Feekes 9 treatment had the higher marginal return compared to the Feekes 6 + 9 treatment. For the variety Gallagher, the Feekes 9 fungicide treatment had a positive return at all three grain sale prices. Returns for Feekes 6 + 9 treatment were negative at the $0.11 kg^{-1} and $0.18 kg^{-1} sale prices. While the return was positive at the $0.26 kg^{-1} sale price, it was still less than that for the Feekes 9 treatment. At Stillwater during that same growing season, positive returns were found for all fungicide treatments for both varieties at all three grain sale prices. At this location for the variety Bentley, the highest return was observed with the Feekes 6 + 9 treatment at all three sale prices. For the variety Gallagher, the highest return was found with the Feekes 9 treatment at all three sale prices, followed by the Feekes 6 + 9 fungicide treatment (Table 6).

Although no significant yield effects due to fungicide use were found at either location during the 2017-2018 growing season, some positive returns compared to the non-treated control were still observed. For the variety Bentley at Apache, positive returns were only found for the Feekes 9 fungicide application, and this was consistent across all three grain sale prices. Similar results were observed for the variety Gallagher, but it took a minimum sale price \$0.18 kg^{-1} before the marginal return became positive. At Stillwater, positive returns for the variety Bentley were observed under all scenarios except for the Feekes 6 treatment at the \$0.11 kg^{-1} sale price, with the highest return occurring with Feekes 6 + 9 treatment at all three grain sale prices. Negative returns were mostly observed with the variety Gallagher at this location, except for the Feekes 6 treatment at the \$0.18 and \$0.26 kg^{-1} sale prices.

Positive marginal economic returns during the study period were still achieved based on the costs of the fungicides used. Since Headline SC (pyraclostrobin) was used at Feekes 6 and Tebucure Fungicide 3.6 (tebuconazole) was used at Feekes 9, the cost for the Feekes 6 application was higher. There was the potential of the Feekes 6 application being more profitable if a cheaper fungicide was used, but these fungicides were partly chosen to take into account the different modes of action used.

CONCLUSIONS

Results from this study showed that a dual foliar fungicide application approach can be a sound management practice by reducing disease levels, protecting more yield potential, and providing greater economic return than a single fungicide application. However, this management practice was highly dependent on variety and location. Due to the timing of disease occurrence in most cases during the course of this study, a single fungicide application was more profitable than the dual application approach overall. Fungicide use in general was often a good management practice, resulting in greater economic returns than by not using this practice at all. Based on the results of this study, understanding the susceptibility of the variety used to certain fungal diseases and scouting for those diseases should dictate fungicide use, including the dual application approach, instead of using multiple prophylactic applications in Oklahoma.

Table 1. Monthly cumulative precipitation (mm) and mean air temperature (°C) during the 2016-2017 and 2017-2018 growing seasons. Deviation from the past 20-year average is in parentheses.†

		Apache		Stillwater	
Season	Month	Precipitation	Temperature	Precipitation	Temperature
		mm	°C	mm	°C
2016-2017					
	Oct.	13 (-77)	18.9 (+2.3)	98 (+22)	19.6 (+3.4)
	Nov.	33 (-5)	12.6 (+2.1)	22 (-26)	12.6 (+2.6)
	Dec.	27 (-4)	3.8 (-0.4)	10 (-23)	3.1 (-0.7)
	Jan.	47 (+14)	4.7 (+1.0)	65 (+33)	4.7 (+1.7)
	Feb.	109 (+76)	9.9 (+4.1)	56 (+18)	10.0 (+4.8)
	Mar.	79 (+25)	13.7 (+2.8)	49 (-20)	13.2 (+2.5)
	Apr.	136 (+50)	15.7 (+0.1)	253 (+151)	16.2 (+2.9)
	May	43 (-64)	19.8 (-0.8)	66 (-45)	19.9 (-0.8)
	June	73 (-33)	24.8 (-0.7)	73 (-38)	25.6 (-0.0)
2017-2018					
	Oct.	115 (+24)	16.5 (+0.0)	162 (+86)	16.4 (+0.3)
	Nov.	4 (-35)	11.3 (+0.7)	8 (-40)	11.1 (+1.0)
	Dec.	9 (-23)	4.2 (+0.1)	24 (-10)	4.2 (+0.4)
	Jan.	5 (-28)	2.8 (-0.9)	6 (-26)	2.4 (-0.6)
	Feb.	56 (+23)	4.5 (-1.3)	63 (+25)	3.9 (-1.3)
	Mar.	18 (-36)	12.1 (+1.2)	29 (-39)	11.1 (+0.4)
	Apr.	33 (-53)	12.9 (-2.8)	52 (-49)	12.3 (-1.0)
	May	110 (+3)	23.6 (+3.0)	98 (-13)	24.1 (+3.4)
	June	4 (-102)	29.1 (+3.6)	5 (-106)	29.0 (+3.4)

† All data retrieved from the Oklahoma Mesonet.

Table 2. Analysis of variance (ANOVA) results for leaf rust disease ratings, powdery mildew disease ratings, test weight, protein content, and grain yield at Apache, OK and Stillwater, OK during the 2016-2017 and 2017-2018 growing seasons.

	Apache		Stillwater	
Source of variation	2016-2017	2017-2018	2016-2017	2017-2018
	------------------ Leaf rust (AUDPC) ------------------			
Fungicide treatment	<0.0001	-	<0.0001	-
Variety	0.0191	-	0.0014	-
Fungicide × Variety	0.0042	-	0.0020	-
	------------- Powdery mildew (AUDPC) -------------			
Fungicide treatment	-	<0.0001	-	0.0010
Variety	-	0.0301	-	<0.0001
Fungicide × Variety	-	0.0032	-	0.2354
	----------------- Test weight (kg hL^{-1}) -----------------			
Fungicide treatment	0.0043	0.2317	<0.0001	0.6810
Variety	<0.0001	<0.0001	<0.0001	<0.0001
Fungicide × Variety	0.2530	0.8356	0.0004	0.1182
	------------------ Protein content (%) ------------------			
Fungicide treatment	0.8787	0.9146	0.9648	0.8878
Variety	0.0002	0.2269	0.7578	0.5030
Fungicide × Variety	0.0229	0.1876	0.3400	0.4668
	----------------- Grain yield (kg ha^{-1}) -----------------			
Fungicide treatment	0.0258	0.3311	<0.0001	0.0879
Variety	0.0283	<0.0001	<0.0001	0.9469
Fungicide × Variety	0.1046	0.3645	0.0039	0.1130

Table 3. Main effect results for leaf rust disease ratings, powdery mildew disease ratings, test weight, protein content, and grain yield at Apache, OK and Stillwater, OK during the 2016-2017 and 2017-2018 growing seasons.

	Apache		Stillwater	
Main effect	2016-2017	2017-2018	2016-2017	2017-2018
	------------------ Leaf rust (AUDPC) ------------------			
Fungicide treatment				
Control	20.3 A	-	30.2 A	-
Feekes 6	15.3 B	-	16.2 B	-
Feekes 9	7.9 C	-	12.2 BC	-
Feekes 6 + 9	7.1 C	-	10.1 C	-
Variety				
Bentley	17.2 A	-	26.8 A	-
Gallagher	8.1 B	-	7.6 B	-
	------------- Powdery mildew (AUDPC) -------------			
Fungicide treatment				
Control	-	6.0 A	-	14.6 A
Feekes 6	-	2.4 B	-	7.9 BC
Feekes 9	-	5.5 A	-	12.0 AB
Feekes 6 + 9	-	3.9 AB	-	3.9 C
Variety				
Bentley	-	8.0 A	-	14.6 A
Gallagher	-	0.9 B	-	4.6 B
	----------------- Test weight (kg hL^{-1}) -----------------			
Fungicide treatment				
Control	73.1 B	73.4 A	70.9 D	68.7 A
Feekes 6	74.0 AB	74.0 A	73.3 C	68.0 A
Feekes 9	74.2 A	74.0 A	74.3 B	68.4 A
Feekes 6 + 9	74.6 A	73.5 A	75.1 A	68.8 A
Variety				
Bentley	72.3 B	74.3 A	71.2 B	67.1 B
Gallagher	75.6 A	73.1 B	75.6 A	69.8 A
	------------------ Protein content (%) ------------------			
Fungicide treatment				
Control	10.4 A	14.3 A	10.8 A	11.6 A
Feekes 6	10.5 A	14.4 A	10.9 A	11.9 A
Feekes 9	10.3 A	14.4 A	10.8 A	11.8 A
Feekes 6 + 9	10.4 A	14.4 A	10.9 A	11.7 A
Variety				
Bentley	9.9 B	14.5 A	10.9 A	11.6 A
Gallagher	10.8 A	14.3 A	10.8 A	11.9 A
	----------------- Grain yield (kg ha^{-1}) -----------------			
Fungicide treatment				
Control	4120 B	2150 A	2050 C	3030 B
Feekes 6	4190 B	2260 A	3030 B	3430 A
Feekes 9	4710 A	2290 A	2990 B	3150 AB

Feekes 6 + 9	4760 A	2160 A	3460 A	3400 A
Variety				
Bentley	4650 A	2690 A	2390 B	3260 A
Gallagher	4240 B	1740 B	3373 A	3250 A

Table 4. Grain yield and test weight fungicide treatment × variety interaction results for Stillwater, OK during the 2016-2017 growing season.

	Bentley		Gallagher	
Fungicide treatment	Grain yield	Test weight	Grain yield	Test weight
	-- kg ha^{-1} --	-- kg hL^{-1} --	-- kg ha^{-1} --	-- kg hL^{-1} --
Control	1450 D	67.2 AB	2650 B	70.1 A
Feekes 6	2620 B	65.8 B	3440 A	70.2 A
Feekes 9	2290 C	67.2 AB	3680 A	69.7 A
Feekes 6 + 9	3190 A	68.4 A	3730 A	69.2 A

Table 5. Protein content fungicide treatment × variety interaction results for Apache, OK during the 2016-2017 growing season.

	Variety	
Fungicide treatment	Bentley	Gallagher
	---------- % ----------	
Control	9.5 B	11.3 A
Feekes 6	10.1 AB	10.9 AB
Feekes 9	9.9 AB	10.6 AB
Feekes 6 + 9	10.4 A	10.4 B

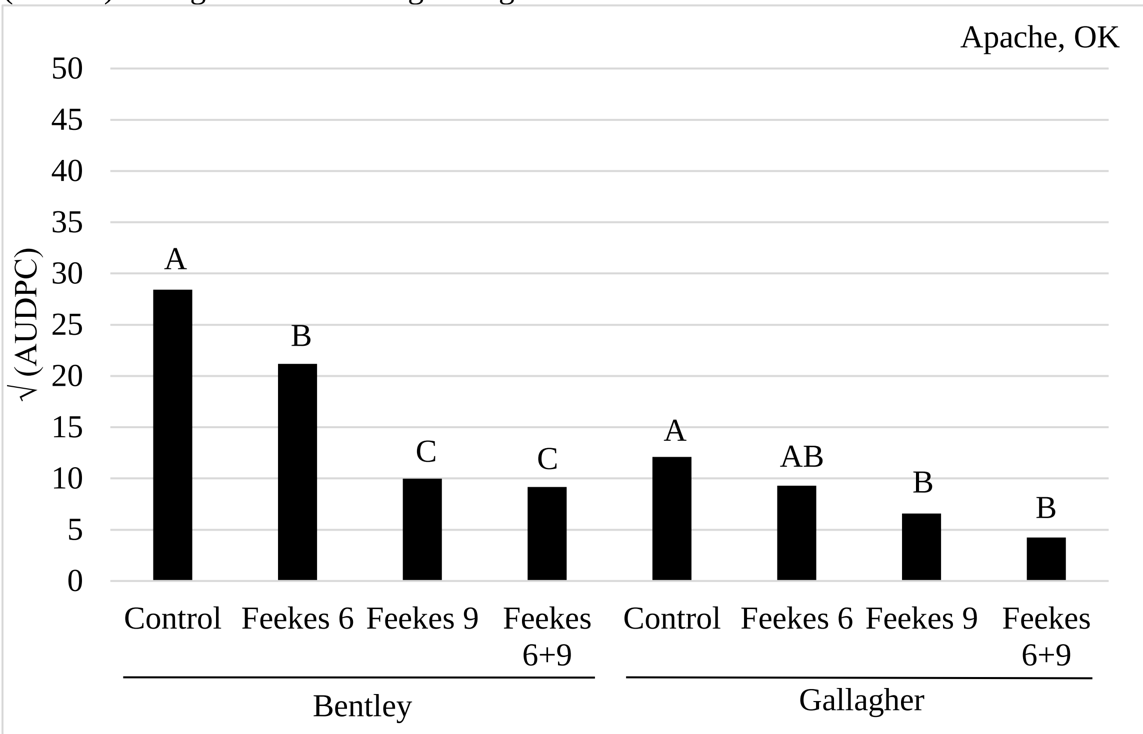
Table 6. Marginal economic return ($ ha^{-1}) for the fungicide treatments by year, location, and variety at grain sale prices of $0.11, $0.18, and $0.26 kg^{-1}.

		2016-2017				2017-2018			
		Apache		Stillwater		Apache		Stillwater	
Fungicide treatment	Treatment cost†	Bentley	Gallagher	Bentley	Gallagher	Bentley	Gallagher	Bentley	Gallagher
	--- $ ha^{-1} ---	---------------------------------- $0.11 kg^{-1} ----------------------------------							
Control	0	-	-	-	-	-	-	-	-
Feekes 6	$57.87	-65.81‡	-34.21	+72.74	+29.95	-53.14	-37.97	-15.89	-8.88
Feekes 9	$15.83	+95.06	+5.56	+78.08	+98.77	+5.45	-5.74	+5.18	-9.71
Feekes 6 + 9	$73.70	+37.18	-41.00	+120.75	+47.16	-83.91	-60.98	+10.20	-74.02
		---------------------------------- $0.18 kg^{-1} ----------------------------------							
Control	0	-	-	-	-	-	-	-	-
Feekes 6	$57.87	-71.11	-18.44	+98.65	+88.50	-49.98	-24.69	+12.10	+23.78
Feekes 9	$15.83	+168.99	+19.82	+140.69	+175.16	+19.64	+0.98	+19.19	-5.63
Feekes 6 + 9	$73.70	+111.11	-19.20	+250.39	+127.73	-90.71	-52.49	+66.14	-74.23
		---------------------------------- $0.26 kg^{-1} ----------------------------------							
Control	0	-	-	-	-	-	-	-	-
Feekes 6	$57.87	-76.40	-2.66	+246.90	+147.06	-46.82	-11.42	+40.09	+56.45
Feekes 9	$15.83	+242.92	+34.08	+203.31	+251.56	+33.82	+7.70	+33.20	-1.55
Feekes 6 + 9	$73.70	+185.04	+2.60	+380.01	+208.30	-97.52	-44.01	+122.08	-74.44

† Treatment cost includes a $12.35 ha^{-1} application fee for each time fungicide was applied.

‡ Values represent the difference in marginal return compared to the non-treated control fungicide treatment.

Figure 1. Leaf rust area under the disease progress curve (AUDPC) results for the fungicide treatment × variety interaction for Apache, OK (top) and Stillwater, OK (bottom) during the 2016-2017 growing season.



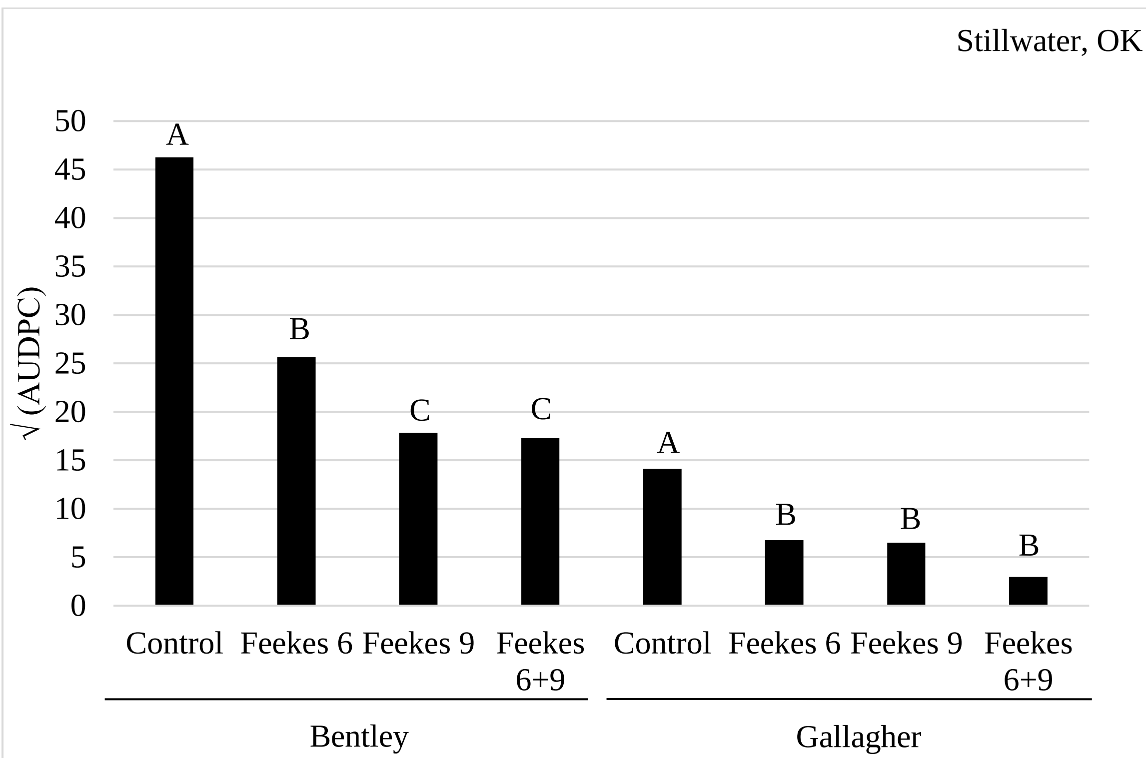
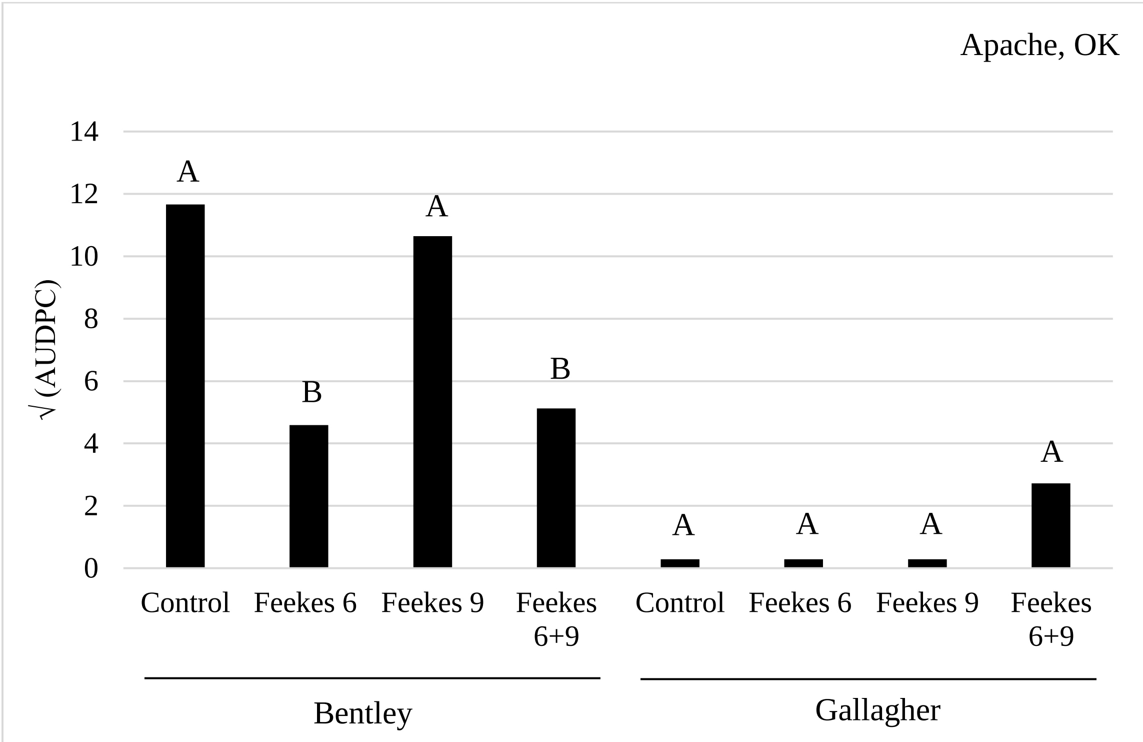


Figure 2. Powdery mildew area under the disease progress curve (AUDPC) results for the fungicide treatment × variety interaction for Apache, OK during the 2017-2018 growing season.



CHAPTER IV

FUNGICIDE + INSECTICIDE APPLICATIONS FOR PROTECTING WINTER WHEAT GRAIN YIELD AND INCREASING PROFITABILITY

ABSTRACT

Winter wheat producers in Oklahoma often tank-mix an insecticide when making foliar fungicide applications, but little is known about this practice. Trials were established at two locations (Chickasha and Lahoma) during two seasons from 2016-2018 using a randomized complete block design in a split-plot arrangement with four replications. The main plot factor was two varieties, one susceptible to leaf and stripe rust (Ruby Lee) and the other resistant (Gallagher at Chickasha 2016-2017 and Doublestop CL Plus at Lahoma 2016-2018). The subplot factor consisted of 16 different fungicide and insecticide treatment combinations applied at Feekes 6, Feekes 9, and Feekes 6 + 9. Results showed that a fungicide + insecticide application can provide greater yield than each pesticide applied alone. However, this was highly dependent on the year and location due to the timing of fungal disease and/or insect pressure, and higher yield from the fungicide + insecticide treatments only occurred at the Feekes 6 timing. Greater marginal economic return from using a fungicide + insecticide compared to each pesticide applied alone was also year and location dependent. This greater marginal return for the fungicide + insecticide treatments was observerd at both Feekes 6 and

Feekes 9 but occurred at the Feekes 6 application timing the majority of the time. Pesticide use in general was often a good management practice and resulted in greater yield and marginal economic returns than by not using this practice at all. Based on the results of this study, scouting for fungal diseases and insects should dictate whether fungicide + insecticide tank-mixes should be used intead of making prophylactic applications in Oklahoma.

INTRODUCTION

Winter wheat (*Triticum aestivum* L.) is the number one production crop in Oklahoma. During 2017-2018, winter wheat was planted on 1.8 million hectares across the state, and 1.0 million hectares were harvested for grain (USDA-NASS, 2018). Total grain production that season was 1.9 million Mg which resulted in a $361,000,000 value for the Oklahoma economy (USDA-NASS, 2018). As a result of its economic impact, there is considerable focus devoted to improving winter wheat management in order to keep input costs low and to maximize economic returns. A significant portion of its management includes protecting the crop from fungal pathogens and insect pests.

Diseases caused by plant pathogenic (i.e., disease-causing) organisms, including fungi, are a major source of crop damage. Fungal diseases are considered the number one cause of crop loss worldwide (McGrath, 2004), and in the southern Great Plains, hard red winter wheat yield losses are estimated at 3 to 10% annually (Edwards et al., 2012). Several fungal pathogens of concern in Oklahoma include *Pyrenophora tritici- repentis* (tan spot), *Zymoseptoria tritici* (Septoria leaf blotch), *Parastagonospra nodorum*

(Stagonospora glume blotch), *Cochliobolus sativus* (spot blotch), *Blumeria graminis* f. sp. *graminis* (powdery mildew), *Puccinia triticina* (leaf rust), and *Puccinia striiformis* f. sp. *tritici* (stripe rust).

In additional to fungal diseases, insects can cause devastating damage (Bockus et al., 2010). Some of these species that have destructive tendencies include leaf beetles and grasshoppers. Others such as wireworms or Hessian fly may be concealed or hidden within the plant itself or the soil (Bockus et al., 2010). Aphids were considered the most prominent insect pest of winter wheat for many years (Chambers and Adams, 1986; Hasken and Poehling, 1994), and are one of the most yield-limiting insects of winter wheat in the southern Great Plains (Royer, 2007). The two most common aphids in Oklahoma are the bird cherry-oat aphid (*Rhopalosiphum padi* L.) and the greenbug (*Schizaphis graminum* Rondani) (Ismail et al., 2003). These species specifically can limit wheat profitability significantly if infestations occur during early growth stages by transmitting a luteovirus or by direct feeding (Starks and Burton, 1977; Kieckhefer and Kantack 1986; Kieckhefer and Gellner 1992; Kieckhefer et al., 1994; Riedell and Kieckhefer 1995; Webster et al., 2000; Kindler et al., 2002).

Oklahoma wheat producers face a challenging task when it comes to controlling these pests and the timing of implementing appropriate management practices. Properly timed foliar pesticide applications can play a significant role in protecting the crop from these pests, maintaining yield potential and quality, and attempting to maximize profitability. Edwards et al. (2012) addressed the agronomic and economic response of hard red winter wheat to foliar fungicide applied at Feekes 9-10 in the southern Great Plains at two locations (Lahoma and Apache, OK) from 2005-2010. Susceptible cultivars at Apache treated with a fungicide had 10% higher yield compared to the same cultivars non-treated, but no difference between the fungicide treatments was observed for the intermediate and resistant cultivars. At Lahoma, response to the foliar fungicide application was 10, 11, and 24% greater for the resistant, intermediate, and susceptible cultivars, respectively. Response to foliar fungicide application in susceptible cultivars was not unexpected, but a significant response to foliar fungicide application for the resistant and intermediate cultivars was likely due to greater leaf rust incidence and severity at Lahoma across all years except 2010. An economic analysis also showed that there was greater than 80% likelihood that foliar fungicide use produced enough additional grain yield to offset the foliar fungicide cost in nine out of 36 price scenarios at Apache, OK and 35 out of 45 price scenarios at Lahoma (Edwards et al., 2012). Another study by Thompson et al. (2014) also found foliar fungicide treatment at Feekes 9-10.5 on hard red winter wheat in the southern Great Plains can be an economically sound management strategy under some conditions. Experiments conducted at Apache, OK and Lahoma, OK during 2005-2012 found differences on average net returns between fungicide-treated plots and non-treated plots for resistant, intermediate, and susceptible varieties across years were -\$28, -\$19, and -\$6 ha^{-1} at Apache, OK and \$36, \$36, and \$116 ha^{-1} at Lahoma, OK . Despite the variable response, fungicide treatment tended to protect producers from the downside risk of large yield losses in years of high disease incidence and severity, especially when growing wheat varieties susceptible to common foliar diseases (Thompson et al., 2014).

Regarding control of insects, a study was conducted to evaluate the effectiveness and timing of insecticidal seed treatment (thiamethoxam) and foliar insecticide (lambda-cyhalothrin) for managing wheat stem maggot [*Meromyza Americana* Fitch (Diptera: Chloropidae)] and wheat stem sawfly [*Cephus cinctus* Norton (Hymenoptera: Cephidae)] in spring wheat in North Dakota during 2008-2009 (Knodel et al., 2009). A foliar application at Feekes 3-5 and Feekes 9 reduced the number of whiteheads caused by wheat stem maggot. A combination of the low rate seed treatment plus a foliar application of lambda-cyhalothrin at Feekes 3-5 also resulted in a significantly lower number of whiteheads caused by wheat steam maggot, but the different rates of seed treatment alone was shown to be ineffective at reducing the number of whiteheads. None of the treatments reduced the percentage of damaged stems from wheat stem sawfly. There were also no yield differences among the treatments (Kodel et al., 2009). Another study performed by Royer et al. (2011) evaluated the effect of temperature on the field efficacy of three classes of registered insecticides for greenbug control in winter wheat fields. The insecticides were selected to represent different modes of action (organophosphate, pyrethroid, and neonicotinoid) and offer systemic (imidacloprid: neonicotinoids), contact (chlorpyrifos and lambda-cyhalothrin: pyrethroid) or a combination of systemic and contact (dimethoate: organophosphate). Results indicated any insecticide applied during the winter provided up to 70 to 80% control of greenbug on average as long as temperatures exceed 13℃ during the 14 days following application with no significant rainfall occurred (Royer et al., 2011).

Although foliar fungicide and insecticide efficacy have been examined individually in the southern Great Plains, little is known about the impact of a tank-mix of these two pesticides on winter wheat. Because wheat producers in Oklahoma are implementing this practice, there is a need for research on this subject to help guide recommendations. Therefore, the objective of this study was to determine whether a fungicide + insecticide application results in increased winter wheat grain yield and profitability compared to each pesticide applied alone in Oklahoma.

METHODOLOGY

Research trials were established at Lahoma, OK (36°23'2.57" N, 98° 6'21.73" W) and Chickasha, OK (35° 2'44.96" N, 97°54'28.37" W) during the 2016-2017 and 2017-2018 growing seasons. The experimental design was a randomized complete block in a split-plot arrangement with four replications. The main plot factor consisted of two wheat varieties (‘Ruby Lee’ and ‘Doublestop CL Plus’). In 2016-2017, ‘Gallagher’ was used at Chickasha, OK due to seed availability. Ruby Lee was chosen based on its susceptibility to rust diseases, while Gallagher and Doublestop CL Plus were chosen based on their resistance to those same diseases. The subplot factor consisted of 16 different pesticide treatments applied at Feekes 6, Feekes 9, or a combination of both timings (Table 1). Fungicide treatment consisted of Headline SC (pyraclostrobin) at a rate of 266 mL ha^{-1} for the Feekes 6 application and Tebucure Fungicide 3.6 (tebuconazole) at a rate of 118 mL ha^{-1} for the Feekes 9 application. Insecticide treatments at Feekes 6 and Feekes 9 consisted of Silencer (lambda-cyhalothrin) at a rate of 114 mL ha^{-1}. All pesticide applications were made using a CO_2 backpack sprayer with a 1.5 m boom calibrated to deliver 187 L ha^{-1} spray solution using TT11003 nozzles (Teejet Technologies, Glendale Heights, Illinois). Due to space limitations at Chickasha during 2016-2017, only eight pesticide treatments were used (Table 1). Pesticide treatments were applied during the first growing season on 7 Mar. 2017 and 15 Apr. 2017 at Chickasha and on 8 Mar. 2017 and 20 Apr. 2017 at Lahoma. Application dates for the second growing season were 24 Mar. 2018 and 30 Apr. 2018 for Chickasha and 30 Mar. 2018 and 23 Apr. 2018 for Lahoma.

All trials were established using conventional tillage following winter wheat. Planting dates for Chickasha were 21 Oct. 2016 and 30 Oct. 2017. For Lahoma, planting dates were 19 Oct. 2016 and 11 Oct. 2017. All plots were planted with a Hege 500 small-plot cone seeder (Wintersteiger, Salt Lake City, UT) which consisted of eight rows each spaced 15 cm apart. Seed was planted at a rate of 67 kg ha^{-1}, and all seed was treated with Sativa IMF Max (imidacloprid, metalaxyl, tebuconazole, and fludioxonil) at a rate of 148 mL kg^{-1}. Plots were planted to a length of 11.6 m and later shortened 9.3 m at harvest. At Lahoma during 2016-2017, plots were planted to a 9.3 m length due to the lack of space and later trimmed to 7.0 m at harvest. Fertilizers and herbicides were applied according to Oklahoma State Universtity best management recommendations.

Disease and insect ratings were collected on all plots immediately before each fungicide and insecticide application as well as two weeks after each application. Aphid counts were taken at 30 cm sections in the front and back of the plots and combined to get a total insect count for the whole plot. Disease incidence and severity ratings for each plot were a collection of all fungal diseases present at the time of each rating and were scored from a 45 cm section within the middle of the plot. Incidence was rated on a 0 to 100 % scale of plants expressing disease symptoms. Severity was rated based on symptoms expressed on the entire plant using a 1 to 5 scale: 1 = <15% resistant, 2 = 16-39% moderately resistant, 3 = 40-64% intermediate, 4 = 65-80% moderately susceptible, and 5 = 81-100% susceptible. Disease incidence and severity numbers were combined to create an index number for each rating timing. The index number was created by multiplying the incidence and severity values and then dividing it by the product of the maximum incidence number of 100 and the maximum severity number of five. These index numbers were then used to calculate the area under the disease progress curve (AUDPC) (Madden et al., 2007).

At plant maturity, wheat seed was mechanically harvested using a Hege 140 plot combine (Wintersteiger, Salt Lake City, UT). Seed weight and moisture were collected from each plot. Harvest dates were 5 June 2017 and 6 June 2018 for Chickasha and 12 June 2017 and 11 June 2018 for Lahoma. Seed samples also collected from each plot were non-destructively analyzed for protein content using a Perten Model DA7200 diode array infrared instrument (Perten Instruments, Hagersten, Sweden). Grain yield and protein content values were adjusted to 12% moisture content.

A partial budget economic analysis was conducted for the pesticide treatments at grain sale prices of \$0.11 kg^{-1}, \$0.18 kg^{-1}, and \$0.26 kg^{-1}. Treatment costs are reported in Table 1. Treatment costs also included a \$12.35 ha^{-1} application fee for each time a pesticde was applied (i.e, Feekes 6 and/or Feekes 9). The marginal economic return was calculated for each pesticide treatment by multiplying the yield and grain sale price and then subtracting the treatment cost. Values are reported as the difference in marginal return compared to the non-treated control.

Statistical methods

Statistical analyses were performed in SAS v9.4 (SAS Institute Inc., Cary, NC). Analysis of variance (ANOVA) using PROC GLIMMIX was conducted for test weight, protein contetn, and grain yield. Data were analyzed separately by year and location. Variety, pesticide treatment, and their interaction were considered fixed effects. Replication and replication × variety were considered random effects. Means were separated using Fisher's Protected LSD at the 5% significance level.

FINDINGS

Weather

Monthly precipitation total and average air temperature during the study period are presented in Table 2. Precipitation amounts during the 2016-2017 growing season were below the 20-year average for both locations at the beginning of the season heading into the winter months, but precipitation returned during the winter leading to above average precipitation during that time. Temperatures at Chickasha were primarily above the 20-year average during the beginning of the season throughout the winter. Temperatures at Lahoma were primarily average during this same time. Above average precipitation and temperatures were experienced at both locations during February and continued throughout April. In fact, the extremely warm temperatures in February coaxed plants out of winter dormancy approximately two weeks earlier than normal at both locations. Even though precipitation was slightly below average during grain-fill (i.e., May), temperatures were also below normal during this time.

The 2017-2018 growing season began with very dry conditions and below average precipitation across both locations from October throughout December. January throughout April at Chickasha resulted in precipitation above the 20-year average with

Lahoma experiencing the opposite. Temperatures during this same time were fairly cool at both locations. The cooler temperatures coming out of winter delayed spring green-up about 10 days later than normal. In fact, April ended up being one of the coldest on record. This was followed by the hottest May on record. Spring precipitation (i.e., March through May) at both locations was slightly above average overall for Chickasha but below normal at Lahoma.

Diseases

Leaf rust was the primary disease present throughout both locations during the 2016-2017 growing season. Levels of leaf rust incidence and severity were slightly higher at Chickasha then at Lahoma even though leaf rust at Lahoma was more active earlier in the season compared to Chickasha. The disease steadily increased during Feekes 9 to Feekes 11.1 at both locations. While the number of treatments was limited at Chickasha due to space limitations, the plots treated with fungicide on average had lower disease levels than those that did not (Table 3). At Lahoma, where leaf rust persisted longer over the season than at Chickasha, plots which received fungicide at both Feekes 6 and Feekes 9 (i.e., treatments 8, 10, 14, and 16) generally had lower levels of disease than those plots which received only one application. Additionally, Ruby Lee exhibited more disease symptoms than the resistant variety at both locations as expected (Table 3).

Powdery mildew and stripe rust were the predominant diseases observed at Chickasha during 2017-2018; whereas, powdery mildew was the predominant disease observed at Lahoma that same growing season. At Chickasha, powdery mildew was fairly aggressive at Feekes 6 and persisted until Feekes 9. With some precipitation that fell around that time, stripe rust appeared close to Feekes 9 and persisted through Feekes

11.1. Similar to observations at Lahoma in the previous season, plots at Chickasha which received fungicide at both Feekes 6 and Feekes 9 (i.e., treatments 8, 10, 14, and 16) generally had lower levels of disease than those plots which received only one application (i.e., treatments 2, 4, 5, 7, 9, 11, 13, 15) (Table 3). The drought conditions experienced at Lahoma across the growing season limited disease development overall, with little difference in powdery mildew levels among the pesticide treatments. Again, Ruby Lee showed more disease susceptibility across both locations as expected (Table 3).

Insects

Insect density was uniformly low across both locations during both years of this study. Bird cherry-oat aphids and greenbugs were the predominate insect present but were never above thresholds levels at any time during the study (Kindler et al., 2003). In 2016-2017 at Chickasha, the highest aphid populations were found around Feekes 5 to Feekes 7. At Lahoma during the same growing season, aphid numbers were lower than those at Chickasha but were consistent with their presence around Feekes 5 to Feekes 7. However, a consistent reduction in aphid numbers with the Feekes 6 insecticide application (i.e., treatments 3, 4, 9, 10, 12, 13, 15, and 16) was not apparent at either location that year (Table 4.)

At Chickasha during, 2017-2018, aphid numbers and observation timing were comparable to the previous year; however, noticeable differences in aphid numbers among the pesticide treatments showed lower aphid numbers when insecticide was applied at Feekes 6 (i.e., treatments 3, 4, 9, 10, 12, 13, 15, and 16) (Table 4). At Lahoma, aphids were present at Feekes 5 to Feekes 6 but were not found again throughout the rest of the growing season. No noticeable differences in aphid numbers due to the pesticide treatments were found for this location.

Test weight

No variety × pesticide treatment interaction was observed during this study (Table 5). The pesticide treatment main effect was significant at both locations but only during the 2016-2017 growing season (Table 5). At Chickasha, results showed that fungicide applied alone at Feekes 9 (treatment 5) had higher test weight than all treatments applied only at Feekes 6 (treatments 2, 3, and 4) and the insecticide-only treatment at Feekes 9 (treatment 6) (Table 6). None of the treatments that received fungicide + insecticide at Feekes 9 (treatments 7, 14, 15, and 16) had significantly greater test weight than the fungicide applied alone at Feekes 9 (Table 6). At Lahoma, the fungicide only applied at Feekes 9 (treatment 5) was among the treatments exhibiting the highest test weight (Table 6). The test weight for treatments containing multiple fungicide applications (treatments 8, 10, 14, and 16) was also among the highest. None of the treatments with fungicide + insecticide had significantly higher test weight compared to the treatments with fungicide-only at any application timing (Table 6).

The variety main effect at Chickasha during 2017-2018 showed Doublestop CL Plus having higher test weight than Ruby Lee (Table 6). This may have been due to the stripe rust observed on Ruby Lee from Feekes 9 through Feekes 11.1 that was not observed on Doublestop CL Plus.

Protein

No variety × pesticide treatment interaction was observed during this study (Table 5). The pesticide treatment main effect was significant at Lahoma during the 2016-2017 growing season but not at Chickasha. At Lahoma, all but one treatment containing two fungicide applications (treatments 8, 10, 14, and 15) were among those with the highest protein content. However, none of the treatments with fungicide + insecticide were significantly greater than those with fungicide-only at any application timing (Table 7).

A pesticide treatment main effect was also observed at Chickasha during 2017-2018 ($P < 0.01$) but not at Lahoma (Table 5). The fungicide alone applied at both Feekes 6 and Feekes 9 (treatment 8) was among the treatments with the highest protein content, but treatments with fungicide applied only at Feekes 6 or Feekes 9 alone (treatments 2 and 5, respectively) were not (Table 7). This was likely due to the aggressive powdery mildew levels around Feekes 6 and the stripe rust development from Feekes 9 to Feekes 11.1. The treatment with insecticde applied at Feekes 6 followed by fungicide + insecticide at Feekes 9 (treatment 15) was the only instance where the tank-mix resulted in significantly higher protein content compared to the pesticides applied alone (i.e., treatments 9 and 12).

Grain Yield

No variety × pesticide treatment interaction was observed during this study, but the pesticide main effect was significant for all site-years (Table 5). At Chickasha during 2016-2017, results indicated that fungicide treatment alone at either application timing (i.e., treatment 5) provided no benefit compared to the non-treated control (Table 8). However, having the fungicide + insecticide at Feekes 9 only (treatment 7), the insecticide applied at Feekes 6 followed by a fungicide at Feekes 9 (treatment 9), or insecticide applied at Feekes 6 followed by fungicide + insecticide at Feekes 9 (treatment 15) resulted in increased yield compared to the non-treated control. None of the treatments with fungicide + insecticide provided significant additional grain yield. At Lahoma that same season, the fungicide + insecticide applied at Feekes 6 (treatment 4) had significantly greater yield than either pesticide applied alone at that application timing (Table 8). However, this treatment did not have significantly greater yield compared the fungicide-only application at Feekes 9 (treatment 5). Additionally, treatment 13 (fungicide + insecticide applied at Feekes 6 followed by insecticide at Feekes 9) compared to treatments 11 and 12 was the only other instance where the tank-mix resulted in significantly greater yield. Other than the fungicide + insecticide applied at Feekes 6 (treatment 4) and fungicide applied at Feekes 9 (treatment 10), a two-pass program containing any combination of the pesticides was needed in order to have significantly greater yield than the non-treated control (Table 8).

Similar to Lahoma the previous season, the fungicide + insecticide applied at Feekes 6 (treatment 4) at Chickasha had significantly greater yield than either pesticide applied alone at that application timing (treatments 2 and 3) (Table 8). However, this treatment did not have significantly greater yield compared the fungicide-only application at Feekes 9 (treatment 5). Both the fungicide + insecticide at Feekes 6 and the fungicide at Feekes 9 were significantly greater than the control. When these two treatments were put together (i.e., treatment 10), it was the only other treatment that was statistically greater than the non-treated control, and it was the only other instance where the tank-mix resulted in significantly greater yield than when the pesticides were applied alone (Table 8). At Lahoma, the only treatments which yielded significantly greater than the control were those which had insecticide applied at Feekes 6 (treatments 3, 4, 12, and

15). None of the treatments containing fungicide + insecticide at any application timing yielded significantly greater then either pesticide applied alone at those timings (Table 8).

Economics

Marginal economic return (\$ ha^{-1}) was examined under multiple scenarios using wheat grain sale prices at \$0.11 kg^{-1}, \$0.18 kg^{-1}, and \$0.26 kg^{-1} (Table 9). Pesticide treatment costs, which comprised of product and application costs, are included in Table 1 and also in Table 9. Since there was no evidence of a variety × pesticide treatment for any site-year for grain yield, the marginal economic return was averaged over both varieties. At Chickasha during 2016-2017, the highest marginal return at all three sale prices was found with the treatment of fungicide + insecticide applied at Feekes 9 (treatment 7). The treatment that provided the next closest return was the one with an insecticide applied alone at Feekes 6 and fungicide applied alone at Feekes 9 (i.e., treatment 9), but it took a higher grain sale price to do so. At Lahoma during the same growing season, the treatment with fungicide applied alone at Feekes 9 (treatment 5) had the highest return overall at the \$0.11 kg^{-1} sale price. As the grain sale price increased to \$0.18 kg^{-1} and higher, the fungicide + insecticide at Feekes 6 in combination with an insecticide applied at Feekes 9 (treatment 13) resulted in the highest return. Total, there were four treatments (4, 13, 14, and 15) at the \$0.11 kg^{-1} sale price and five treatments (4, 10, 13, 14, and 15) at the \$0.18 and \$0.26 kg^{-1} sale prices that contained a fungicide + insecticide tank-mix which resulted in a higher marginal return than when each pesticide was applied alone at those timings (Table 9).

During 2017-2018 at Chickasha, a positive marginal return at \$0.11 kg^{-1} was only observed for the single fungicide application at Feekes 9 (treatment 5) and the fungicide

+ insecticide at Feekes 6 (treatment 4), with the fungicide at Feekes 9 having the highest return (Table 9). As the grain sale price increased to \$0.18 kg^{-1}, the fungicide treatment at Feekes 9 still had the highest return, but the fungicide + insecticide applied at Feekes 6 overtook it as providing the highest return at the \$0.26 kg^{-1} sale price. Additionally, treatments 10 and 16 were the only other treatments containing a tank-mix which resulted in a higher marginal return than when each pesticide was applied alone at those timings. At Lahoma, the insecticide applied alone at Feekes 6 (treatment 3) was the only treatment to provide a positive marginal return at the \$0.11 kg^{-1} sale price, and it also remained as the treatment with the highest return by a significant amount when the price was increased to the \$0.18 kg^{-1}. At the \$0.26 kg^{-1} sale price, the insecticide applied alone at Feekes 6 (treatment 3) narrowly edged the insecticide applied at Feekes 6 followed by insecticide + fungicide applied at Feekes 9 (treatment 15) as having the highest return. Treatment 15 was the only instance where the fungicide + insecticide tank-mix had a greater marginal return than each pesticide applied alone at that timing (Table 9). The lack of seeing greater marginal returns with the treatments containing fungicide was likely explained by the low amount of disease present at Lahoma that year.

Positive marginal returns during the study period were achieved based on the costs of the fungicides and insecticide used. Since Headline SC (pyraclostrobin) was used at Feekes 6 and Tebucure Fungicide 3.6 (tebuconazole) was used at Feekes 9, the cost for the Feekes 6 application was higher. There was the potential for treatments containing fungicide applied at Feekes 6 being more profitable if a cheaper fungicide was used, but these fungicides were partly chosen to take into account the different modes of action used. Additionally, less increase in grain yield was needed for insecticide use to be profitable since it was much cheaper than the fungicides.

CONCLUSIONS

Results from this study showed that a fungicide + insecticide application can be a sound management practice by providing a greater yield than each pesticide applied alone. However, this management practice was highly dependent on the year and location due to the timing which fungal pathogens and/or insects that were present, and it only occurred at the Feekes 6 timing. Greater marginal economic return of using a fungicide + insecticide compared each pesticide applied alone was observed at both application timings, especially as the grain sale price increased, but it occurred with the Feekes 6 application timing the majority of the time. Pesticide use, in general, was often a good management practice and resulted in greater yields and marginal economic returns than by not using this practice at all. Based on the results of this study, scouting for diseases and insects should dictate whether fungicide + insecticide tank-mixes should be used instead of making prophylactic applications in Oklahoma.

Table 1. Pesticide treatments used at Chickasha, OK and Lahoma, OK during the 2016-2017 and 2017-2018 growing seasons.

Pesticide treatment†	Treatment cost ($ ha^{-1})‡	Chickasha		Lahoma	
		2016-2017§	2017-2018	2016-2017	2017-2018
1. Non-treated control	0	x	x	x	x
2. Fungicide (Feekes 6)	57.87		x	x	x
3. Insecticide (Feekes 6)	16.58	x	x	x	x
4. Fung. + Insect. (F6)	62.10		x	x	x
5. Fungicide (Feekes 9)	15.83	x	x	x	x
6. Insecticide (Feekes 9)	16.58	x	x	x	x
7. Fung. + Insect. (F9)	20.05	x	x	x	x
8. Fung. (F6) & Fung. (F9)	73.70		x	x	x
9. Insect. (F6) & Fung. (F9)	32.41	x	x	x	x
10. Fung. + Insect. (F6) & Fung. (F9)	77.93		x	x	x
11. Fung. (F6) & Insect. (F9)	74.45		x	x	x
12. Insect. (F6) & Insect. (F9)	33.16		x	x	x
13. Fung. + Insect. (F6) & Insect. (F9)	78.68		x	x	x
14. Fung. (F6) & Fung. + Insect. (F9)	77.93		x	x	x
15. Insect. (F6) & Fung. + Insect. (F9)	36.64	x	x	x	x
16. Fung. + Insect. (F6) & Fung. + Insect. (F9)	82.15		x	x	x

† Fungicide applied at Feekes 6 consisted of Headline SC (pyraclostrobin) at a rate of 266 mL ha^{-1}. Fungicide applied at Feekes 9 consisted of Tebucure Fungicide 3.6 (tebuconazole) at a rate of 118 mL ha^{-1}. Insecticide applied at Feekes 6 and Feekes 9 consisted of Silencer (lambda-cyhalothrin) at a rate of 114 mL ha^{-1}.

‡ Treatment cost includes a $12.35 ha^{-1} application fee for each time fungicide was applied.

§ All treatments were not included due to space limitations.

Table 2. Monthly cumulative precipitation (mm) and mean air temperature (°C) for Chickasha, OK and Lahoma, OK during the 2016-2017 and 2017-2018 growing seasons. Deviation from the past 20-year average is in parentheses.†

Growing season	Month	Chickasha		Lahoma	
		Precipitation	Temperature	Precipitation	Temperature
		mm	°C	mm	°C
2016-2017	Oct.	43 (-7)	19.6 (+3.1)	64 (-7)	15.6 (+0.0)
	Nov.	28 (-6)	12.7 (+2.5)	9 (-27)	8.9 (+0.0)
	Dec.	21 (-6)	3.7 (-0.4)	10 (-17)	2.4 (+0.0)
	Jan.	29 (+3)	4.5 (+1.1)	60 (+38)	3.1 (+1.2)
	Feb.	51 (+6)	10 (+4.2)	53 (+21)	8 (+4.1)
	Mar.	70 (+16)	13.8 (+2.7)	80 (+23)	11.5 (+2.3)
	Apr.	82 (+9)	16.1 (+0.2)	148 (+73)	14.6 (+ 0.3)
	May	94 (-2)	20.1 (-0.4)	82 (-7)	19.1 (-0.9)
	June	50 (-14)	25.4 (-0.4)	65 (-38)	25.6 (-0.0)
2017-2018	Oct.	43 (-7)	16.6 (+0.2)	58 (-14)	16 (+0.4)
	Nov.	27 (-10)	11.4 (+1.2)	4 (-32)	9.8 (+0.9)
	Dec.	23 (-4)	4.1 (+0.0)	2 (-25)	3.0 (+0.5)
	Jan.	30 (+4)	2.6 (-0.9)	.2 (-21)	1.7 (-0.3)
	Feb.	53 (+7)	4.6 (-1.3)	34 (+2)	2.8 (1.2)
	Mar.	72 (+17)	11.9 (+0.9)	24 (-33)	10.3 (+ 1.0)
	Apr.	79 (+6)	12.9 (-2.9)	55 (-21)	11.5 (-2.9)
	May	96 (-2)	23.6 (+2.6)	80 (-10)	23.9 (+3.9)
	June	49 (-15)	29.3 (+3.4)	4 (-99)	29.6 (+4.0)

†All data retrieved from the Oklahoma Mesonet.

Table 3. Area under the disease progress curve (AUDPC) mean results by variety and pesticide treatment for Chickasha, OK and Lahoma, OK during the 2016-2017 and 2017-2018 growing seasons.

	Chickasha		Lahoma	
Variable	2016-2017	2017-2018	2016-2017	2017-2018
	-------------------- AUDPC --------------------			
Variety				
Gallagher/Doublestop CL Plus†	6.6	7.3	8.7	0.08
Ruby Lee	9.0	7.8	9.9	0.61
Pesticide treatment				
1. Non-treated control	10.4	8.9	15.2	0.03
2. Fungicide (Feekes 6)	-	7.1	10.9	0.03
3. Insecticide (Feekes 6)	9.8	8.8	13.1	0.03
4. Fung. + Insect. (F6)	-	7.5	9.9	2.05
5. Fungicide (Feekes 9)	5.2	8.2	8.8	0.03
6. Insecticide (Feekes 9)	9.0	9.1	15.2	0.03
7. Fung. + Insect. (F9)	6.9	7.9	8.0	0.64
8. Fung. (F6) & Fung. (F9)	-	6.6	5.9	0.64
9. Insect. (F6) & Fung. (F9)	6.2	8.3	9.9	2.05
10. Fung. + Insect. (F6) & Fung. (F9)	-	6.0	5.6	0.64
11. Fung. (F6) & Insect. (F9)	-	7.6	8.2	0.03
12. Insect. (F6) & Insect. (F9)	8.9	8.3	14.6	0.03
13. Fung. + Insect. (F6) & Insect. (F9)	-	7.1	7.9	0.03
14. Fung. (F6) & Fung. + Insect. (F9)	-	6.1	6.8	0.64
15. Insect. (F6) & Fung. + Insect. (F9)	6.5	7.8	9.2	0.64
16. Fung. + Insect. (F6) & Fung. + Insect. (F9)	-	6.2	6.5	0.03

† Gallagher was used at Chickasha during 2016-2017. Doublestop CL Plus was used at all other site-years.

Table 4. Aphid count mean results for Chickasha, OK and Lahoma, OK during the 2016-2017 and 2017-2018 growing seasons.

	Chickasha		Lahoma	
Variable	2016-2017	2017-2018	2016-2017	2017-2018
	-------------------- Number of aphids‡ --------------------			
Variety				
Gallagher/Doublestop CL Plus†	10.9	6.4	7.6	1.1
Ruby Lee	12.7	2.0	5.7	10.7
Pesticide treatment				
1. Non-treated control	14.9	10.3	5.8	7.6
2. Fungicide (Feekes 6)	-	7.6	4.5	7.4
3. Insecticide (Feekes 6)	12.1	0.0	5.8	5.0
4. Fung. + Insect. (F6)	-	0.0	8.3	4.8
5. Fungicide (Feekes 9)	9.6	4.6	11.5	7.6
6. Insecticide (Feekes 9)	12.8	2.0	5.0	6.6
7. Fung. + Insect. (F9)	13.6	10.1	8.1	6.9
8. Fung. (F6) & Fung. (F9)	-	10.1	6.6	6.6
9. Insect. (F6) & Fung. (F9)	7.8	2.1	7.6	5.3
10. Fung. + Insect. (F6) & Fung. (F9)	-	5.5	5.9	6.3
11. Fung. (F6) & Insect. (F9)	-	9.1	7.9	7.3
12. Insect. (F6) & Insect. (F9)	9.0	0.1	4.3	4.3
13. Fung. + Insect. (F6) & Insect. (F9)	-	0.5	8.1	4.1
14. Fung. (F6) & Fung. + Insect. (F9)	-	4.8	6.3	5.8
15. Insect. (F6) & Fung. + Insect. (F9)	14.9	0.1	6.5	3.6
16. Fung. + Insect. (F6) & Fung. + Insect. (F9)	-	0.0	4.1	5.0

† Gallagher was used at Chickasha during 2016-2017. Doublestop CL Plus was used at all other site-years.

‡ This number respresents the average number of insects across four ratings at both locations in 2016-2017 and five ratings at both locations in 2017-2018.

Table 5. Analysis of variance (ANOVA) results for test weight, protein content, and grain yield at Chickasha, OK and Lahoma, OK during the 2016-2017 and 2017-2018 growing seasons.

	Chickasha		Lahoma	
Source of variation	2016-2017	2017-2018	2016-2017	2017-2018
	----------------- Test weight (kg hL^{-1}) -----------------			
Variety	0.1651	0.0004	0.0651	0.0872
Pesticide treatment	<0.0001	0.8585	0.0004	0.3540
Variety × Pesticide	0.0930	0.3268	0.3592	0.8624
	------------------ Protein content (%) ------------------			
Variety	0.9802	0.0090	0.0001	0.0029
Pesticide treatment	0.7509	0.0003	0.0169	0.1200
Variety × Pesticide	0.4044	0.4247	0.4916	0.4735
	----------------- Grain yield (kg ha^{-1}) -----------------			
Variety	0.2094	0.0754	0.0044	0.0198
Pesticide treatment	<0.0001	0.0021	<0.0001	0.0397
Variety × Pesticide	0.2552	0.8518	0.3203	0.7294

Table 6. Variety and pesticide treatment main effect test weight results for Chickasha, OK and Lahoma, OK during the 2016-2017 and 2017-2018 growing seasons.

	Chickasha		Lahoma	
Main effect	2016-2017	2017-2018	2016-2017	2017-2018
	----------------- kg hL^{-1} -----------------			
Variety				
Gallagher/Doublestop CL Plus†	69.3 A	78.4 A	74.3 A	73.5 A
Ruby Lee	68.5 A	75.9 B	73.7 A	72.3 A
Pesticide treatment				
1. Non-treated control	67.9 BC	77.0 A	72.7 F	73.2 AB
2. Fungicide (Feekes 6)	-	77.2 A	73.4 DEF	72.9 AB
3. Insecticide (Feekes 6)	67.5 C	77.0 A	73.6 C-F	73.1 AB
4. Fung. + Insect. (F6)	-	77.0 A	74.5 ABC	72.4 B
5. Fungicide (Feekes 9)	69.6 A	77.0 A	74.0 A-E	72.5 AB
6. Insecticide (Feekes 9)	68.7 B	77.2 A	73.2 EF	72.8 AB
7. Fung. + Insect. (F9)	69.9 A	76.9 A	73.7 B-F	72.9 AB
8. Fung. (F6) & Fung. (F9)	-	77.1 A	74 A-E	72.4 B
9. Insect. (F6) & Fung. (F9)	70.1 A	77.6 A	74.7 AB	72.8 AB
10. Fung. + Insect. (F6) & Fung. (F9)	-	77.3 A	74.6 AB	72.4 B
11. Fung. (F6) & Insect. (F9)	-	77.0 A	73.2 EF	73.4 A
12. Insect. (F6) & Insect. (F9)	68.0 BC	77.1 A	74.3 A-D	73.3 AB
13. Fung. + Insect. (F6) & Insect. (F9)	-	77.2 A	74.5 ABC	73.2 AB
14. Fung. (F6) & Fung. + Insect. (F9)	-	77.1 A	74.8 A	73.4 A
15. Insect. (F6) & Fung. + Insect. (F9)	69.8 A	77.3 A	74.7 AB	72.8 AB
16. Fung. + Insect. (F6) & Fung. + Insect. (F9)	-	77.6 A	74.1 A-E	72.9 AB

† Gallagher was used at Chickasha during 2016-2017. Doublestop CL Plus was used at all other site-years.

Table 7. Variety and pesticide treatment main effect protein content results for Chickasha, OK and Lahoma, OK during the 2016-2017 and 2017-2018 growing seasons.

	Chickasha		Lahoma	
Variable	2016-2017	2017-2018	2016-2017	2017-2018
	---------------- % ----------------			
Variety				
Doublestop CL Plus	10.5 A	12.7 A	12.3 A	15.9 A
Ruby Lee	10.5 A	11.6 B	10.6 B	15.1 B
Pesticide treatment†				
1. Non-treated control	10.3 A	11.9 F	11.4 B-E	15.5 A-D
2. Fungicide (Feekes 6)	-	12.1 B-F	11.5 B-E	15.6 ABC
3. Insecticide (Feekes 6)	10.6 A	12.0 DEF	11.3 CDE	15.4 BCD
4. Fung. + Insect. (F6)	-	12.1 B-F	11.3 DE	15.5 BCD
5. Fungicide (Feekes 9)	10.6 A	12.0 DEF	11.5 B-E	15.7 ABC
6. Insecticide (Feekes 9)	10.4 A	12.0 EF	11.3 CDE	15.3 CD
7. Fung. + Insect. (F9)	10.5 A	12.2 B-E	11.4 B-E	15.5 A-D
8. Fung. (F6) & Fung. (F9)	-	12.3 ABC	12.0 A	15.8 AB
9. Insect. (F6) & Fung. (F9)	10.4 A	12.0 C-F	11.6 A-D	15.6 A-D
10. Fung. + Insect. (F6) & Fung. (F9)	-	12.2 A-D	11.7 AB	15.6 A-D
11. Fung. (F6) & Insect. (F9)	-	12.2 B-E	11.4 B-E	15.6 ABC
12. Insect. (F6) & Insect. (F9)	10.4 A	11.9 F	11.2 E	15.5 BCD
13. Fung. + Insect. (F6) & Insect. (F9)	-	12.3 ABC	11.6 A-E	15.5 BCD
14. Fung. (F6) & Fung. + Insect. (F9)	-	12.6 A	11.6 ABC	15.8 A
15. Insect. (F6) & Fung. + Insect. (F9)	10.6 A	**12.4 AB‡**	11.6 ABC	15.2 D
16. Fung. + Insect. (F6) & Fung. + Insect. (F9)	-	12.2 BCD	11.4 B-E	15.7 AB

† Gallagher was used at Chickasha during 2016-2017. Doublestop CL Plus was used at all other site-years.
‡ **Bolded values** represent the Fung. + Insect. treatments which have significantly greater yield than both pesticides applied alone at that application timing.

Table 8. Variety and pesticide treatment main effect grain yield results for Chickasha, OK and Lahoma, OK during the 2016-2017 and 2017-2018 growing seasons.

	Chickasha		Lahoma	
Variable	2016-2017	2017-2018	2016-2017	2017-2018
	-------------------- kg ha^{-1} --------------------			
Variety				
Gallagher/Doublestop CL Plus†	2650 A	3840 A	4770 B	2720 B
Ruby Lee	2500 A	4220 A	5530 A	2940 A
Pesticide treatment				
1. Non-treated control	2440 DE	3790 D	4740 GH	2720 E
2. Fungicide (Feekes 6)	-	4000 CD	4840 E-H	2760 B-E
3. Insecticide (Feekes 6)	2290 E	3850 CD	4950 D-G	2920 ABC
4. Fung. + Insect. (F6)	-	**4360 AB**‡	**5460 ABC**	2880 A-D
5. Fungicide (Feekes 9)	2540 CD	4180 ABC	5210 B-E	2760 B-E
6. Insecticide (Feekes 9)	2590 BCD	3910 CD	4530 H	2790 B-E
7. Fung. + Insect. (F9)	2770 AB	3920 CD	4790 F-H	2760 B-E
8. Fung. (F6) & Fung. (F9)	-	3900 CD	5160 C-F	2740 DE
9. Insect. (F6) & Fung. (F9)	2810 A	4030 BCD	5220 B-E	2880 A-E
10. Fung. + Insect. (F6) & Fung. (F9)	-	**4380 A**	5620 AB	2780 B-E
11. Fung. (F6) & Insect. (F9)	-	4090 A-D	5170 C-F	2760 CDE
12. Insect. (F6) & Insect. (F9)	2470 DE	3860 CD	5030 D-G	2920 AB
13. Fung. + Insect. (F6) & Insect. (F9)	-	3990 CD	**5760 A**	2870 A-E
14. Fung. (F6) & Fung. + Insect. (F9)	-	3980 CD	5490 ABC	2870 A-E
15. Insect. (F6) & Fung. + Insect. (F9)	2710 ABC	3870 CD	5270 BCD	2980 A
16. Fung. + Insect. (F6) & Fung. + Insect. (F9)	-	4420 A	5230 B-E	2860 A-E

† Gallagher was used at Chickasha during 2016-2017. Doublestop CL Plus was used at all other site-years.
‡ **Bolded values** represent the Fung. + Insect. treatments which have significantly greater yield than both pesticides applied alone at that application timing.

Table 9. Marginal economic return ($ ha^{-1}) for the pesticide treatments by year and location at grain sale prices of $0.11, $0.18, and $0.26 kg^{-1}. Values represent the difference in marginal return compared to the non-treated control.

Pesticide treatment	Treatment cost†	Chickasha 2016-2017	Chickasha 2017-2018	Lahoma 2016-2017	Lahoma 2017-2018
	--- $ ha^{-1} ---	$0.11 kg^{-1}			
1. Non-treated control	0	-	-	-	-
2. Fungicide (Feekes 6)	57.87	-	-34.77	-45.77	-53.47
3. Insecticide (Feekes 6)	16.58	-33.08	-9.98	+6.52	+5.42§
4. Fung. + Insect. (F6)	62.10	-	**+1.70**‡	**+18.20**	-43.40
5. Fungicide (Feekes 9)	15.83	-4.83	+27.07	+36.97	-11.43
6. Insecticide (Feekes 9)	16.58	-0.08	-2.28	-39.68	-7.78
7. Fung. + Insect. (F9)	20.05	+16.25	-4.65	-14.55	-14.55
8. Fung. (F6) & Fung. (F9)	73.70	-	-61.60	-26.40	-71.50
9. Insect. (F6) & Fung. (F9)	32.41	+8.29	-4.91	+21.49	-14.81
10. Fung. + Insect. (F6) & Fung. (F9)	77.93	-	-11.93	+21.07	-71.33
11. Fung. (F6) & Insect. (F9)	74.45	-	-41.45	-26.05	-70.05
12. Insect. (F6) & Insect. (F9)	33.16	-29.86	-25.46	-0.16	-11.16
13. Fung. + Insect. (F6) & Insect. (F9)	78.68	-	-55.58	**+35.72**	-61.08
14. Fung. (F6) & Fung. + Insect. (F9)	77.93	-	-55.93	**+5.67**	-61.43
15. Insect. (F6) & Fung. + Insect. (F9)	36.64	-6.94	-27.84	**+22.76**	-6.94
16. Fung. + Insect. (F6) & Fung. + Insect. (F9)	82.15	-	-11.75	-27.15	-66.75
		$0.18 kg^{-1}			
1. Non-treated control	0	-	-	-	-
2. Fungicide (Feekes 6)	57.87	-	-20.07	-38.07	-50.67
3. Insecticide (Feekes 6)	16.58	-43.58	-5.78	+21.22	+19.42
4. Fung. + Insect. (F6)	62.10	-	**+42.30**	**+69.30**	-31.50
5. Fungicide (Feekes 9)	15.83	+2.17	+54.37	+70.57	-8.63
6. Insecticide (Feekes 9)	16.58	+10.42	+6.82	-54.38	-2.18
7. Fung. + Insect. (F9)	20.05	+39.35	+5.15	-11.05	-11.05

8. Fung. (F6) & Fung. (F9)	73.70	-	-53.90	+3.70	-70.10
9. Insect. (F6) & Fung. (F9)	32.41	+34.19	+12.59	+55.79	-3.61
10. Fung. + Insect. (F6) & Fung. (F9)	77.93	-	**+30.07**	**+84.07**	-67.13
11. Fung. (F6) & Insect. (F9)	74.45	-	-20.45	+4.75	-67.25
12. Insect. (F6) & Insect. (F9)	33.16	-27.76	-20.56	+20.84	+2.84
13. Fung. + Insect. (F6) & Insect. (F9)	78.68	-	-40.88	**+108.52**	-49.88
14. Fung. (F6) & Fung. + Insect. (F9)	77.93	-	-41.93	**+58.87**	-50.93
15. Insect. (F6) & Fung. + Insect. (F9)	36.64	+11.96	-22.24	**+60.56**	**+11.96**
16. Fung. + Insect. (F6) & Fung. + Insect. (F9)	82.15	-	**+33.05**	+7.85	-56.95
		------------------------- $0.26 kg^{-1} -------------------------			
1. Non-treated control	0	-	-	-	-
2. Fungicide (Feekes 6)	57.87	-	-3.27	-29.27	-47.47
3. Insecticide (Feekes 6)	16.58	-55.58	-0.98	+38.02	+35.42
4. Fung. + Insect. (F6)	62.10	-	**+88.70**	**+127.70**	-17.90
5. Fungicide (Feekes 9)	15.83	+10.17	+85.57	+108.97	-5.43
6. Insecticide (Feekes 9)	16.58	+22.42	+17.22	-71.18	+4.22
7. Fung. + Insect. (F9)	20.05	+65.75	+16.35	-7.05	-7.05
8. Fung. (F6) & Fung. (F9)	73.70	-	-45.10	+38.10	-68.50
9. Insect. (F6) & Fung. (F9)	32.41	+63.79	+32.59	+94.99	+9.19
10. Fung. + Insect. (F6) & Fung. (F9)	77.93	-	**+78.07**	**+156.07**	-62.33
11. Fung. (F6) & Insect. (F9)	74.45	-	+3.55	+39.95	-64.05
12. Insect. (F6) & Insect. (F9)	33.16	-25.36	-14.96	+44.84	+18.84
13. Fung. + Insect. (F6) & Insect. (F9)	78.68	-	-24.08	**+191.72**	-37.08
14. Fung. (F6) & Fung. + Insect. (F9)	77.93	-	-25.93	**+119.67**	-38.93
15. Insect. (F6) & Fung. + Insect. (F9)	36.64	+33.56	-15.84	**+103.76**	**+33.56**
16. Fung. + Insect. (F6) & Fung. + Insect. (F9)	82.15	-	**+84.25**	+47.85	-45.75

† Treatment cost includes a $12.35 ha^{-1} application fee for each application timing where applicable.

‡ **Bolded values** represent the Fung. + Insect. treatments which have significantly greater yield than both pesticides applied alone at that application timing.

§ Green values represent the pesticide treatment with the highest economic return.

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