HARD RED WINTER WHEAT GRAIN YIELD AND QUALITY RESPONSE TO LATE-SEASON NITROGEN FERTILIZER AND FOLIAR FUNGICIDE

By

GIOVANA CRUPPE

Bachelor of Science in Agronomy

Sao Paulo State University

Botucatu, Sao Paulo, Brazil

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Thesis Approved:

Dr. Jeffrey T. Edwards

Thesis Adviser

Dr. Daryl B. Arnall

Dr. Robert M. Hunger

Name: Giovana Cruppe

Date of Degree: May, 2015

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Abstract: Foliar fungicides can protect winter wheat (*Triticum aestivum* L.) grain yield, and farmers sometimes include nitrogen solution with fungicide applications in the hopes that added nitrogen will increase wheat grain protein, yield, or both. The objective of this study was to determine the effect of various nitrogen fertilizer-by-foliar fungicide combinations on wheat normalized difference vegetative index (NDVI), grain yield, test weight, and grain protein. The trial was conducted over six site-years during the 2012-13 and 2013-14 wheat production seasons under dryland and irrigated conditions in central Oklahoma. Experimental design was a factorial arrangement of a randomized complete block design with four replications. Factors were fungicide treatment (no fungicide or 0.77 L ha^{-1} Quilt Xcel), nitrogen source (urea ammonium nitrate (UAN) solution or CoRon), and foliar nitrogen rate (0, 2.8, 5.6, or 28 kg ha^{-1}). All products were applied as tank-mixes at approximately Feekes GS 10.5.1 (anthesis). Applying 28 kg N ha^{-1} significantly decreased NDVI due to leaf burn, regardless of source. Grain yield was not increased by treatments except at the irrigated site, where fungicide increased grain yield by 290 kg ha^{-1} as compared to nontreated plots. Foliar fungicide application increased test weight by as much as 1.42 kg hl^{-1} in three out of six site-years. Other than the 28 kg ha^{-1} N treatment, grain protein was not affected by N application. Applying 28 kg ha^{-1} increased grain protein by approximately 1% and there was no difference between N sources. Results indicate that foliar fungicides could be beneficial in protecting wheat grain yield and test weight, but yield response will be dependent upon variety and environmental conditions. These results also show that foliar N rates necessary to impact grain protein in an otherwise well-fertilized crop also have significant potential for leaf burn, which could negatively impact wheat grain yield in some years.

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CHAPTER I

GENERAL INTRODUCTION

Wheat Production Overview

Wheat (*Triticum aestivum* L.) is one of the most important cereals produced in the world. Total world wheat production during the 2012-2013 growing season was 659.6 million metric tons, and total production in 2013-2014 increased to 716.5 million metric tons (FAOstat, 2015). In the United States (US) wheat is among the principal food grains cultivated, with US total wheat production of 57 million metric tons in 2013-2014, harvested from ~18.7 million hectares of wheat with average yield of 3.17 Mg ha^{-1} (NASS, 2014). The US is the third largest wheat producer in the world, behind only China and India, and it is also the major exporter, followed by France, Australia, Canada, and the Russian Federation (FAOstat, 2013). The southern Great Plains, a region constituted by Colorado, Kansas, New Mexico, Texas, and Oklahoma constitutes 60% of the total US wheat production (USDA, 2013). In the last 10 years, the state of Oklahoma produced, on average, over 3 million metric tons of winter wheat per year from a planted area of over 2 million hectares. Wheat yields, however, remain at 2.2 Mg ha^{-1}, which is well below the national average (NASS, 2014). Several yield limiting factors are likely restricting grain yield in the region.

Factors that limit and reduce wheat growth can be defined as biotic or abiotic (Afzal, et al., 2008). Temperature, available water, and physical and chemical soil properties are examples of abiotic factors that wheat farmers have little control over. On the contrary, biotic factors like fertilization, pests, diseases, and weed infestation, also interfere with plant development, but these factors can be managed by wheat farmers. According to Madden and Nutter Jr (1995) foliar diseases are the major biotic stress in wheat, and can cause large yields losses depending on the wheat growth stage that the diseases occur.

In the southern Great Plains, the foliar diseases leaf rust (*Puccinia recondita* f. sp. *tritici*), powdery mildew (*Erysiphe graminis* f. sp. *tritici*), and stripe rust (*Puccinia striiformis*), are common and can cause large yield losses in individual fields. Besides those diseases, stem rust (*Puccinia graminis* f. sp. *tritici*) and tan spot (*Pyrenophora tritici-repentis*) can also reduce wheat yield. Disease severity varies with pathogen pressure, cultivar, and environmental conditions and occurrence varies greatly according to year and site (Cook, et al., 1999) . According to Roelfs (1989) , large-scale yield reductions in winter wheat have been observed from Pennsylvania to Kansas and Oklahoma due to leaf rust infestation. In the same publication, it was also reported that seasons with optimum temperature and moisture to achieve greater yields also resulted in the greatest losses from foliar disease (i.e. these conditions are also ideal for disease severity) (Kolmer, et al., 2012). Appel, et al. (2013) reported in the Kansas Cooperative Plant Disease Survey that the disease loss estimate for wheat was 6.2% or 590,000 Mg of wheat in Kansas in 2013-2014.

Yield-defining factors, such as stand establishment, as well as water and nutrient uptake, photosynthesis, and other processes can be affected by disease activity resulting in yield losses (Reis, et al., 1999). These effects can be inhibited or at least minimized using management practices such as cultural control (Cook, 2003), crop rotation, alternative host removal, or tolerant-cultivars (Gooding and Davies, 1997). The use of tolerant or resistant cultivars has been widely implemented in the United States; however, pathogens such as the one causing leaf rust have the capacity to develop races that break the resistance of the host (Kolmer, et al., 1997). Therefore application of fungicide is sometimes warranted and has increased over the years since 1960 due to the creation of systemic fungicides (Hewiit, 1998). Fungicides can provide return as high as three times the cost invested (Ordish and Dufour, 1969).

1.2. Fungicide

In the Great Plains, fungicides are usually applied to winter wheat with the objective of controlling foliar fungal diseases (Wegulo, et al., 2011). Many studies have demonstrated the inconsistent effects of foliar fungicide application, resulting in a decrease, increase, or no effect on wheat grain yield (Bertelsen, et al., 2001, Edwards, et al., 2012, Entz, et al., 1990, Homdork, et al., 2000, Thompson, et al., 2014, Zhang, et al., 2010). In Nebraska, Wegulo, et al. (2009) reported that fungicide application prevented yield losses of up to 42% when comparing nontreated plots to the highest yield of fungicide-treated plots. In another experiment conducted in Nebraska, five different fungicides were applied at five different timings, resulting in yield increases ranging from

622 kg ha^{-1} to 2056 kg ha^{-1} and net returns ranging from \$60 ha^{-1} to \$294 ha^{-1}. The best net return was achieved with azoxystrobin + propiconazole (Quilt) applied at visible flag leaf and collar (Zadoks 39) (Wegulo, et al., 2011).

In an experiment conducted in North Dakota, Ransom and McMullen (2008) found an increase in both wheat grain yield and grain quality when foliar fungicide was applied at anthesis, resulting in yield increases from 5.5 to 44 %. Their study evaluated multiple cultivars in multiple environments and yield differences were associated, aside from fungicide application, to differences in cultivar yield potential and cultivar disease resistance. Gooding, et al. (1994) showed that wheat grain yield can sometimes be increased (average of 7.6%) with late-season fungicide applied at flag leaf emergence using propiconazole and tridemorph. The author reported that besides disease control, yield improvement was also associated with delayed flag leaf senescence. Pepler, et al. (2005) proved the association of delayed flag leaf senescence and yield increase; however, the author showed that there is a limitation in this beneficial relationship, especially in cool temperatures or soil-moisture-deficit environments. Conversely, Blandino and Reyneri (2009) found that flag leaf longevity due to triazole application did not improve wheat grain yield.

Factors such as weather conditions, wheat price, timing of application, foliar disease incidence and severity, and development stage are key to determining potential fungicide efficacy and profitability (Wegulo, et al., 2011). In northwestern Europe for example, application of foliar fungicides is one of the major reasons wheat yields increased rapidly during the last half of the twentieth century (Orson, 1995).

Like grain yield, there are contrasting reports in the literature regarding the effect of foliar fungicides on grain quality. Grain test weight, which is density measurement, is one of the most important parameters of wheat grain quality (Clark, 1993). Poorly filled grains reduce wheat grain test weight, and controlling foliar diseases can decrease the intensity and the incidence of grain shriveling, (Dimmock and Gooding, 2002). Although fungicide application may improve grain quality by increasing test weight, research suggests that there may be a tradeoff between increased grain yield associated with the use of fungicides and grain protein content (Angus and Fischer, 1991, Terman, et al., 1969). According to Kibite and Evans (1984) for many years plant breeders have tried without success to produce wheat cultivars that combined high grain yield and high grain protein content. Thus, the increased grain yield associated with fungicide application could possibly lead to decreased grain protein content; however, the compromise between benefits of fungicide use and the decrease in grain protein content is still not fully resolved (Dimmock and Gooding 2002).

One possibility to overcome the tradeoff between wheat grain yield and grain protein content is the late-season application of nitrogen (N). The application of N fertilizer is correlated with increased wheat grain protein content and wheat farmers could possibly use this strategy to achieve both higher yields and grain quality.

1.3. Nitrogen

Nitrogen is an essential nutrient to plant development because it is part of several important molecules such as protein, chlorophyll, adenosine triphosphate, and other enzymes (Miflin and Lea, 1983). Fertilizer N in the southern Great Plains is most commonly applied to winter wheat before or at planting to promote tiller formation, and early season growth for grazing by cattle. A second N application is usually applied as topdress, in late winter prior to jointing (Feekes GS 6) to enhance seeds per head and seed size. The importance of N applications to wheat is known worldwide, and the division of N applications during the growing season is very important to optimize plant N uptake (Mascagni and Sabbe, 1991).The plant's capacity to uptake and store N during early growth stages is very low when compared to later growth stages. This is because young plants do not have an extensive root system to effectively uptake N and they also do not have large amounts of biomass to store enough N to last the entire season (Sinclair and Rufty, 2012). Soil N losses can be attributed to denitrification, volatilization, leaching, and immobilization (Raun and Schepers, 2008).

Nitrogen fertilizer has been shown to increase, decrease, or have no effect on wheat grain yield and grain quality (Finney, et al., 1957, Johnson, et al., 1973, Kindred, et al., 2008). Cassman, et al. (1992) emphasized the importance of preplant and in-season N fertilizer application in winter wheat to enhance both grain yield and grain protein content. According to Gauer, et al. (1992) in order to increase wheat grain protein content, applying higher levels of N is not useful. It seems that the timing of application has more influence than the amount of N applied, when N is not a limiting factor. Many researchers investigated the optimal timing of N to winter wheat to increase grain protein. Some of the findings suggest that late-season N application in addition to the pre-plant and in-season applications may improve wheat grain quality and even grain yields (Bly and Woodard, 2003). However, this additional application is not common practice among hard red winter wheat farmers due its inconsistent effects, cost of an additional field operation, and uncertain net returns.

While Strong (1982) did not find significant differences in grain yield when N was applied at planting or at later growth stages (i.e. at and after flowering), the author found significant increases in grain protein content with N fertilizer applied at later growth stages. In an experiment conducted in Oklahoma, the wheat grain yield response to foliar N fertilization was inconsistent; but the greatest increase, when compared to treatment that only received broadcast N, in grain yield (~ 940 kg ha^{-1}) resulted from the application of 22 kg N ha^{-1} as UAN postflowering (Woolfolk, et al., 2002). This stresses the importance of timing of application as one of the most important factors determining the influence of foliar urea on wheat grain yield (Gooding and Davies, 1992). In addition, Gooding, et al. (1991) emphasized that differences in genetic and environmental conditions could also be responsible for the different plants responses to late-season foliar N applied as urea. The idea that genetic and environmental conditions may affect plants response was validated in a study by Pushman and Bingham (1976). In addition to increases in grain protein content and grain yield, late-season N application has also resulted in greater recovery of applied N. Wuest and Cassman (1992) indicated that when the fertilizer was applied at planting the N recovery varied from 30% to 55% but when also applied at anthesis N recovery increased to 55% to 80%.

While nitrogen application can increase wheat grain yield and grain protein content, it also can be associated with the increase of wheat foliar disease incidence and severity (Simón, et al., 2002). The infection severity of obligate parasites such as *Puccinia ssp.* (the rusts) and *Erysiphe graminis* (powdery mildew) increases with higher levels of N due to the decrease of phenolics content (Taiz and Zeiger, 2010). Phenolics are compounds important to plant defense, as they are responsible for lignin and pigment biosynthesis, structural integrity, eradication of microorganisms and some pathogens, and protection against stress. Thus, lower content of those compounds will make the plant more susceptible to pathogen occurrence.

As described above, application of either late-season nitrogen or fungicide can result in positive outcomes, but those advantages may be accompanied by unintended consequences. For instance, late N application may increase wheat protein content, but may also increase disease incidence; whereas fungicide application may increase grain yields due to lower disease incidence but have the dilution effect of grain protein content. Given that the potential negative impact from application of either fungicide or N can be offset by the positive outcome from the application of the other factor, the combination of both fungicide and late-season N application may be a suitable management strategy for wheat farmers in the southern Great Plains.

CHAPTER II

REVIEW OF LITERATURE

Foliar fungicides are usually applied to winter wheat to control fungal diseases and to protect wheat yield potential. Despite being a relatively dry region (growing season rainfall ranging from 230 to 550 mm) fungal diseases can still reduce wheat growth, development, and yield in the southern Great Plains. In fact, leaf rust (*Puccinia recondita* f. sp. *tritici*) is estimated to have caused an average yearly yield loss of approximately 2.2 % in the state of Oklahoma in the past ten years, with the greatest losses occurring in 2009 (6%) and 2008 (5%) (USDA, 2014). Other foliar diseases, such as powdery mildew (*Erysiphe graminis* f. sp. *tritici*), tan spot (*Pyrenophora tritici-repentis*), and stripe rust (*Puccinia striiformis*), can also result in large yield losses. The control of these diseases through foliar fungicide application has shown inconsistent effects on wheat grain yield and grain quality across the southern Great Plains.

Previous literature indicates that wheat grain yield and grain quality response to foliar fungicide application is highly dependent upon environmental conditions and cultivar disease resistance (i.e. susceptible, intermediate, or resistant), which will determine disease incidence and severity (Cox, et al., 1989). In a long-term study conducted in Oklahoma, foliar fungicide resulted in a grain yield increase of up to 11% in intermediate disease resistance cultivars, whereas in susceptible cultivars fungicide application resulted in yields 24% greater than the same nontreated cultivars (Edwards, et al., 2012). It is suggested that high-yielding wheat cultivars without specific disease resistance can sometimes achieve greater grain yield and grain quality using fungicide than nontreated resistant cultivars (Kelley, 2001). On the other hand, Entz, et al. (1990) did not find benefits of foliar fungicide application to wheat under low disease incidence. This non-beneficial effect was also stated by Edwards, et al. (2014), who reported that wheat grain yield was not affected or even was decreased due to foliar fungicide application in the absence of disease.

Foliar fungicide applications have also been associated with the increase of wheat grain quality (Varga, et al., 2007). Kelley (1993) demonstrated an increase of up to 1.28 kg hl^{-1} in wheat test weight due to foliar fungicide applications when compared to nontreated plots. In addition to test weight, grain protein content is also considered among the most important parameters determining wheat grain quality and end-use (Hay and Porter, 2006). High protein levels are desirable for hard red winter wheat (Woolfolk, et al., 2002), provided protein does exceed acceptable levels. Low levels (< 12%) of grain protein are associated with N deficiencies during grain filling (Brown, et al., 2005). When N fertilizer is supplied to wheat during vegetative growth stages, the available N will increase both grain yield and grain protein content; however, the absolute increase in grain yield will be greater than the increase in grain protein causing the dilution of protein, thus decreasing the total percentage of protein in the grain (Stone and Savin, 2000). Once the N amount required for wheat yield potential has been supplied, though, any addition N fertilization applied during reproductive growth stages will mostly likely increase the grain protein percentage (Brown, et al., 2005).

One practice that can be adopted to enhance wheat grain quality in terms of protein content is the addition of N fertilizer at or shortly after anthesis (Gooding and Davies, 1992). A positive response of wheat grain protein content to late-season N fertilization has been observed in previous studies. Finney, et al. (1957) reported that applying urea solutions ranging from 11 to 56 kg N ha^{-1} at and two days after flowering resulted in an increase in grain protein content of as much as 4.4%. Moreover, Blandino, et al. (2015) showed increases in grain protein content of 0.6% with liquid foliar N applied at anthesis, whereas when N was applied to the soil at heading, the grain protein content increase was 1.92% for common wheat. Research also suggests that wheat grain protein content response to late-season N fertilization is dependent upon plant N status (Brown and Petrie, 2006), cultivar genetics, and environmental conditions. Extra late-season N fertilization could easily be implemented by wheat farmers utilizing a foliar fungicide program (Blandino, et al., 2015), because addition of N to the spray tank would not require an extra field application.

Studies have been performed to determine the influence of the interaction between N and fungicide, but the effects of this combination are inconsistent and results are sometimes contradictory. With the objective to determine the effects of the addition of strobilurins to triazole fungicides, Ruske, et al. (2003) added late season foliar N in an attempt to compensate the grain protein dilution sometimes caused by fungicide applications. Nitrogen applied as urea at anthesis or ammonium nitrate at flag leaf improved wheat grain protein content as much as 0.9% in their experiment. In a study conducted in Croatia, Varga, et al. (2007) found that the lowest values of test weight were associated to severe disease incidence and were obtained from treatments with higher levels of N with no addition of fungicide. The addition of fungicide application to the higher N treatments improved test weight by 7.5% in disease-susceptible cultivars and 2.6% in disease-resistant cultivars. The combination of fungicide and higher levels of N also resulted in the highest levels of grain protein content, but these differences were not significant. Kelley (1993) concluded that the effects of the interaction between N and foliar fungicide on wheat grain yield are extremely dependent of environmental conditions, varying according to the disease incidence and cultivar resistance. Kelley (1993) also reported that increases in wheat grain protein content were achieved due to N fertilization, but not as a result of foliar fungicide application.

The combination of foliar fungicides and late-season nitrogen application has the potential to allow southern Great Plains wheat farmers to increase wheat grain yield and protein in a single treatment. Understanding the effect of this combination is fundamental when providing recommendations on improving wheat grain yield and grain quality. Thus, the objectives of this research are to determine the effect of various fertilizer-by-foliar fungicide combinations on winter wheat vegetative development, grain yield, test weight, and grain protein content in a well fertilized wheat crop in the southern Great Plains. The hypotheses of this study are that fungicides will increase grain yield, different nitrogen products (urea ammonium nitrate (UAN)) and Controlled-Release Nitrogen (CoRon)) will perform similarly, and late-season nitrogen application will increase grain protein but have no effect on yield or test weight.

CHAPTER III

METHODOLOGY

3.1. Location and Soils

Field experiments were conducted during the 2012-2013 and 2013-2014 wheat growing seasons. In 2012-2013, the experiment was conducted at the Oklahoma State University (OSU) North Central Research Station near Lahoma on a Grant Silt Loam soil (fine-silty, mixed, superactive, thermic Udic Argiustoll). In 2013-2014, a total of four dryland and one irrigated experiments were conducted across central Oklahoma. Dryland experiments were placed at the OSU Agronomy Research Station in Stillwater on a Norge Loam soil (fine-silty, mixed, active, thermic Udic Paleustoll); at the OSU South Central Agricultural Research Station near Chickasha on a Dale Silt Loam soil (fine-silty, mixed, superactive, thermic Pachic Haplustoll); at the OSU North Central Research Station near Lahoma on a Grant Silt Loam soil (fine-silty, mixed, superactive, thermic Udic Argiustoll); and at the OSU Cimarron Valley Research Station near Perkins, on a Teller Loam soil (fine-loamy, mixed, active, thermic Udic Argiustolls). The irrigated trial was also located at the OSU Cimarron Valley Research Station near Perkins, on a Teller Fine Sandy Loam soil (fine-loamy, mixed, active, thermic Udic Argiustoll).

3.2. Treatments and Experimental Design

The cultivar Ruby Lee was chosen for this study because it is widely grown and has desirable characteristics such as high yield potential, dual-purpose adaptation, and above average forage production. It is also susceptible to leaf rust (*Puccinia recondita* f. sp. *tritici*), stripe rust (*Puccinia striiformis*) and powdery mildew (*Erysiphe graminis* f. sp. *tritici*) (Edwards, et al., 2012).

Experimental design was a factorial arrangement of a randomized complete block design with four replications and a 2 x 2 x 3 factorial treatment structure plus a control treatment. Factors were fungicide treatment (no fungicide or 0.77 L ha^{-1} Quilt Xcel[†]), foliar nitrogen source (urea ammonium nitrate (UAN) solution or CoRoN[‡]) and foliar nitrogen rate (0, 2.8, 5.6, or 28 kg ha^{-1}) (Table A1). The 28 kg ha^{-1} as CoRon was not included in the 2012-2013 site-year. The liquid UAN (28-0-0) was chosen because it is a common nitrogen fertilizer source available in the Great Plains region; and the Controlled-Release Nitrogen, CoRoN (25-0-0), was used as low-salt product readily available in Oklahoma (Arnall, et al., 2012).

3.3. Field Methodology

Preplant N fertilizer was applied as urea (46-0-0) in each field to ensure N was not a limiting factor to wheat growth. All experimental sites were conventionally tilled

[†] 122.22 g/L propiconazole (1-[[2-(2,4-dichlorophenyl)-4-propyl-1,3-dioxolan-2-yl] methyl]-1,2,4-triazole) plus 141.39 g/L azoxystrobin (Methyl (2E) -2-(2-{[6-(2-cyanophenoxy) pyrimidin-4-yl]oxy phenyl)-3-methoxyacrylate) - Syngenta Crop Protection, Inc. Greensboro, NC
[‡] 25% Controlled-Release Nitrogen – Helena Chemical Company, Collierville, TN

such that less than 10% of crop residue remained on the soil surface at planting. In 2012-2013, the field experiment was sown with a conventional-drill planter (Great Plains, Salina, KS). In 2013-2014 all plots were sown under conventional tillage methods using a Hege small-plot conventional-drill planter, with buffer between all plots. Planting density was approximately 67 kg ha^{-1} of Ruby Lee seed, with row spacing of 15-cm and 56 kg ha^{-1} of diammonium phosphate (DAP, 18-46-0) applied in furrow at planting time. Sowing dates are provided in Table 1. Treatments were applied at beginning of anthesis, or Feekes 10.5.1(Large, 1954), using 15 GPA water carrier delivered through a CO_2 pressurized backpack sprayer approximately 30 cm above crop canopy.

Topdress N (46-0-0) was applied at approximately Feekes 3 in each field. The exception was Stillwater 2013-2014, which had high residual N in the soil, and did not require additional N fertilizer. Overall, nitrogen fertilizer was supplied at levels to ensure a total of ~ 120 kg N ha^{-1} at the dryland sites and ~200 kg N ha^{-1} at the irrigated site was available for wheat grain production. In order to control weeds, 0.47 kg ha^{-1} MCPA ((4-Chloro-2-methylphenoxy) acetic acid) and 0.25 kg ha^{-1} pyroxsulam (N-(5,7-dimethoxy[1,2.4]triazolo[1,5-a]pyrimidin-2-yl)-2-methoxy-4-(trifluoromethyl)-3-pyridinesulfonamide) were applied in all plots during the fall. Insects were controlled as necessary using commercially available pesticides.

Irrigation at Perkins was scheduled based on an atmospheric water balance that employed meteorological, soil, and crop data for a daily estimation of soil water depletion in the effective rooting zone. The FAO Penman-Monteith method (Allen, et al., 1998) was used to estimate daily potential evapotranspiration using weather data retrieved from a nearby weather station from the Mesonet network. Crop coefficient values (Kc) for winter wheat were derived from the FAO Crop Water Information (Food and Agriculture Organization, 2013) and adjusted according to crop phenological stages observations in the field. In the beginning of the growing season crop coefficient values (Kc) used for irrigation scheduling were 0.4 and increased up to 1.2 during mid-season. A 15-d running sum of ET0 was subtracted from a 15-d running sum of rainfall, and irrigation was applied to replenish soil profile to field capacity when the 15-d water balance achieved ~50% depletion of available soil water holding capacity in the root zone.

At physiological maturity (growth stage Feekes 11.4), a linear meter sample was collected from each plot for estimation of harvest index and aboveground biomass. Plots end trimmed at harvest area and were harvested with a Hege self-propelled small plot combine, and harvest dates are presented in Table 1. In the 2012-2013 field experiment, plot size at harvest was 1.65 m by 5 m which is the combine width. In the 2013-2014 field experiments, plots at harvest were 5.2 meters long and consist of eight 15-cm rows for a total width of 1.2 meters In addition to grain yield, grain test weight, weight of thousand seeds, and protein content were measured from the harvested area.

3.4. Measurements and Analysis

In order to evaluate wheat vegetative development, three readings using the GreenSeekerTM hand held optical sensor unit (Trimble Tech Industries, Inc.) were made to collect normalized difference vegetative index (NDVI). This method uses a patented procedure to measure crop reflectance and to calculate NDVI (Raun, et al., 2005). In

Lahoma 2012, the first measurement was taken just before application, then 10 and 16 days after the nitrogen and fungicide application. In 2013 field experiments besides the Hand-Held GreenSeeker, readings were made using the GreenSeekerTM sensor (model 505, NTech Industries, Ukiah, CA) at same days before and after treatment application as made in 2012 field experiment.

A Perten DA7200 (Perten Instruments Inc., Springfield, Illinois) near-infrared reflectance spectroscopy (NIR) analyze was used to measure wheat grain protein content. The NIR technology is based on the sum of absorbances at numerous wavelengths by several constituents such as proteins, starch, fiber, and others (Batten, 1998). This technique is favorable for many reasons, such as the short time needed to prepare and to analyze each sample, determination of various constituents simultaneously, total preservation of the sample, no need to recalibrate once it is first calibrated, and accuracy of results. Thus, the NIR technology has many advantages when compared to others methods.

3.5. Statistical Analysis

Data were analyzed using SAS Version 9.2 (SAS Institute, Cary, NC, 2001). Significance of foliar fungicide, foliar nitrogen source, foliar nitrogen rate, and their interaction were analyzed as standard ANOVA, using the SAS GLIMMIX procedure. Treatment responses were evaluated as contrasts using the SLICE option and a PDIFF option in a LSMEANS statement to separate the means at $\alpha = 0.05$. Regression analyses were used to determine the relationship between NDVI measured shortly after anthesis and wheat grain yield using the PROC REG procedure. Linear-plateau models using PROC NLIN were performed to assess NDVI threshold for wheat grain yield potential for each site-year.

CHAPTER IV

RESULTS AND DISCUSSION

4.1. Weather conditions

Wheat growing conditions varied considerably among site-years, impacting yield potential and disease development (Table 2). The 2012-2013 growing season at Lahoma was characterized by severe drought at planting , during autumn, and early winter, with average monthly rainfall approximately 25% less than the 15-yr normal; however, above normal-precipitation, as well as adequate temperature and relative humidity in April and May provided favorable conditions for wheat foliar disease incidence and severity and grain yield (Edwards, et al., 2013). The lower temperatures extended the 2012-2013 wheat growing season resulting in greater disease incidence, but also greater yields. The weather in the following year at all locations (2013-2014 growing season) was opposite to that observed in Lahoma 2012-2013, with favorable conditions at planting but severe drought throughout the remainder of the growing season. Lahoma in 2012-2013 also had cooler spring temperatures when compared to the subsequent season. Weather conditions during 2013-2014 were dryer than the 15-yr normal in all locations, which resulted in lower grain yields and no disease incidence in the test plot area or Oklahoma in general

(Edwards, 2014). In addition to the lower precipitation totals, a late spring freeze at Stillwater on 11 April 2014 (Table 3) further reduced wheat yields at this location.

4.2. Normalized Difference Vegetative Index

The response of NDVI to treatments varied considerably among site-years, probably due to the high variability of environmental conditions during the growing seasons (Table 4). Fungicide application, N rate, or their interaction, affected NDVI at all locations except for Lahoma in the 2013-2014 growing season. The application of 0.77 L ha^{-1} Quilt Xcel affected NDVI values in three out of six site-years (i.e. Perkins dryland Stillwater, and Lahoma 2013). Nitrogen rate affected NDVI at Perkins irrigated and Chickasha in 2013-2014, but N source had no effect on NDVI. The foliar fungicide X N source treatment at Chickasha and foliar fungicide X N rate treatment at Lahoma 2012-2013 were the only significant interactions.

Foliar fungicide decreased average NDVI by 2.5% at Perkins under dryland conditions (Figure 1). The negative effect of foliar fungicide on NDVI at this location could be attributed to a phytotoxic reaction, which may have been worsened due to severe drought conditions. Nicolas (2004) reported similar phytotoxicity in winter wheat plants when 505.5 g l^{-1} chlorothalonil was applied to healthy plants, decreasing NDVI values when compared to nontreated plants. On the other hand, Quilt Xcel increased NDVI 6.4% at Stillwater compared to no fungicide treatment, regardless of N application (Figure 1).

Nitrogen rate significantly affected NDVI at Chickasha (Figure 1) and there was a significant interaction between foliar fungicide and N source (Figure A1). The application of 5.6 kg N ha^{-1} as UAN resulted in the greatest average NDVI (0.73). The application of foliar fungicide combined with 28 kg N ha^{-1} resulted in the lowest average NDVI (0.65 with UAN and 0.68 with CoRon) (Table A2); however, this decrease in NDVI was not observed with N at lower rates (Figure A1). The foliar fungicide X N source interaction observed at Chickasha indicates that high rates of N as CoRon resulted in less damage to the plants than high rates of N as UAN when combined with foliar fungicide applications.

At Perkins under irrigated conditions, the application of 5.6 kg N ha^{-1} resulted in 6% greater NDVI than 28 kg N ha^{-1} (average of 0.71), and 4% greater than the nontreated control (average of 0.72) (Table A2, Figure 1). The application of the highest rate of N (i.e. 28 kg ha^{-1}) significantly reduced NDVI values due to leaf burn in Perkins irrigated, regardless of N source. This injury also occurred at Lahoma in the 2012-2013 growing season, and, as shown in Figure 1 was accentuated when N application was coupled with foliar fungicide. The leaf burn caused by high rates of nitrogen observed in this study has been previously reported (Bly and Woodard, 2003, Woolfolk, et al., 2002). Leaf burn occurrence and severity as a consequence of liquid N fertilizer application is worsened in low relative humidity with high temperature (Bly and Woodard, 2003), and by the application of highly concentrated solutions. Following these assumptions, application of the 28 kg N ha^{-1} combined with dry and warm weather conditions should have led to leaf burn symptoms on the driest site-years (i.e. Stillwater, Perkins dryland, Chickasha, and Lahoma 2013-2014). However leaf burn occurred at Lahoma 2012-2013 and at Perkins irrigated (Figure 2) site-years, which were characterized by high relative humidity and moderate average temperatures at the day of treatment application (Table 5). According to data obtained from the Oklahoma Mesonet, average relative humidity at Perkins (Table 2) is generally low, however, supplemental irrigation (values are shown in parenthesis on Table 2) applied before treatment application most likely increased average relative humidity at this location on the day of treatment application.

Wheat plants in the dryland fields were visibly under drought stress at the time of treatment application (i.e. flowering) due to low total precipitation during April and May of 2014 (Table 2). Under adverse environmental conditions, such as drought, plants have the ability to increase the amount of the epicuticular wax in order to reduce transpiration as a mechanism of resistance or tolerance (Clarke and Richards, 1988, Jenks and Ashworth, 1999). However, the increase of the wax layer can also affect the uptake and efficiency of chemical products such as fertilizers and fungicides (Clarke and Richards, 1988), which could partially explain why leaf burn did not occur in the driest site-years. Although the objective of this study was not to determine the optimal timing of N fertilization, leaf burn in this study indicated that N fertilization rate and timing need to be carefully evaluated in order to avoid injury. Previous studies show that injury occurring later in the growing season tended to have greater negative impact on the photosynthetic rate and consequently greater yield losses than injuries caused before flag leaf appearance (Vargas, et al., 2015) .

4.3. Grain yield

Foliar fungicide application affected wheat grain yield in two out of six site-years (i.e. Perkins irrigated and Perkins dryland), and there was a significant interaction between foliar fungicide and N source at Chickasha (Figure 3), (Table 6). The greatest yields were obtained at Lahoma during the 2012-2013 growing season, when total growing season rainfall was 320 mm, and the lowest yields were obtained at Lahoma in the subsequent year, when total growing season rainfall was 170 mm. At the irrigated site, seasonal precipitation plus irrigation totaled 485 mm, but grain yield average still remained below that observed at Lahoma in the 2012-2013 wheat growing season (~700 kg ha^{-1}) (Table A3).

Foliar fungicide significantly affected wheat grain yield in contrasting ways at both irrigated and non-irrigated sites at Perkins. Under irrigated conditions, application of 0.77 L ha^{-1} Quilt Xcel increased yield by 290 kg ha^{-1} as compared to nontreated plots. On the contrary, foliar fungicide application caused a slight grain yield decrease of 105 kg ha^{-1} when compared with nontreated plots at the dryland site. The contrasting results found at Perkins were probably the result of an extremely dry season (Table 2) with no disease incidence (Edwards, et al., 2014). Under dryland conditions, application of foliar fungicide in the absence of disease may have caused phytotoxicity (Figure 1) probably resulting in the yield decrease. The NDVI measurements at the dryland site (Table A2) also indicated a possible phytotoxicity reaction. Given the weather conditions during the 2013-2014 growing season, there was no need for foliar fungicide application in central Oklahoma (Edwards, 2014). The intensive irrigation in the irrigated site, on the other hand, may have increased disease incidence, which would explain the positive yield response to foliar fungicide.

There was no significant effect of N source, N rate, or the interaction between N treatments and foliar fungicide on wheat grain yield in any of the studied sites (Table 6). Wheat grain yield can be divided into four critical yield components: grains per m^2, grain weight, spikes per m^2 , and grains per spike (Slafer, et al., 2014). Each of these four components is established in different wheat growth stages, and in order to increase final grain yield, proper management, such as N fertilization should be done at or prior to these key developmental phases. Wheat grain weight is the last component to be determined, as potential grain weight is established prior to anthesis and actual grain weight is established through grain fill until harvest. The initial hypothesis of this study was that late season N would have little effect on wheat grain yield, as treatments were applied at anthesis and by this growth stage three out of four critical yield components would have already been established and the results confirm this hypothesis. These results agree with Bly and Woodard (2003), who did not find grain yield increases for UAN at 33.7 kg N ha^{-1} applied postpollination to hard red winter wheat. The non-effect of late season N fertilization on wheat grain yield under irrigated conditions also was reported by Dubetz (1977); however, previous researches also indicated different effects of late-season N on wheat grain yield. Woolfolk, et al. (2002) reported that the application of UAN at 22 kg ha^{-1} postflowering can have inconsistent effects on yield. In their study, late-season N decreased yields by 354 kg ha^{-1} at Stillwater in 1999 when compared to nontreated plots. On the contrary, the same application at Perkins increased grain yield by 940 kg ha^{-1} the subsequent growing season.

The results from this study indicate that a post-flowering NDVI of 0.72 is enough for wheat to achieve optimal potential productivity, and yields can be severely limited if

NDVI readings are less than that threshold (Figure 4). In fact, grain yields decreased linearly from 3294 kg ha^{-1} to less than 1650 kg ha^{-1} with a decrease (from 0.72 to less than 0.30) in NDVI values measured 10-days following anthesis. This indicates that if the wheat crop is exposed to limiting weather conditions early in the growing season severe enough to decrease NDVI, the yield potential is never regained. This was the case for the wheat at Lahoma, Perkins dryland, and Stillwater, during the 2013-2014 growing season. At Chickasha, the wheat crop had average NDVI following anthesis around the 0.72 threshold; however, a severe drought during the anthesis- physiological maturity period limited grain yields which never surpassed 3500 kg ha^{-1}. Figure 4 also indicates that if favorable weather conditions occur during the anthesis – physiological maturity interval, a wheat crop with NDVI of approximately 0.72 can result in grain yield ranging anywhere from 4605 to 5301 kg ha^{-1}, as was the case for Perkins 2013-2014 under irrigated conditions and Lahoma 2012-2013 (Table A3).

Drought stress prior to anthesis can reduce the potential number of spikes per plant and the number of kernels per spike, while a drought between anthesis and physiological maturity can decrease final grain weight (Innes and Blackwell, 1981). In an experiment conducted in Turkey with the objective to evaluate the effects of water stress at different wheat growth stages, Ozturk and Aydin (2004) reported that treatments under continuous drought stress (i.e. no water after the second node visible until maturity) resulted in the lowest grain yields (average of 1533 kg ha^{-1}), while treatments that were exposed to drought stress only later in the season (i.e. after milky stage) resulted in average grain yield of 3391 kg ha^{-1}. In addition, treatments under continuous irrigation resulted in the greatest grain yields (average of 4459 kg ha^{-1}). Their findings are similar to the effects of water stress observed in our study: Stillwater, Perkins dryland, and Lahoma during the 2013-2014 were site-years characterized by continuous drought stress resulting in lower yields (Table A3). Although the precipitation in April at Chickasha was still lower than the long term mean (Table 2), the available water holding capacity of the Dale silt loam at this site probably decreased the detrimental drought effects before anthesis when compared to soils with lower available water holding capacity such as in Stillwater and Perkins. Yields at Chickasha, however, were still affected by a late-season drought stress (i.e. post-anthesis) and remained ~ 2805 kg ha^{-1}. On the other hand, Perkins irrigated 2013-2014 was well-irrigated and at Lahoma 2012-2013 the available water throughout the growing season was close-to-normal mean resulting in greater yields at both locations (Table A3).

4.4. Grain protein content

Foliar fungicide did not affect grain protein content except at Lahoma in the 2012-2013 growing season (Table 7), where fungicide application increased protein content by 0.3% as compared to non-fungicide treatments. There were three significant interactions including fungicides; fungicide X N rate and fungicide X N source X N rate at Chickasha (Figure A2) and fungicide X N source at Perkins dryland. Nitrogen rate affected protein content at Lahoma, Perkins irrigated, and Perkins dryland in the 2013-2014 growing season (Table 7). The greatest average protein content was at Stillwater, where there was a trend (p = 0.07) of greater protein content with increased N rate.

Average grain protein increased from 17.2% in the nontreated plots to 17.9% with 28 kg N ha^{-1}, regardless of fungicide application or N source in Stillwater (Table A4).

There was a significant interaction between foliar fungicide and N source at Perkins under dryland conditions (Figure A3). Late-season N applied as UAN or CoRon without foliar fungicide resulted in similar increase in protein content with the increase of N rate (Figure A3). Average protein content at 2.8 kg N ha^{-1} was 14.6% for UAN and 15.1% for CoRon, and at 28 kg N ha^{-1} protein content increased to 15.7% for UAN and 16% for CoRon. The greatest average protein content in Perkins dryland (16.8%) resulted when 28 kg N ha^{-1} as UAN was added to foliar fungicide. Nonetheless it was hard to make sense of the physiological meaning of the three-way significant interaction (Fungicide X N source X N rate) in Chickasha. While the treatment 2.8 kg N ha^{-1} UAN with foliar fungicide resulted in the greatest protein content (17.5%), no patterns of increase in protein content were associated consistently with the treatments (Figure A2).

At Perkins irrigated and Lahoma 2013-2014 where N rate significantly affected grain protein, the greatest grain protein content response to late-season N was with 28 kg N ha^{-1}, regardless of N source or foliar fungicide treatment (Figure 5). Confirming our findings, Brown, et al. (2005) reported that increases in grain protein content due to late-season N are not significantly affected by N source. However, the interest in low-salt N sources has increased over the years in function of the reduce leaf burn injury. At Perkins irrigated the highest rate of N increased protein by 1.0 % when compared to 5.6 kg N ha^{-1} and by 1.5% when compared to nontreated plots. Increases in protein content were 1% and 0.7% when comparing 28 kg N ha^{-1} to nontreated plots at Perkins dryland and at Lahoma, respectively. While the increases in grain protein content at Perkins dryland

(1%) and at Lahoma (0.7%) are equivalent to increases reported by Blandino, et al. (2015) in Italy when foliar liquid N was applied at anthesis (0.6%), grain protein response at Perkins irrigated to late season N (1.5%) was similar to the effect of 40 kg ha^{-1} of granular N applied to the soil at heading (increased grain protein content by 1.92%) (Blandino, et al., 2015). The drought stress in the 2013-2014 wheat growing season may have accelerated the grain filling and ripening growth stages, but the irrigation supplied at Perkins extended those final reproductive phases (i.e. grain filling and ripening) explaining why late season N fertilization was more effective at this site. This benefit of late-season N for grain protein content due to a longer grain maturity process was also reported in previous studies (Blandino, et al., 2015) .

Results of our study also agreed with Bly and Woodard (2003), who found the greatest augment in protein content when 33.7 kg N ha^{-1} was applied to wheat postpollination. Other researchers also indicated that N applied at later wheat growth stages can increase wheat grain protein content (Finney, et al., 1957, Gooding and Davies, 1992). Moreover, some researchers suggest that late-season N influence on grain protein content is dependent upon wheat cultivar (Varga and Svečnjak, 2006) and N fertilization applied throughout the growing season (Dubetz, 1977). Unlike yield, increases in grain protein content were expected in response to application of late season nitrogen. Treatments in this study were applied at flowering and, as discussed previously, grain yield components would have already been determined and reached their maximum potential by this time, thus any extra N taken up by wheat plants at this point would most likely increase grain protein content rather than grain yield. The drawback of such treatments is that the N rate necessary to impact grain protein content also had significant potential for leaf burn, which could negatively impact wheat grain yield some years.

4.5. Test weight and 1000-kernel weight

Foliar fungicide application increased test weight in three out of six site-years (Lahoma 2012-2013, Stillwater, and Perkins dryland), regardless of N treatment (Table 8). There was a significant interaction between fungicide, N rate, and N source at Chickasha (Figure A4). Average test weight varied considerably among site-years, ranging from 72.5 kg hl^{-1} at Chickasha to 78.4 kg hl^{-1} at Perkins irrigated (Table A5).

The greatest increased in test weight occurred at Lahoma 2012-2013, where the application of Quilt Xcel resulted in average test weight of 75.0 kg hl^{-1} compared to 73.8 in the non-fungicide treatments (Figure 6). Fungicide application increased wheat test weight by 0.7 and 0.5 kg hl^{-1} at Stillwater and Perkins dryland, respectively. Similar results were described by Varga, et al. (2007), who reported an average increase in wheat test weight of 1.0 kg hl^{-1} due to application fungicide. Foliar fungicide X N rate X N source interaction at Chickasha was the only significant interaction observed for test weight. Although no patterns of increase in test weight were associated consistently with the treatments, CoRon at 2.8 kg N ha^{-1} resulted in the greatest average test weight when added to foliar fungicide, and in the lowest average test weight without foliar fungicide. At 28 kg N ha^{-1} the addition of foliar fungicide did not significantly affect the average test weight, regardless of N source (Figure A4).

Foliar fungicide application did not affect 1000-kernel weight except at Perkins under irrigated conditions, where average 1000-kernel weight increased from 4.0 to 4.2 g due to fungicide application (Table A6, figure 7). There were two significant interactions; at Chickasha (fungicide X N source) and at Lahoma 2012-2013 (fungicide X N source X N rate) (Table 9). At Chickasha, application of UAN or CoRon at 5.6 kg N ha^{-1} without foliar fungicide resulted in the greatest average 1000-kernel weight. At the highest N rate (i.e. 28 kg ha^{-1}) average 1000-kernel weight of plots with or without foliar fungicide were similar for both N sources (Figure 7). At Lahoma 2012-2013, the control and control plus fungicide application resulted in the greatest average of 1000-kernel weight, 3.2 and 3.5 g, respectively. All three rates of UAN (i.e. 2.8, 5.6, and 28 kg ha^{-1}) with foliar fungicide resulted in greater responses than without fungicide (Figure 7). These results suggest that although there was an interaction (fungicide X N source X N rate), the addition of foliar fungicide was fundamental to increasing average 1000-kernel weight.

CHAPTER V

CONCLUSIONS

The low disease pressure experienced in all site-years of this study makes it challenging to draw conclusions about the effects of foliar fungicides and the interaction between fungicides and N treatments on wheat grain yield and grain quality. Despite the inconsistent results of this study, foliar fungicide application resulted in enhancement of wheat grain quality in terms of test weight, with increases as great as 1.2 kg hl^{-1} in three out of six site-years. Additionally, our results indicate that grain yield response to foliar fungicides will be dependent upon environmental conditions. Under favorable growing conditions (i.e. Perkins irrigated), foliar fungicide increased wheat grain yield by 290 kg ha^{-1}; whereas the application of fungicide under dry conditions (i.e. Perkins dryland) decreased grain yield by 105 kg ha^{-1}. This decrease in grain yield was also associated with a 2.5% decrease in NDVI values probably due to phytotoxicity. The lack of grain yield response to late-season N application partially confirmed the initial hypothesis of this study, which was that nitrogen fertilization applied at or shortly after anthesis would impact grain protein content but not grain yield, as by this time grain yield potential has already been established. Thus, the application of 28 kg N ha^{-1} has shown promising results in increasing wheat grain protein content. However, the benefits of increased grain protein content (~1.0 %) following the application of 28 kg N ha^{-1} might be offset by the potential for leaf burn observed with the highest N rate, which could negatively impact wheat grain yield. While N rate was a significant factor in three out of six site-years increasing grain protein content, N source was not, as both CoRon and UAN had similar effects on grain protein content. The decision of whether or not to apply foliar fungicide and late-season N should be based on current weather conditions, weather forecast, and cultivar. These factors combined will determine disease incidence and severity and also increase the likelihood of positive grain yield and grain quality response to foliar fungicide and late-season N applications.

REFERENCES

Afzal, S.N., M. Haque, M. Ahmedani, A. Rauf, M. Munir, S.S. Firdous, et al. 2008. Impact of stripe rust on kernel weight of wheat varieties sown in rainfed areas of Pakistan. Pak J. Bot. 40: 923-929.

Angus, J. and R. Fischer. 1991. Grain protein responses to nitrogen applied to wheat growing on a red earth. Aust. J. Agric. Res. 42: 735-746.

Appel, J., E. De Wolf, W. Bockus and R. Bowden. 2013. Preliminary 2013 8 Kansas wheat disease loss estimates. Kansas Coop. Plant Disease Survey 9.

Arnall, D.B., M.J. Mullock and B. Seabourn. 2012. Can protein levels be economically increased? Fluid Journal 20: 2-5.

Bertelsen, J., E. De Neergaard and V. Smedegaard-Petersen. 2001. Fungicidal effects of azoxystrobin and epoxiconazole on phyllosphere fungi, senescence and yield of winter wheat. Plant Pathol. 50: 190-205.

Blandino, M. and A. Reyneri. 2009. Effect of fungicide and foliar fertilizer application to winter wheat at anthesis on flag leaf senescence, grain yield, flour bread-making quality and DON contamination. Eur. J. Agron. 30: 275-282. doi:DOI 10.1016/j.eja.2008.12.005.

Blandino, M., P. Vaccino and A. Reyneri. 2015. Late-Season Nitrogen Increases Improver Common and Durum Wheat Quality. Agron. J. 107: 680-690.

Bly, A.G. and H.J. Woodard. 2003. Foliar nitrogen application timing influence on grain yield and protein concentration of hard red winter and spring wheat. Agron. J. 95: 335-338.

Brown, B., M. Westcott, N. Christensen, B. Pan and J. Stark. 2005. Nitrogen management for hard wheat protein enhancement. Washington State Univer. Cooper. Ext.

Brown, B.D. and S. Petrie. 2006. Irrigated hard winter wheat response to fall, spring, and late season applied nitrogen. Field Crops Res. 96: 260-268.

Cassman, K.G., D.C. Bryant, A.E. Fulton and L.F. Jackson. 1992. Nitrogen supply effects on partitioning of dry-matter and nitrogen to grain of irrigated wheat. Crop Sci. 32: 1251-1258.

Clark, W. 1993. Interaction of winter wheat varieties with fungicide programmes and effects on grain quality. Aspects of Applied Biology. 36: 397-406.

Clarke, J. and R. Richards. 1988. The effects of glaucousness, epicuticular wax, leaf age, plant height, and growth environment on water loss rates of excised wheat leaves. Canadian. Plant Sci. 68: 975-982.

Cook, R.J. 2003. Take-all of wheat. Physiol. Molecular Plant Pathol. 62: 73-86.

Cook, R.J., M.J. Hims and T.B. Vaughan. 1999. Effects of fungicide spray timing on winter wheat disease control. Plant Pathol. 48: 33-50.

Cox, W., G. Bergstrom, W. Reid, M. Sorrells and D. Otis. 1989. Fungicide and nitrogen effects on winter wheat under low foliar disease severity. Crop Sci. 29: 164-170.

Dimmock, J. and M. Gooding. 2002. The influence of foliar diseases, and their control by fungicides, on the protein concentration in wheat grain: a review. Agric. Sci. 138: 349-366.

Dubetz, S. 1977. Effects of high rates of nitrogen on Neepawa wheat grown under irrigation. I. Yield and protein content. Canadian J. Plant Sci. 57: 331-336.

Edwards, J.T., R.M. Hunger and M.E. Payton. 2012. Agronomic and economic response of hard red winter wheat to foliar fungicide in the southern plains. Crop Manag. http://dx.doi.org/10.1094/CM-2012-0730-01-RS.

Edwards, J.T., R.D. Kochenower, R.E. Austin, M.W. Knori, R.P. Lollato, G. Cruppe, B.F. Carver, and R.M. Hunger. 2013. Oklahoma small grains variety performance tests 2012-2013. Okla. State Univer. Coop. Ext. Current Report 2143.

Edwards, J.T., R.D. Kochenower, S.R. Calhoun, M.W. Knori, R.P. Lollato, G. Cruppe, B.F. Carver, and R.M. Hunger. 2014. Oklahoma small grains variety performance tests 2013-2014. Okla. State Univer. Coop. Ext. Current Report 2143.

Entz, M., C.V.D. Berg, E. Stobbe, B. Rossnagel, G. Lafond and H. Austenson. 1990. Effect of late-season fungicide application on grain yield and seed size distribution in wheat and barley. Canadian Plant Sci. 70: 699-706.

FAOstat. 2013. Food and Agriculture Organization of the United Nations. Exporters: Commodities by country. Available at http://faostat.fao.org/desktopdefault.aspx?pageid=342.

FAOstat. 2015. Food and Agriculture Organization of the United Nations. World Wheat Market. Available at http://www.fao.org/worldfoodsituation/csdb/en/.

Finney, K., J. Meyer, F. Smith and H. Fryer. 1957. Effect of foliar spraying of Pawnee wheat with urea solutions on yield, protein content, and protein quality. Agron. J. 49: 341-347.

Gauer, L., C. Grant, L. Bailey and D. Gehl. 1992. Effects of nitrogen fertilization on grain protein content, nitrogen uptake, and nitrogen use efficiency of six spring wheat (Triticum aestivum L.) cultivars, in relation to estimated moisture supply. Canadian Plant Sci. 72: 235-241.

Gooding, M. and W. Davies. 1992. Foliar urea fertilization of cereals: a review. Fertilizer Res. 32: 209-222.

Gooding, M., P. Kettlewell and T. Hocking. 1991. Effects of urea alone or with fungicide on the yield and breadmaking quality of wheat when sprayed at flag leaf and ear emergence. Agric. Sci.117: 149-155.

Gooding, M.J. and W.P. Davies. 1997. Wheat production and utilization: systems, quality and the environment CAB international.

Gooding, M.J., S.P. Smith, W.P. Davies and P.S. Kettlewell. 1994. Effects of late-season applications of propiconazole and tridemorph on disease, senescence, grain development and the wheat breadmaking quality of winter-wheat. Crop Prot 13: 362-370. doi:Doi 10.1016/0261-2194(94)90051-5.

Hay, R.K.M. and J.R. Porter. 2006. The physiology of crop yield. Second Edition ed. Blackwell Publishing Ltd, Oxford, UK.

Homdork, S., H. Fehrmann and R. Beck. 2000. Effects of field application of tebuconazole on yield, yield components and the mycotoxin content of fusarium-infected wheat grain. Phytopathol. 148: 1-6.

Hunter, A.S. and G. Stanford. 1973. Protein content of winter wheat in relation to rate and time of nitrogen fertilizer application. Agron. J. 65: 772-774.

Innes, P. and R. Blackwell. 1981. The effect of drought on the water use and yield of two spring wheat genotypes. Agric. Sci. 96: 603-610.

Jenks, M.A. and E.N. Ashworth. 1999. Plant epicuticular waxes: function, production, and genetics. Horticult. Reviews 23: 1-68.

Johnson, V., A. Dreier and P. Grabouski. 1973. Yield and protein responses to nitrogen fertilizer of two winter wheat varieties differing in inherent protein content of their grain. Agron. J. 65: 259-263.

Kelley, K. 1993. Nitrogen and foliar fungicide effects on winter wheats. Prod. Agric. 6: 53-57.

Kelley, K.W. 2001. Planting date and foliar fungicide effects on yield components and grain traits of winter wheat. Agron. J. 93: 380-389.

Kibite, S. and L. Evans. 1984. Causes of negative correlations between grain yield and grain protein concentration in common wheat. Euphytica 33: 801-810.

Kindred, D.R., T.M. Verhoeven, R.M. Weightman, J.S. Swanston, R.C. Agu, J.M. Brosnan, et al. 2008. Effects of variety and fertilizer nitrogen on alcohol yield, grain yield, starch and protein content, and protein composition of winter wheat. J Cereal Sci. 48: 46-57.

Kolmer, J., I. Crute, E. Holub and J. Burdon. 1997. Virulence dynamics and genetics of cereal rust populations in North America. The gene-for-gene relationship in plant-parasite interactions, ed. IR Crute, EB Holub, JJ Burdon: 139-156. Wallingford, UK: CAB Int.

Madden, L. and F. Nutter Jr. 1995. Modeling crop losses at the field scale. Canadian Plant Pathol. 17: 124-137.

Mascagni, H.J. and W.E. Sabbe. 1991. Late spring nitrogen applications on wheat on a poorly drained soil. J. Plant Nutr. 14: 1091-1103.

Miflin, B.J. and P.J. Lea. 1983. Citation Classic - The pathway of nitrogen assimilation in plants. Cc/Agr. Biol. Environ.: 18-18.

USDA-NASS. 2014. United States Department of Agriculture. National Agricultural Statistics Service. Available at http://www.nass.usda.gov/Statistics_by_Subject/index.php?sector=CROPS. United States Department of Agriculture.

Nicolas, H. 2004. Using remote sensing to determine of the date of a fungicide application on winter wheat. Crop Prot. 23: 853-863.

Ordish, G. and D. Dufour. 1969. Economic bases for protection against plant diseases. Annu. Rev. Phytopathol. 7: 31-50.

Orson, J. 1995. Crop protection practices in wheat and barley crops. A Vital Role for Fungicides in Cereal Production. BIOS Scientific Publishers, Cirencester, UK: 9-18.

Ozturk, A. and F. Aydin. 2004. Effect of water stress at various growth stages on some quality characteristics of winter wheat. Agron. Crop Sci. 190: 93-99.

Pepler, S., M.J. Gooding, K.E. Ford and R.H. Ellis. 2005. A temporal limit to the association between flag leaf life extension by fungicides and wheat yields. Eur. J. Agron. 22: 363-373.

Pushman, F.M. and J. Bingham. 1976. The effects of a granular nitrogen fertilizer and a foliar spray of urea on the yield and bread-making quality of ten winter wheats. Agricult. Sci. 87: 281-292.

Ransom, J.K. and M.V. McMullen. 2008. Yield and disease control on hard winter wheat cultivars with foliar fungicides. Agron. J. 100: 1130-1137.

Raun, W., J. Solie, K. Martin, K. Freeman, M. Stone, G. Johnson, et al. 2005. Growth stage, development, and spatial variability in corn evaluated using optical sensor readings** Contribution from the Oklahoma Agricultural Experiment Station and the International Maize and Wheat Improvement Center (CIMMYT). J. Plant Nutr. 28: 173-182.

Raun, W.R. and J. Schepers. 2008. Nitrogen management for improved use efficiency. Nitrogen in agricultural systems: 675-693.

Reis, E.M., C.A. Medeiros and M.C. Blum. 1999. Wheat yield as affected by diseases. Wheat: Ecology and physiology of yield determination. The Haworth Press, Inc., New York, NY: 229-238.

Roelfs, A. 1989. Epidemiology of the cereal rusts in North America. Canadian Plant Pathol. 11: 86-90.

Ruske, R., M. Gooding and S. Jones. 2003. The effects of adding picoxystrobin, azoxystrobin and nitrogen to a triazole programme on disease control, flag leaf senescence, yield and grain quality of winter wheat. Crop Prot. 22: 975-987.

Simón, M., A. Perelló, C. Cordo and P. Struik. 2002. Influence of on yield, yield components, and test weight of wheat under two nitrogen fertilization conditions. Crop Sci. 42: 1974-1981.

Sinclair, T.R. and T.W. Rufty. 2012. Nitrogen and water resources commonly limit crop yield increases, not necessarily plant genetics. Global Food Security 1: 94-98.

Slafer, G.A., R. Savin and V.O. Sadras. 2014. Coarse and fine regulation of wheat yield components in response to genotype and environment. Field Crops Res. 157: 71-83.

Stone, P.J. and R. Savin. 2000. Grain quality and its physiological determinants. In: E. H. Satorre and G. A. Slafer, editors, Wheat: Ecology and Physiology of Yield Determination. Food Products Press, Binghamton, NY. p. 85-120.

Strong, W. 1982. Effect of late application of nitrogen on the yield and protein content of wheat. Animal Prod. Sci. 22: 54-61.

Taiz, L. and E. Zeiger. 2010. Secondary Metabolites and Plant Defense. In: L. Taiz and E. Zeiger, editors, Plant Physiology. Sinauer Associates Inc., Sunderland. p. 369-400.

Terman, G., R. Ramig, A. Dreier and R. Olson. 1969. Yield-protein relationships in wheat grain, as affected by nitrogen and water. Agron. J. 61: 755-759.

Thompson, N.M., F.M. Epplin, J.T. Edwards and R.M. Hunger. 2014. Economics of foliar fungicides for hard red winter wheat in the USA southern Great Plains. Crops Prot. 59: 1-6.

USDA-ARS. 2014. United States Department of Agriculture. Agricultural Research Service. Small grain losses due to rust. Available at http://www.ars.usda.gov/main/docs.htm?docid=10123. United States Department of Agriculture.

Varga, B. and Z. Svečnjak. 2006. The effect of late-season urea spraying on grain yield and quality of winter wheat cultivars under low and high basal nitrogen fertilization. Field Crops Res. 96: 125-132.

Varga, B., Z. Svečnjak, Z. Jurković and M. Pospišil. 2007. Quality responses of winter wheat cultivars to nitrogen and fungicide applications in Croatia. Acta Agronomica Hungarica 55: 37-48.

Vargas, V.P., L. Sangoi, P.R. Ernani, G.J. Picoli and H. Cantarella. 2015. Maize leaf phytotoxicity and grain yield are affected by nitrogen source and application method. Agron. J. 107: 671-679.

Wegulo, S.N., J.A. Breathnach and P.S. Baenziger. 2009. Effect of growth stage on the relationship between tan spot and spot blotch severity and yield in winter wheat. Crop Prot. 28: 696-702.

Wegulo, S.N., M.V. Zwingman, J.A. Breathnach and P.S. Baenziger. 2011. Economic returns from fungicide application to control foliar fungal diseases in winter wheat. Crop Prot. 30: 685-692.

Woolfolk, C.W., W.R. Raun, G.V. Johnson, W.E. Thomason, R.W. Mullen, K.J. Wynn, et al. 2002. Influence of late-season foliar nitrogen applications on yield and grain nitrogen in winter wheat. Agron. J. 94: 429-434.

Wuest, S. and K. Cassman. 1992. Fertilizer-nitrogen use efficiency of irrigated wheat: II. Partitioning efficiency of preplant versus late-season application. Agron. J. 84: 689-694.

Zhang, Y.-J., X. Zhang, C.-J. Chen, M.-G. Zhou and H.-C. Wang. 2010. Effects of fungicides JS399-19, azoxystrobin, tebuconazloe, and carbendazim on the physiological and biochemical indices and grain yield of winter wheat. Pesticide Bioche. Physiol. 98: 151-157.

Table 1. Planting and harvest dates for hard red winter wheat at Lahoma for the 2012-2013 growing season and at Lahoma, Chickasha, Stillwater, Perkins irrigated, and Perkins dryland for the 2013-2014 wheat growing season.

Location	Growing season	Planting	Harvest
Lahoma	2012-2013	5-Oct-12	24-Jun-13
Lahoma	2013-2014	9-Oct-13	16-Jun-14
Chickasha	2013-2014	22-Oct-13	13-Jun-14
Stillwater	2013-2014	11-Oct-13	16-Jun-14
Perkins irrigated	2013-2014	11-Oct-13	11-Jun-14
Perkins dryland	2013-2014	11-Oct-13	17-Jun-14

Table 2. Monthly rainfall, average temperature, relative humidity, and 15-yr averages (1997-2013) for all site-years.

Month	Lahoma			Chickasha		Stillwater		Perkins	
	2012-13	2013-14	15-yr	2013-14	15-yr	2013-14	15-yr	2013-14	15-yr
	Precipitation								
	mm								
October	2	35	77	12	90	26	71	37	75
November	13	34	35	37	38	41	45	30	49
December	7	16	32	7	35	16	37	22	38
January	9	1	21	1	39	2	33	3	38
February	100	11	38	9	40	10	42	11 (38†)	37
March	14	11	62	36	61	31	73	28 (29)	72
April	82	5	76	64	89	21	99	34 (59)	90
May	92	57	81	40	91	17	113	41 (152)	123
Total‡	319	169	422	207	483	164	514	206 (278)	522
	Temperature								
	C°								
October	15.0	14.9	15.3	16.3	16.1	15.5	15.8	15.7	16.2
November	10.4	7.0	8.7	8.2	10.0	7.9	9.8	8.2	10.1
December	3.8	-0.2	2.2	0.7	3.8	0.8	3.5	1.2	3.8
January	2.9	0.9	1.9	1.3	3.6	1.9	3.0	2.0	3.3
February	3.2	0.4	4	2.4	5.9	1.9	5.2	2.3	5.5
March	7.1	6.3	9.1	8.0	11.0	7.6	10.6	7.7	10.6
April	10.8	14.5	14.2	15.7	15.8	15.6	15.7	15.7	15.6
May	18.4	21.1	19.8	21.1	21.0	21.4	20.6	21.3	20.6
	Relative humidity								
	%								
October	57	69	68	72	68	72	69	73	71
November	59	68	70	66	67	66	68	70	70
December	62	74	73	76	70	76	70	79	72
January	67	57	70	53	68	53	68	53	70
February	71	69	71	64	67	65	67	68	71
March	67	61	70	59	65	59	64	61	68
April	73	55	70	55	65	55	65	60	68
May	74	57	71	62	70	66	71	63	71

† Irrigation amount are shown in parenthesis

‡ Winter wheat growing season, OK (October- May)

Table 3. Wheat freeze damage injury measured 11 April 2014 at Stillwater, OK.

Sample†	Total wheat spikes	Freeze damaged spikes	% injury
1	31	5	16
2	34	7	21
3	26	5	19
4	23	4	17
5	28	2	7
6	25	4	16
7	29	6	21
8	32	5	16
Total	228	38	17

† Two samples were randomly chosen from each block

Table 4. Analysis of variance of fixed effects of normalized difference vegetative index (NDVI) at each site during the 2012-2013 and 2013-2014 wheat growing seasons.

	2013	2014				
Source of variation	Lahoma	Lahoma	Stillwater	Chickasha	Perkins irrigated	Perkins dryland
Fungicide (F)	*	NS	**	NS	NS	*
N Source (S)	NS	NS	NS	NS	NS	NS
N Rate (R)	***	NS	NS	***	**	NS
F X S	NS	NS	NS	*	NS	NS
F X R	*	NS	NS	NS	NS	NS
S X R	NS	NS	NS	NS	NS	NS
F X S X R	NS	NS	NS	NS	NS	NS

*, **, and *** Significant at $P = 0.05$, $P < 0.01$, and $P < 0.001$, respectively
NS Non-significant

Table 5. Average relative humidity, average temperature, and wind speed at the day of treatment application for Lahoma in 2012-2013, and Lahoma, Chickasha, Stillwater, and Perkins in the 2013-2014 wheat growing season.

Location	Date of treatment application	Relative humidity average	Temperature average	Wind speed
		%	C °	m s^{-1}
Lahoma 2012-13	5/6/2013	75	14	2
Lahoma	5/2/2014	34	14	3
Chickasha	4/24/2014	55	18	5
Stillwater	4/25/2014	49	23	6
Perkins Dryland	4/28/2014	60	19	6
Perkins Irrigated	4/27/2014	42	16	6

Table 6. Analysis of variance of fixed effects of grain yield at each site during the 2012-2013 and 2013-2014 wheat growing seasons.

	2013	2014				
Source of variation	Lahoma	Lahoma	Stillwater	Chickasha	Perkins irrigated	Perkins dryland
Fungicide (F)	NS	NS	NS	NS	*	*
N Source (S)	NS	NS	NS	NS	NS	NS
N Rate (R)	NS	NS	NS	NS	NS	NS
F X S	NS	NS	NS	*	NS	NS
F X R	NS	NS	NS	NS	NS	NS
S X R	NS	NS	NS	NS	NS	NS
F X S X R	NS	NS	NS	NS	NS	NS

* Significant at $P = 0.05$
NS Non-significant

Table7. Analysis of variance of fixed effects of grain protein content at each site during the 2012-2013 and 2013-2014 wheat growing seasons.

	2013	2014				
Source of Variation	Lahoma	Lahoma	Stillwater	Chickasha	Perkins irrigated	Perkins dryland
Fungicide (F)	**	NS	NS	**	NS	*
N Source (S)	NS	NS	NS	NS	NS	NS
N Rate (R)	NS	**	NS	NS	**	**
F X S	NS	NS	NS	NS	NS	*
F X R	NS	NS	NS	*	NS	NS
S X R	NS	NS	NS	NS	NS	NS
F X S X R	NS	NS	NS	**	NS	NS

* and ** Significant at $P = 0.05$ and $P < 0.01$
NS Non-significant

Table 8. Analysis of variance of fixed effects of test weight at each site during 2012-2013 and 2013-2014 wheat growing season.

	2013	2014				
Source of variation	Lahoma	Lahoma	Stillwater	Chickasha	Perkins irrigated	Perkins dryland
Fungicide (F)	***	NS	***	NS	NS	**
N Source (S)	NS	NS	NS	*	NS	NS
N Rate (R)	NS	NS	NS	NS	NS	NS
F X S	NS	NS	NS	NS	NS	NS
F X R	NS	NS	NS	*	NS	NS
S X R	NS	NS	NS	NS	NS	NS
F X S X R	NS	NS	NS	*	NS	NS

*, **, and *** Significant at $P = 0.05$, $P < 0.01$, and $P < 0.001$, respectively.
NS Non-significant

Table 9. Analysis of variance of fixed effects of 100-kernel weight at each site during the 2012-2013 and 2013-2014 wheat growing seasons.

	2013	2014				
Source of variation	Lahoma	Lahoma	Stillwater	Chickasha	Perkins irrigated	Perkins dryland
Fungicide (F)	NS	NS	NS	NS	*	NS
N Source (S)	NS	NS	NS	NS	NS	NS
N Rate (R)	NS	NS	NS	NS	NS	NS
F X S	NS	NS	NS	*	NS	NS
F X R	NS	NS	NS	NS	NS	NS
S X R	NS	NS	NS	NS	NS	NS
F X S X R	*	NS	NS	NS	NS	NS

* Significant at P = 0.05
NS Non-significant

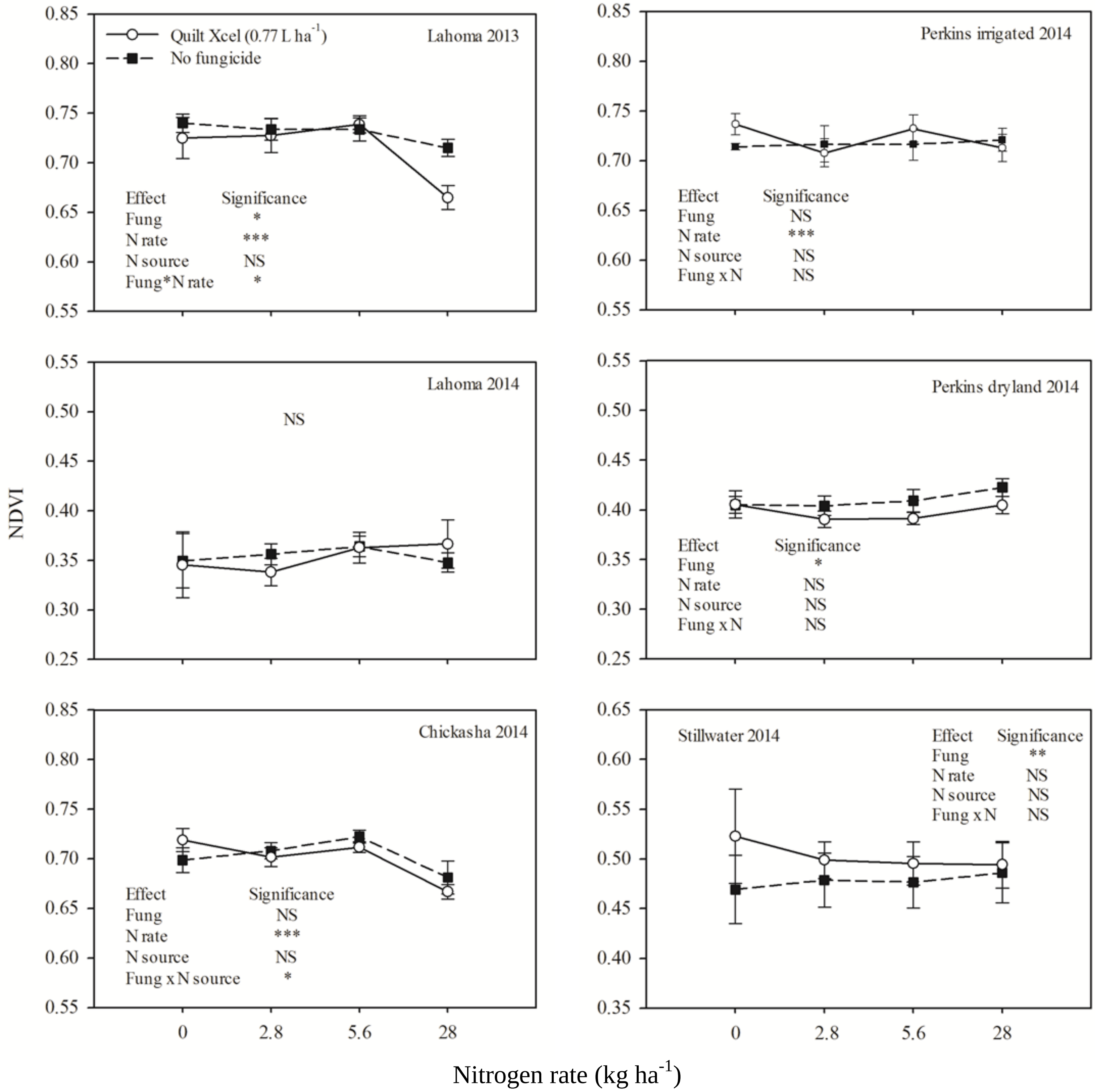

Figure 1.Mean normalized difference vegetative index (NDVI) measured 10 days after treatment application via GreenSeeker sensor as a function of nitrogen (N) rate (0, 2.8, 5.6, or 28 kg ha^{-1}) with and without foliar fungicide (0.77 L ha^{-1} of Quilt Xcel) at Lahoma in 2012-2013 and Perkins Irrigated, Lahoma, Perkins dryland, Chickasha, and Stillwater in 2013-2014. Asterisks indicate statistical significance at *** *P* <0.001; ** *P* <0.01; * *P* = 0.05; NS, non-significant. Vertical errors bars indicated standard error of the mean. Values are averages pooled over N source.

Figure 2. Wheat leaf burn observed approximately ten days after treatment application at Perkins under irrigated conditions during the 2013-2014 wheat growing season.

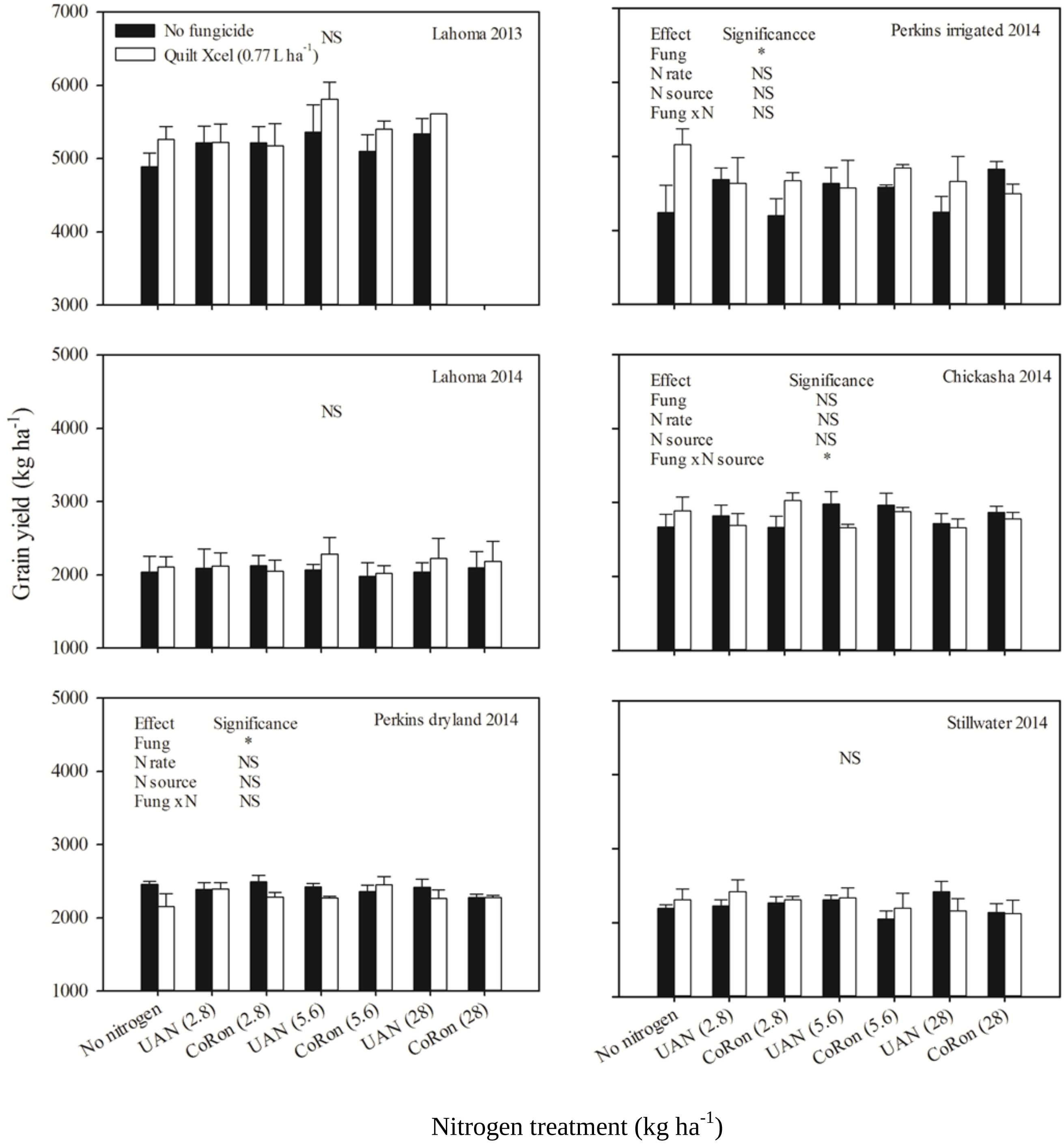

Figure 3. Wheat grain yield (kg ha^{-1}) as affected by nitrogen rate (0, 2.8, 5.6, or 28 kg ha^{-1}), nitrogen source (CoRon or UAN) with and without foliar fungicide (0.77 L ha^{-1} of Quilt Xcel) at Lahoma in 2012-2013 and at Perkins irrigated, Lahoma, Chickasha, Perkins dryland, and Stillwater in 2013-2014. The treatment CoRon at 28 kg ha^{-1} was not included during the 2013 study year. Asterisks indicate statistical significance at * *P* = 0.05; NS, non-significant. Vertical errors bars indicated standard error of the mean.

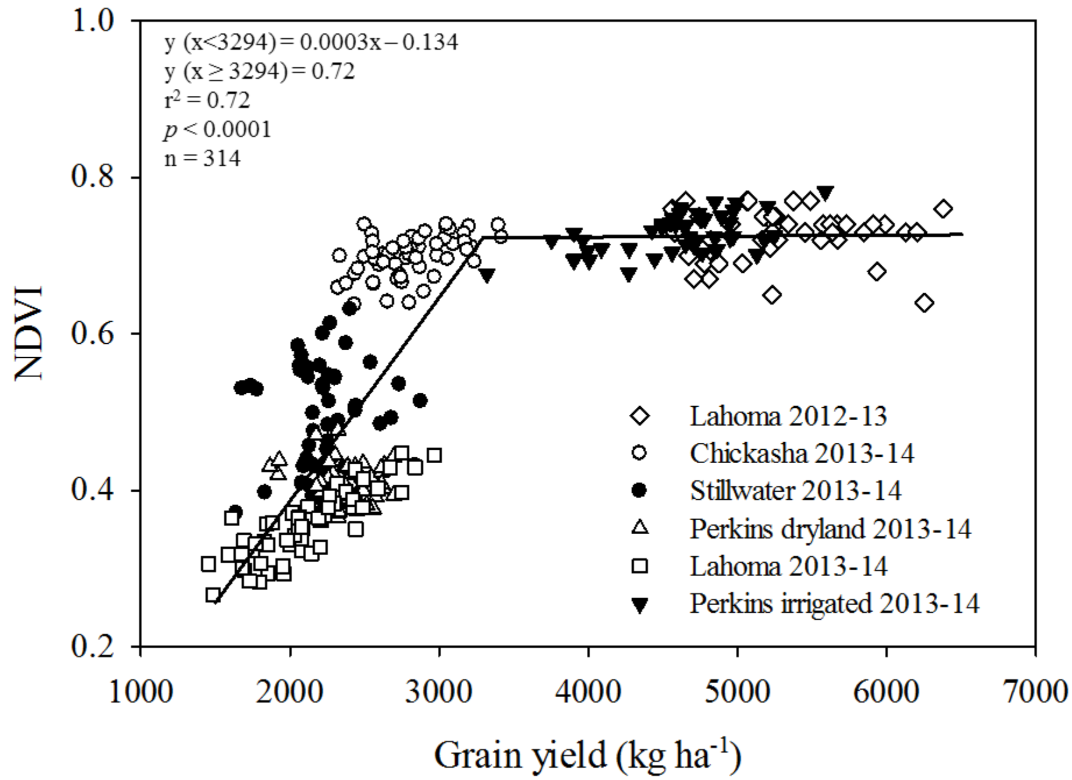

Figure 4. Linear-plateau regression of grain yield (kg ha^{-1}) and normalized difference vegetative index (NDVI) obtained via GreenSeeker sensor taken approximately 10 days after treatment applications in the 2012-2013 and 2013-2014 winter wheat growing season at the six site-years across central Oklahoma.

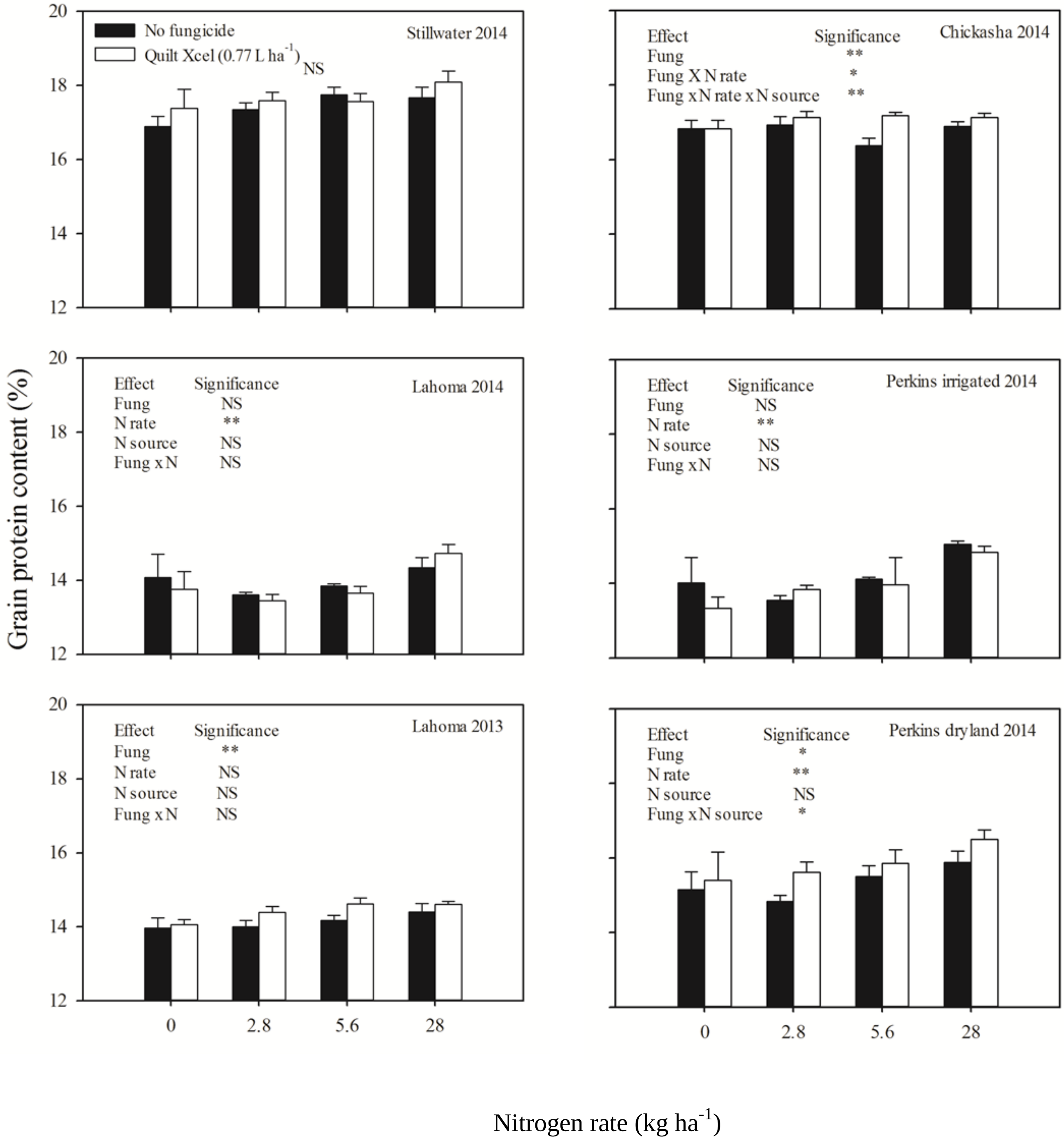

Figure 5. Wheat grain protein content (%) as affected by nitrogen rate (0, 2.8, 5.6, or 28 kg ha^{-1}) with and without foliar fungicide (0.77 L ha^{-1} of Quilt Xcel) at Lahoma in 2012-2013 and Stillwater, Chickasha, Lahoma, Perkins irrigated, and Perkins dryland in 2013-2014. Asterisks indicate statistical significance at ** *P* <0.01; * *P* = 0.05; NS, non-significant. Vertical error bars indicate standard error of the mean.

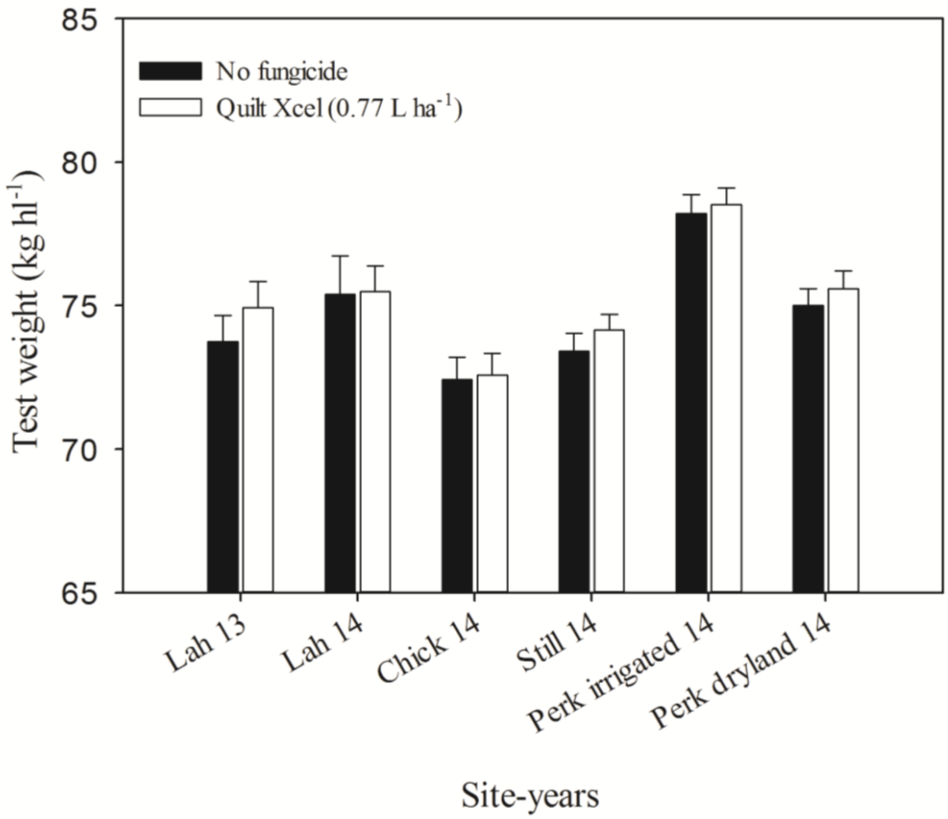

Figure 6. Wheat test weight (kg hl^{-1}) as affected by the application of 0.77 L ha^{-1} Quilt Xcel at anthesis (GS Feekes 10.5) at Lahoma in 2012-2013 and at Lahoma, Chickasha, Stillwater, Perkins irrigated, and Perkins dryland in the 2013-2014 wheat growing season. Vertical error bars indicate standard deviation of the mean.

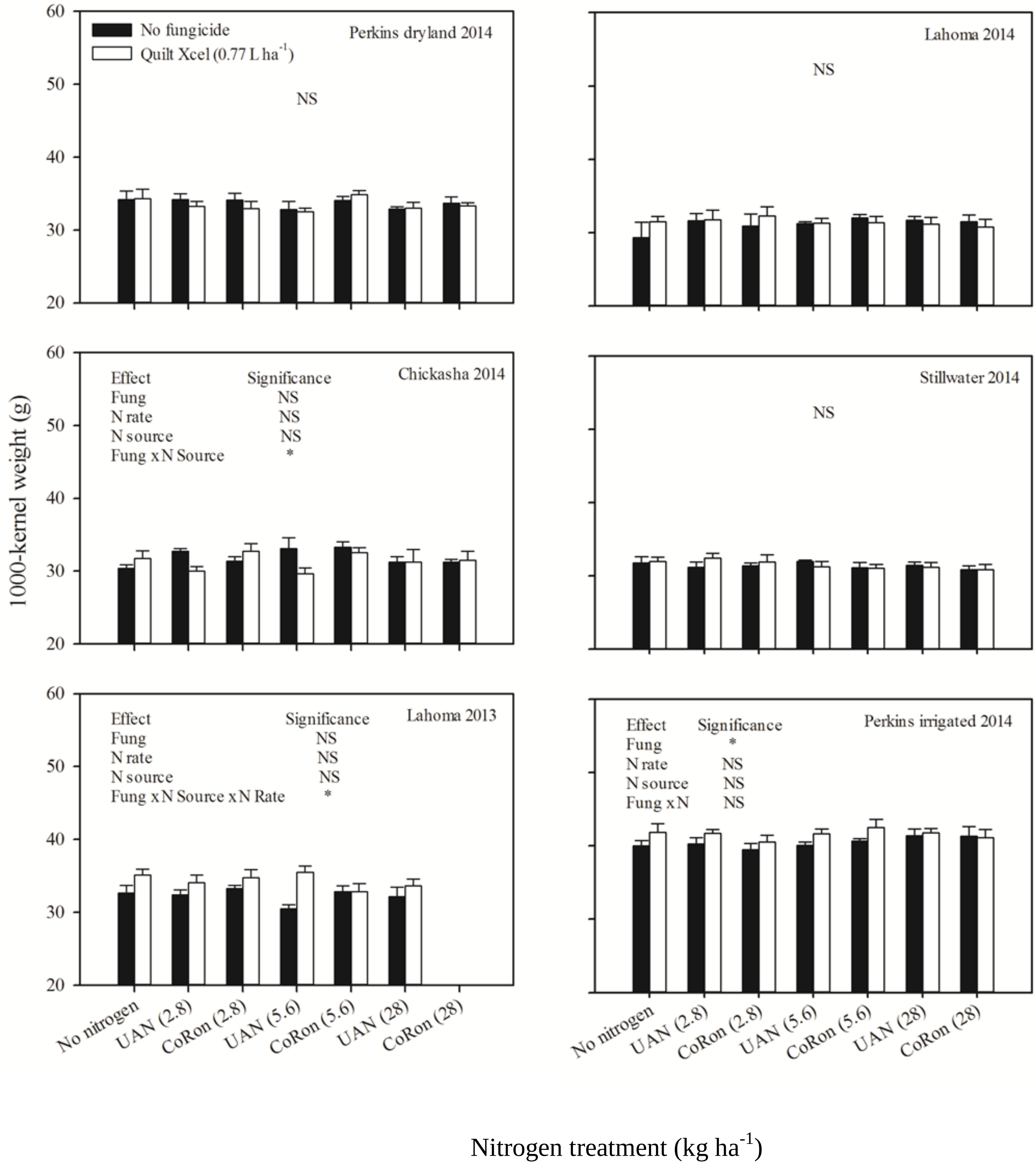

Figure 7. 1000-kernel weight (g) as affected by nitrogen (N) rate (0, 2.8, 5.6, or 28 kg ha^{-1}), N source (CoRon or UAN) with and without foliar fungicide (0.77 L ha^{-1} of Quilt Xcel) at Lahoma in 2012-2013 and at Perkins irrigated, Lahoma, Chickasha, Perkins dryland, and Stillwater in 2013-2014. The treatment CoRon at 28 kg ha^{-1} was not included during the 2013 study year. Asterisks indicate statistical significance at * P = 0.05; NS, non-significant. Vertical errors bars indicated standard error of the mean.

APPENDICES

Table A1. Treatments structure

Treatment	Fungicide (L ha^{-1})	Nitrogen source	Nitrogen rate (kg N ha^{-1})
1	0	No	0
2	0	UAN	2.8
3	0	UAN	5.6
4	0	UAN	28
5	0	CoRon	2.8
6	0	CoRon	5.6
7†	0	CoRon	28
8	0.77	No	0
9	0.77	UAN	2.8
10	0.77	UAN	5.6
11	0.77	UAN	28
12	0.77	CoRon	2.8
13	0.77	CoRon	5.6
14‡	0.77	CoRon	28

† and ‡ Treatments applied only during 2013-2014 growing season

Table A2. Effects of fungicide and nitrogen source and rate on average Normalized Difference Vegetative Index (NDVI) measured approximately 10 days after treatment application at field sites during the 2012-2013 and 2013-2014 growing season.

Nitrogen		Wheat NDVI			
Source	Rate (kg ha^{-1})	No fungicide	Fungicide	No fungicide	Fungicide
		kg hl^{-1}			
		Lahoma 2013		Lahoma 2014	
Control		0.74 a	0.73 a	0.35	0.35
UAN	2.8	0.74 a	0.72 a	0.36	0.34
UAN	5.6	0.73 a	0.74 a	0.36	0.38
UAN	28	0.72 a	0.67 b	0.35	0.37
CoRon	2.8	0.73 a	0.73 a	0.35	0.34
CoRon	5.6	0.74 a	0.74 a	0.36	0.35
CoRon	28	NA	NA	0.34	0.37
		Chickasha 2014		Stillwater 2014	
Control		0.70 abc	0.72 ab	0.44 b	0.52 a
UAN	2.8	0.71 abc	0.69 bc	0.47 b	0.53 a
UAN	5.6	0.73 a	0.71 abc	0.46 b	0.51 ab
UAN	28	0.68 cd	0.65 d	0.51 ab	0.50 ab
CoRon	2.8	0.68 cd	0.72 ab	0.49 ab	0.48 ab
CoRon	5.6	0.70 abc	0.72 ab	0.49 ab	0.49 ab
CoRon	28	0.70 abc	0.68 cd	0.46 b	0.49 ab
		Perkins Irrigated 2014		Perkins dryland 2014	
Control		0.70 c	0.74 ab	0.40 abc	0.41 abc
UAN	2.8	0.75 a	0.73 abc	0.40 abc	0.40 abc
UAN	5.6	0.75 a	0.74 ab	0.41 abc	0.39 bc
UAN	28	0.71 bc	0.71 bc	0.44 a	0.42 ab
CoRon	2.8	0.70 c	0.73 abc	0.41 abc	0.38 c
CoRon	5.6	0.74 ab	0.74 ab	0.41 abc	0.39 bc
CoRon	28	0.72 abc	0.71 bc	0.41 abc	0.39 bc

† 0.77 L ha^{-1} of Quilt Xcel
‡ Means followed by the same letter within a site-year are not statistically different at α = 0.05
§ Urea Ammonium Nitrate Solution
¶ Controlled-released Nitrogen product by Helena Chemical

Table A3. Effects of fungicide and nitrogen source and rate on wheat grain yield average at field sites during the 2012-2013 and 2013-2014 growing seasons.

Nitrogen		Wheat grain yield			
Source	Rate (kg ha^{-1})	No fungicide	Fungicide†	No fungicide	Fungicide
		kg ha^{-1}			
		Lahoma 2013		Lahoma 2014	
Control		4891	5265	2041	2111
UAN‡	2.8	5214	5222	2093	2124
UAN	5.6	5363	5809	2068	2282
UAN	28	5340	5613	2040	2228
CoRon§	2.8	5219	5174	2125	2053
CoRon	5.6	5100	5405	1981	2020
CoRon	28	NA	NA	2099	2187
		Chickasha 2014		Stillwater 2014	
Control		2671	2888	2179	2309
UAN	2.8	2822	2692	2225	2419
UAN	5.6	2982	2658	2312	2333
UAN	28	2718	2658	2418	2162
CoRon	2.8	2663	3028	2269	2310
CoRon	5.6	2968	2878	2053	2196
CoRon	28	2869	2781	2138	2124
		Perkins Irrigated 2014		Perkins dryland 2014	
Control		4244 bc¶	5150 a	2461 a	2157 b
UAN	2.8	4708 abc	4598 abc	2391 ab	2393 ab
UAN	5.6	4714 abc	4533 abc	2424 a	2271 ab
UAN	28	4247 bc	4650 abc	2416 a	2264 ab
CoRon	2.8	4203 c	4633 abc	2495 a	2280 ab
CoRon	5.6	4593 abc	4842 ab	2360 ab	2454 a
CoRon	28	4827 ab	4529 abc	2276 ab	2277 ab

† 0.77 kg ha^{-1} of Quilt Xcel
‡ Urea Ammonium Nitrate Solution
§ Controlled-released Nitrogen product by Helena Chemical
¶ Means followed by the same letter within a site-year are not statistically different at $\alpha = 0.5$

Table A4. Effects of fungicide and nitrogen source and rate on wheat grain protein content average (%) at field sites during the 2012-2013 and 2013-2014 wheat growing seasons

Nitrogen		Wheat grain protein content			
Source	Rate (kg ha^{-1})	No fungicide	Fungicide†	No fungicide	Fungicide
		%			
		Lahoma 2013		Lahoma 2014	
Control		14.0 c‡	14.1 bc	14.1 bcd	13.8 cd
UAN§	2.8	14.0 c	14.5 abc	13.7 cd	13.6 d
UAN	5.6	14.3 abc	14.6 ab	13.8 cd	13.6 d
UAN	28	14.4 abc	14.6 a	14.1 bcd	14.8 ab
CoRon¶	2.8	14.0 c	14.3 abc	13.6 d	13.3 d
CoRon	5.6	14.0 c	14.7 a	13.9 bcd	13.7 cd
CoRon	28	NA	NA	14.6 abc	15.1 a
		Chickasha 2014		Stillwater 2014	
Control		16.9 bcd	16.8 bcd	17.0	17.4
UAN	2.8	16.6 cde	17.5 a	17.4	17.4
UAN	5.6	16.5 de	17.2 ab	17.6	17.5
UAN	28	16.9 bcd	17.1 abc	17.4	17.9
CoRon	2.8	17.3 ab	16.8 bcde	17.3	17.8
CoRon	5.6	16.3 e	17.2 ab	17.9	17.6
CoRon	28	16.9 bcd	17.2 ab	18.0	18.3
		Perkins Irrigated 2014		Perkins dryland 2014	
Control		14.0 abc	13.7 c	15.2 cd	15.4 cd
UAN	2.8	14.0 abc	14.2 abc	14.6 d	15.7 abcd
UAN	5.6	14.6 abc	14.8 ab	15.3 cd	16.6 ab
UAN	28	15.3 a	15.1 ab	15.7 abcd	16.8 a
CoRon	2.8	13.2 c	13.9 abc	15.1 cd	15.5 bcd
CoRon	5.6	14.7 abc	13.2 c	15.7 abcd	15.1 cd
CoRon	28	14.8 ab	15.3 a	16.0 abc	16.2 abc

† 0.77 kg ha^{-1} of Quilt Xcel
‡ Means followed by the same letter within a site-year are not statistically different at $\alpha = 0.05$
§ Urea Ammonium Nitrate Solution
¶ Controlled-released Nitrogen product of Helena Chemical

Table A5. Effects of fungicide and nitrogen source and rate on wheat test weight average (kg hl^{-1}) at field sites during the 2012-2013 and 2013-2014 wheat growing seasons.

Nitrogen		Wheat test weight			
Source	Rate (kg ha^{-1})	No fungicide	Fungicide†	No fungicide	Fungicide
		kg hl^{-1}			
		Lahoma 2013		Lahoma 2014	
Control		73.7 cd‡	75.2 a	74.1	75.1
UAN§	2.8	73.4 d	74.9 ab	75.6	75.5
UAN	5.6	74.3 abcd	75.5 a	75.9	75.6
UAN	28	73.8 bcd	74.8 abc	75.7	75.3
CoRon¶	2.8	73.8 bcd	74.8 abc	75.1	75.9
CoRon	5.6	73.5 d	74.5 abcd	75.6	75.6
CoRon	28	NA	NA	75.8	75.3
		Chickasha 2014		Stillwater 2014	
Control		71.9 cd	72.7 abc	73.4 bcd	74.4 a
UAN	2.8	72.5 bcd	72.6 bcd	73.3 cd	74.4 a
UAN	5.6	72.5 bcd	71.8 d	73.1 d	74.3 a
UAN	28	72.2 cd	72.4 cd	73.4 bcd	74.1 ab
CoRon	2.8	71.8 d	73.4 a	73.5 bcd	74.0 abc
CoRon	5.6	73.2 ab	72.5 bcd	73.5 bcd	74.0 abc
CoRon	28	72.7 abc	72.6 bcd	73.5 bcd	73.8 abcd
		Perkins Irrigated 2014		Perkins dryland 2014	
Control		77.8	78.2	75.3 abcd	75.8 ab
UAN	2.8	78.0	78.5	75.4 abcd	75.7 abc
UAN	5.6	78.4	79.1	74.8 cd	75.3 abcd
UAN	28	77.9	78.6	74.9 bcd	75.3 abcd
CoRon	2.8	78.2	78.4	75.2 bcd	75.6 abc
CoRon	5.6	78.4	78.5	75.1 bcd	76.1 a
CoRon	28	78.9	78.4	74.7 d	75.6 abc

† 0.77 kg ha^{-1} of Quilt Xcel
‡ Means followed by the same letter within a site-year are not statistically different at $\alpha = 0.05$
§ Urea Ammonium Nitrate Solution
¶ Controlled-released Nitrogen product of Helena Chemical

Table A6. Effects of fungicide, nitrogen source and rate on wheat 100-kernel weight (g) at field sites during the 2012-2013 and 2013-2014 wheat growing seasons

Nitrogen		100-kernel weight			
Source	Rate (kg ha^{-1})	No fungicide	Fungicide†	No fungicide	Fungicide
		g			
		Lahoma 2013		Lahoma 2014	
Control		3.2 c‡	3.5 ab	2.9	3.2
UAN§	2.8	3.2 c	3.4 abc	3.2	3.2
UAN	5.6	3.0 d	3.6 a	3.1	3.1
UAN	28	3.1 cd	3.3 bc	3.2	3.1
CoRon¶	2.8	3.3 bc	3.5 ab	3.1	3.3
CoRon	5.6	3.2 c	3.2 c	3.2	3.2
CoRon	28			3.2	3.1
		Chickasha 2014		Stillwater 2014	
Control		3.1 abc	3.1 abc	3.2	3.2
UAN	2.8	3.2 ab	3.0 bc	3.1	3.3
UAN	5.6	3.3 a	2.9 c	3.2	3.1
UAN	28	3.1 abc	3.1 abc	3.2	3.2
CoRon	2.8	3.1 abc	3.2 ab	3.1	3.2
CoRon	5.6	3.3 a	3.2 ab	3.1	3.1
CoRon	28	3.1 abc	3.1 abc	3.1	3.1
		Perkins Irrigated 2014		Perkins dryland 2014	
Control		4.0 bc	4.2 ab	3.5	3.5
UAN	2.8	4.1 abc	4.2 ab	3.4	3.3
UAN	5.6	4.0 bc	4.2 ab	3.3	3.3
UAN	28	4.1 abc	4.2 ab	3.3	3.3
CoRon	2.8	3.9 c	4.1 abc	3.4	3.3
CoRon	5.6	4.1 abc	4.3 a	3.4	3.5
CoRon	28	4.1 abc	4.1 abc	3.4	3.4

† 0.77 kg ha^{-1} of Quilt Xcel
‡ Means followed by the same letter within a site-year are not statistically different at $\alpha = 0.05$
§ Urea Ammonium Nitrate Solution
¶ Controlled-released Nitrogen product of Helena Chemical

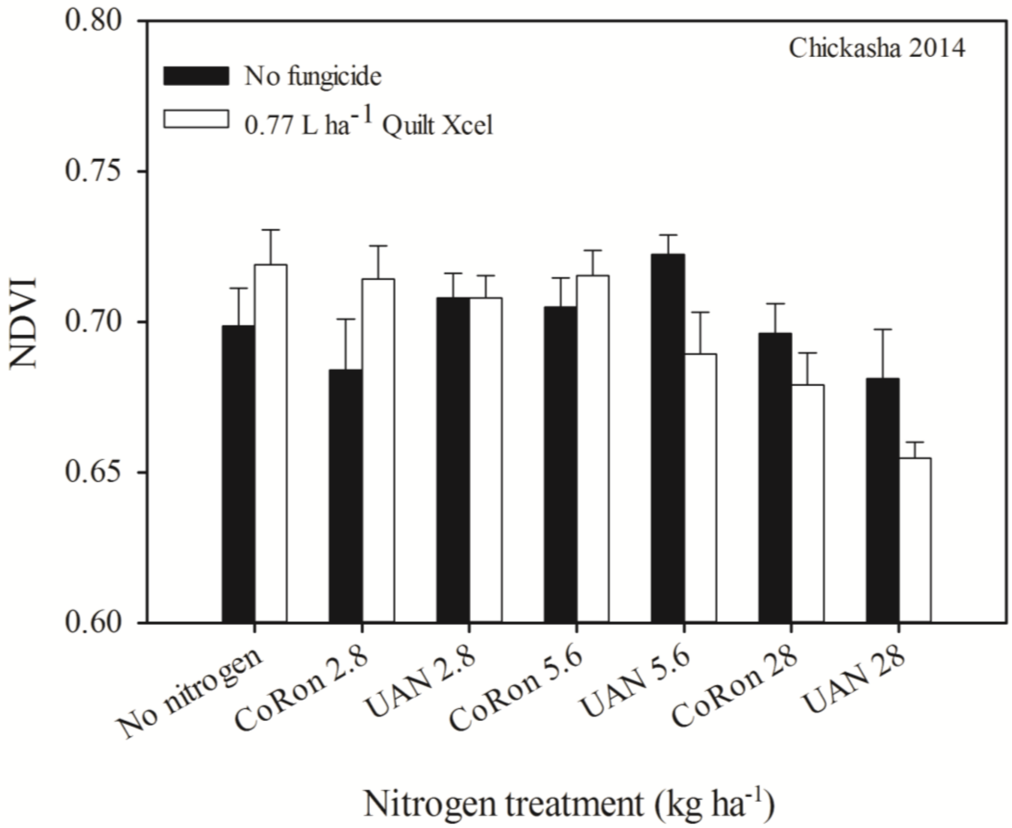

Figure A1. Mean normalized difference vegetative index (NDVI) measured approximately ten days after treatment application obtained via GreenSeeker sensor as a function of nitrogen rate (0,2.8, 5.6, or 28 kg ha^{-1}), nitrogen source (CoRon or UAN) with and withou foliar fungicide (0.77 L ha^{-1} of Quilt Xcel) at Chickasha in the 2013-2014 growing season. Nitrogen rate and interaction between foliar fungicide and nitrogen source were significant at $P < 0.001$ and $P = 0.05$, respecitvely. Vertical erros bars indicated standard error of the mean.

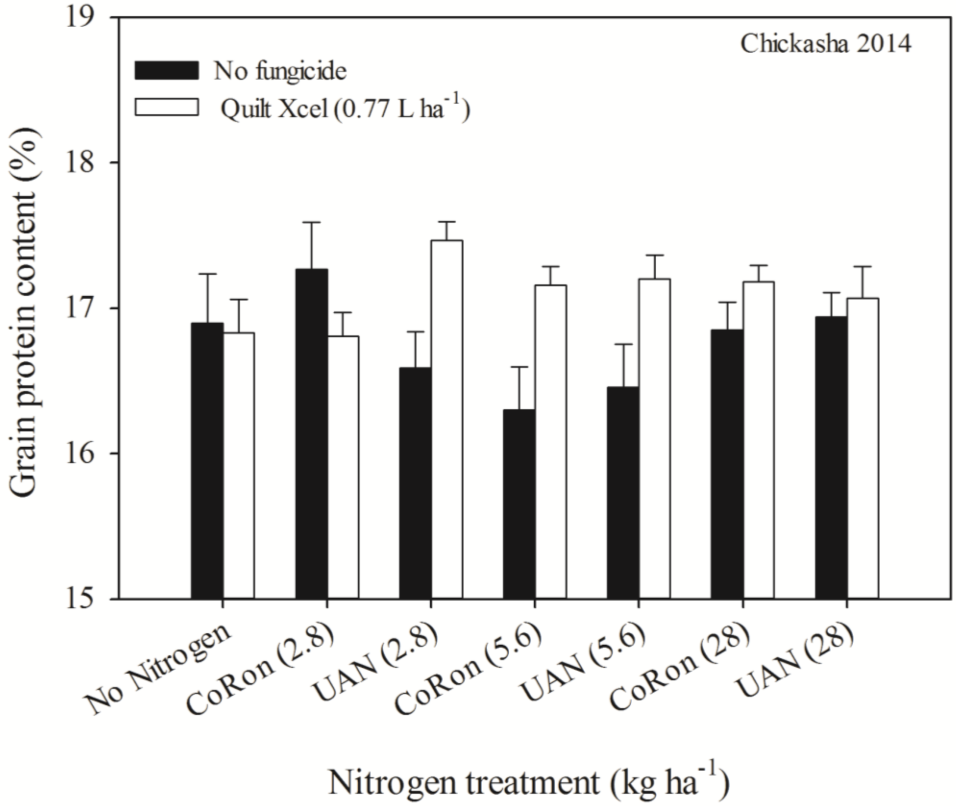

Figure A2. Wheat grain protein content (%) as affected by nitrogen rate (0, 2.8, 5.6, or 28 kg ha^{-1}), nitrogen source (CoRon or UAN) with and without foliar fungicide (0.77 L ha^{-1} of Quilt Xcel) at Chickasha in the 2013-2014 growing season. The interaction between foliar fungicide, nitrogen source, and nitrogen rate was significant at $P = 0.01$. Vertical errors bars indicate standard error of the mean.

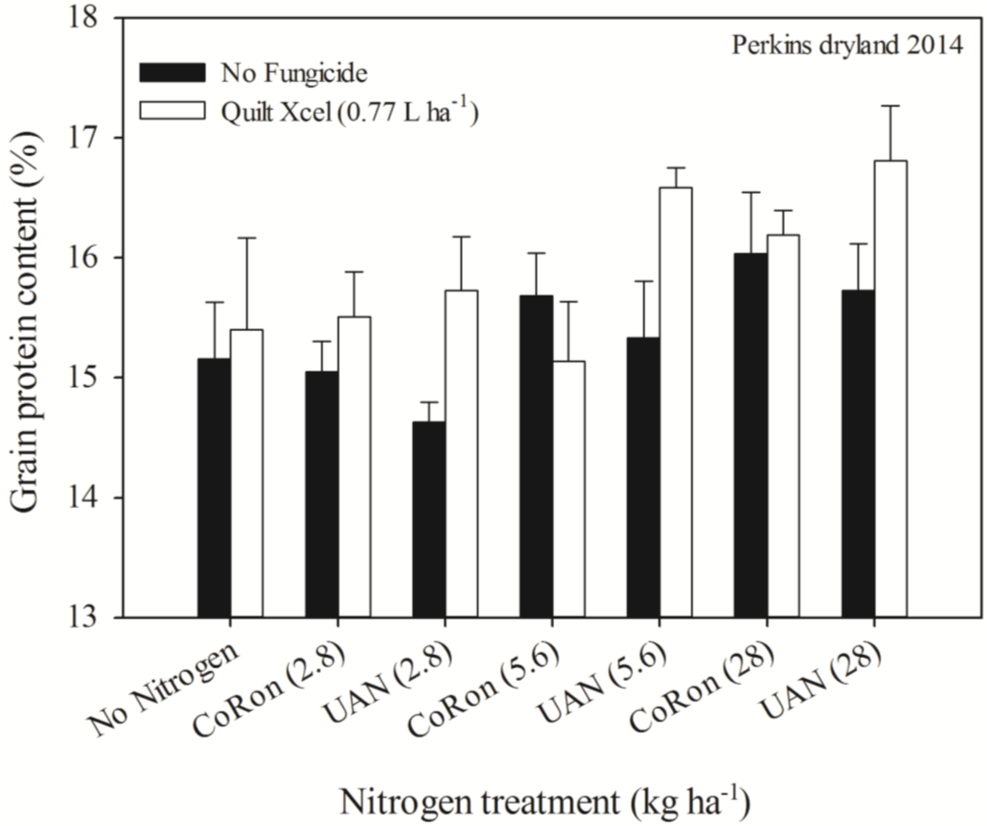

Figure A3. Wheat grain protein content (%) as affected by nitrogen rate (0, 2.8, 5.6, or 28 kg ha^{-1}), nitrogen source (CoRon or UAN) with and without foliar fungicide (0.77 L ha^{-1} of Quilt Xcel) at Perkins dryland in the 2013-2014 growing season. Foliar fungicide, nitrogen rate, and the interaction between foliar fungicide and nitrogen source were significant at $P = 0.05$, $P < 0.01$, and $P = 0.05$, respectively. Vertical errors bars indicate standard error of the mean.

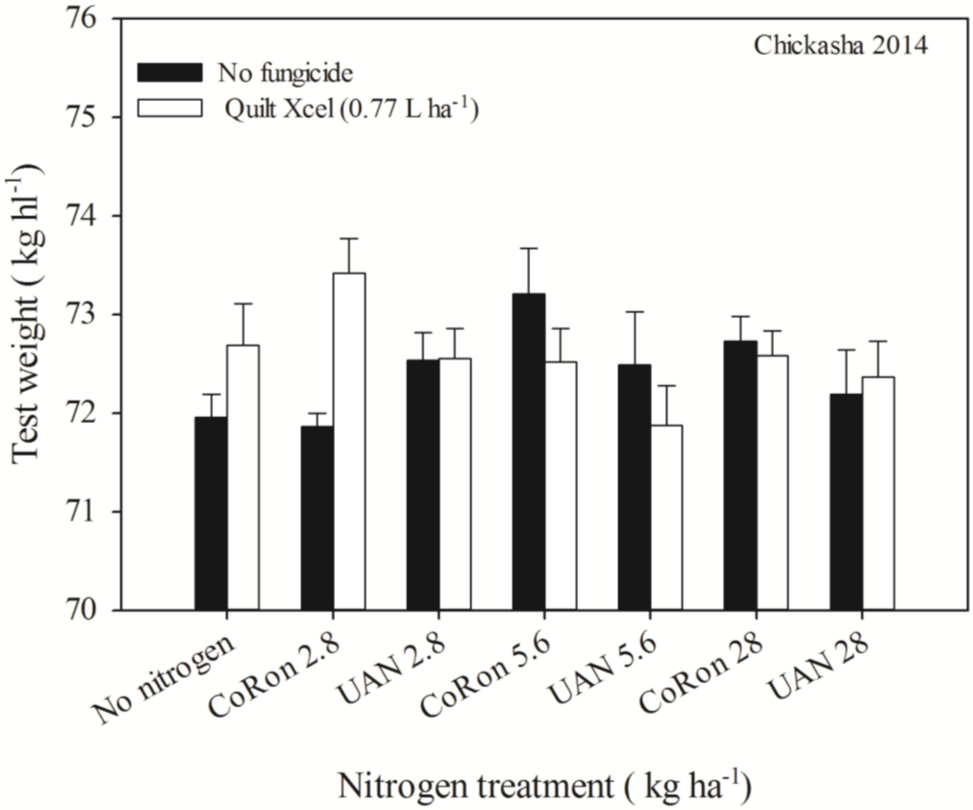

Figure A4. Wheat test weight (kg hl^{-1}) as affected by nitrogen rate (0, 2.8, 5.6, or 28 kg ha^{-1}), nitrogen source (CoRon or UAN) with and without foliar fungicide (0.77 L ha^{-1} of Quilt Xcel) at Chickasha in the 2013-2014 growing season. The interaction between foliar fungicide, nitrogen source, and nitrogen rate was significant at $P = 0.05$. Vertical errors bars indicate standard error of the mean.

VITA

Giovana Cruppe

Candidate for the degree of

Master of Science

Thesis: HARD RED WINTER WHEAT GRAIN YIELD AND QUALITY RESPONSE TO LATE-SEASON NITROGEN FERTILIZER AND FOLIAR FUNGICIDE

Major Field: Plant and Soil Sciences

Biographical:

Education:

Completed the requirements for the Master of Science in Plant and Soil Sciences at Oklahoma State University, Stillwater, Oklahoma. May 2015.

Completed the requirements for the Bachelor of Science in Agronomy at Universidade Estadual Paulista “Julio de Mesquita Filho”, Botucatu, Sao Paulo, Brazil. December 2010.

Experience:

Research scholar at Oklahoma State University in the department of Plant and Soil Sciences, Stillwater, Oklahoma. April – December 2012.

Employed by Dow AgroSciences as technical field assistant, Campo Novo do Parecis, Mato Grosso, Brazil. August 2011-April 2012.

Internship at Ohio State University in the department of Horticulture and Crop Science, Columbus, Ohio. July – November 2010.

Professional Memberships:

American Society of Agronomy 2013– Present
Crop Science Society of America 2013 – Present
Soil Science Society of America 2013 – Present