Plant population and fungicide economically reduce winter wheat yield gap in Kansas

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Abstract

Winter wheat (*Triticum aestivum* L.) water limited yield potential in Kansas averages 5.2 Mg ha^{-1}; however, state-level yields rarely surpassed 3.4 Mg ha^{-1}. Our objective was to quantify the contribution of individual management practices to reduce wheat yield gaps (YG) economically. An incomplete factorial treatment structure established in a randomized complete block design with six replications was used to evaluate 14 treatments during two years in Manhattan, Belleville, and Hutchinson Kansas. Sites were combined based on tillage practice, growing region in Kansas, and disease pressure. Thus, Manhattan had low disease pressure, was no-tilled, and in eastern Kansas for 2015-16 and 2016-17 (two site years). Meanwhile, Belleville and Hutchinson had high disease pressure, were conventionally tilled, and in central Kansas for 2015-16 and 2016-17 (four site years). We individually added six treatments to a farmer's practice control (FP) or removed from a water-limited yield control (Y_w), which received all treatments. Practices were additional split-nitrogen (N), sulfur (S), chloride (Cl), increased plant population, foliar fungicide, and plant growth regulator (PGR). Percent YG was calculated by block and site-year using the Y_w as reference for potential yield. Orthogonal contrasts indicated yield under no-till which had low disease pressure increased from the FP by the full Y_w (+0.37 Mg ha^{-1}), but also by the individual practices split-N (+0.28 Mg ha^{-1}), S (+0.26 Mg ha^{-1}), increased plant population (+0.36 Mg ha^{-1}), and fungicide (+0.18 Mg ha^{-1}). In the conventional till which had high disease pressure, wheat yield was increased by 1.18 Mg ha^{-1} from the Y_w and by 1.44 Mg ha^{-1} from the fungicide. The Y_w and split-N increased grain protein concentration in no-till and conventional-till on average by 9 g kg^{-1} and 12 g kg^{-1}, respectively. Across all inputs, orthogonal contrasts indicated that the FP yield gap was 8% in no-till which had low disease pressure. Likewise, the orthogonal contrasts indicated that across individual treatments the YG

was reduced by split-N (6%), S (5%), Cl (3%), increased plant population (8%), and fungicide (4%). Meanwhile, orthogonal contrasts indicated that the FP yield gap was 20% across all inputs and across individual inputs reduced to 5% from fungicide under conventional-till which had high disease pressure. Fungicide increased net return (+\$106.57 ha^{-1}) under conventional-till which had high disease pressure, and increased plant population under no-till which had low disease pressure (+\$36.65 ha^{-1}). While a high-cost input (i.e. fungicide) only economically reduced YG greater than 20%; however, a low-cost input (i.e. increased plant population) economically reduced YG less than 20%.

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Chapter 1 - Review of Literature

Wheat Production Overview

Wheat (*Triticum aestivum* L.) is among the most important staple crops in the world. During the period of 2005-2014, wheat was the crop with the largest harvested area in the world with a total of 219 million hectares (FAO, 2014a). This total harvested area compares to 166 million hectares harvested for maize (*Zea mays* L.) and 160 million hectares for rice (*Oryza sativa* L.) (FAO, 2014a). During these ten years, average total wheat production in the world was approximately 667 million metric tons, ranking fourth among production crops behind maize (852 million metric tons), rice (694 million metric tons), and tuber and root (767 million metric tons) (FAO, 2014a). China was the largest producer of wheat, with an average of 115 million metric tons (i.e. 17% of global production), followed by India with 82 million metric tons (12%), United States with 58 million metric tons (9%), and Russia with 51 million metric tons , which corresponded to 8% of global wheat production (FAO, 2014a).

The United States produces six classes of wheat in different parts of the country: hard red winter, hard red spring, soft red winter, soft white, hard white, and durum (*Triticum durum* Desf.). In 2016, the United States produced 63 million metric tons from a harvested area of 17.5 million hectares and an average yield of 3.5 Mg ha^{-1} across all wheat classes (USDA-NASS, 2017a). Hard red winter wheat had the largest production among all the wheat classes, adding to 29 million metric tons. This wheat class is primarily grown in Texas, Oklahoma, Kansas, Nebraska, Montana, and Colorado. Total soft red winter wheat production was 9 million metric tons, with the crop primarily grown in Ohio, Kentucky, and Michigan; total soft white winter wheat production was 5.9 million metric tons, primarily produced in Washington and; total spring wheat production was 13.4 million metric tons, primarily cultivated in North and South

Dakota, and Minnesota; and durum wheat, which is primarily grown in North Dakota and Montana, totaled 2.8 million metric tons (USDA-NASS, 2017b).

Kansas is the largest hard red winter wheat producing state in the U.S, with an average planted area ranging from 2.9 to 3.9 million hectares and average production ranging between 7.5 and 12.7 million metric tons in the 2008-2017 period (USDA-NASS, 2017a). Still, wheat yields have nearly plateaued in the last 30 years and have not surpassed an average state yield of 3.4 Mg ha $^{-1}$ until the 2015-2016 growing season, when average yield was 3.8 Mg ha^{-1} (USDA-NASS, 2017a). This yield translated into 12.7 million metric tons produced on approximately 3.3 million hectares. The Kansas winter wheat production region can be divided into west, central, and east sub-regions, according the yearly precipitation totals; and in 2015-16 these regions produced 5.2, 6.1, and 0.9 million metric tons of winter wheat, respectively (USDA-NASS, 2016). Likewise, total production was 8.8 million metric tons produced on only 2.8 million hectares with each region producing 3.1(west), 5.2 (central), and 0.5 (east) million metric tons of wheat in 2016-17 (USDA-NASS, 2017c). Although the eastern region adds to the lowest total production of wheat in the state, its great precipitation totals originates the largest yield gap in the state [i.e. 4.2 Mg ha^{-1}, yield gap being defined as the difference between the maximum attainable wheat yield under water-limited conditions and the average farmer yield (Lollato et al., 2017)]. Wheat production is low in this area as more rainfall occurs allowing for the area to be planted to more valuable crops, such as soybean [*Glycine max* (L.) Merr] (USDA-NASS, 2016), which limits the expansion of the wheat area in the region. Meanwhile, the central region is the largest producer of wheat and also has a yield gap ranging between 2.7-3.1 Mg ha^{-1} (Lollato et al., 2017). In other words, current producer yield correspond to approximately 54% of maximum attainable yield. In rainfed growing regions, such as the majority of the wheat growing region in

Kansas, crop yields can be economically improved to 75 to 80% of the maximum attainable yield (Lobell et al., 2009). Thus, wheat yields can potentially be economically improved by approximately 25% through improved agronomic management, and fulfilling this large yield gap can help meet future food demand from a growing global population.

Closing the Yield Gap

By the year 2050, global population will surpass nine billion people, and this population will directly or indirectly consume cereal grain crops such as corn, wheat, and rice (Godfray et al., 2010). Grain production can be increased mainly in two ways: i) economically decreasing yield gaps by making agriculture more efficient in current cultivated land; or ii) expanding the cropland area into native ecosystems, which has many ecological, economic, and humanitarian impacts. As a consequence, agricultural land has only increased approximately 11% globally since the Green Revolution during the 1960-1980 period (Pretty, 2008). The odds of more land being brought into production are low. Thus, increasing the efficiency of current cultivated land is crucial for future food security.

Yield gaps result from both manageable and unmanageable factors. For example, environmental constraints such as temperature, light intensity (radiation efficiency), precipitation total and distribution, soil type, texture and water holding capacity establish a cap on non-irrigated yield potential. Manageable factors, on the other hand, are crucial in ensuring current yields are economically close to their yield potential for a particular growing season at a given location. These include fertilizer management (placement, type, timing, and rate), variety selection, sowing date, seeding rate, control of diseases, weeds, insects, and irrigation management. New technologies, such as precision agriculture, have the potential to allow for reduction fertilizer rates as compared to flat rate applications, which will be important to improve profitability while reducing the environmental footprint (Cassman, 1999). Not only will management strategies be important for reducing the yield gap, but farmer education will play a pivotal role on successful implementation of new technologies, allowing for the realization of any potential economic benefit.

Intensive Wheat Management Systems

Intensive wheat management systems have often been reported as alternatives to increase food production in current cultivated land (Mohamed et al., 1990). Intensification of wheat has shown to produce yields of 8-11 Mg ha^{-1} in Europe, and 3-6 Mg ha^{-1} in the United States (Neumann et al., 2010). Specifically, intensive wheat management of soft red winter wheat resulted in yields of approximately 7.4 Mg ha^{-1} in Virginia (Thomason et al., 2009), and 7.7 Mg ha^{-1} for hard red winter wheat in the U.S. southern Great Plains (Lollato and Edwards, 2015). Intensification of crop production is region-specific, but this approach often consists of applying increased rates of inputs to achieve maximum yields while being profitable and maintaining or improving environmental quality. The location of a specific field will determine the optimal combination of inputs that will result in maximum yields. Several studies have attempted to intensify wheat production, but these were generally focused on maximization of yield response to single inputs rather than their combination. The inputs commonly studied individually in intensified wheat production include fertilizer rates and products, such as N (Baethgen and Alley, 1989; Dick et al., 2016), phosphorus (P) (Kaitibie et al., 2002), potassium (K) (Singh and Sharma, 2001), Cl (Lamond and Leikam, 2002; Mengel et al., 2009), S (Zhao et al., 1999; Riley et al., 2000), in-season fungicide to control fungal foliar diseases (Edwards et al., 2012; Thompson et al., 2014), insecticide seed treatments (Wilde et al., 2001; Royer et al., 2005), and plant growth regulators to reduce plant height and potentially lodging (Nafziger et al., 1986;

Mohamed et al., 1990). Still, limited literature exists on the wheat response to the combination of these practices, and results are often region-specific and inconsistent (Mohamed et al., 1990). Still, evaluation of intensified cropping systems is necessary as implementation of these systems where economically feasible will be needed to increase food production in regions characterized by yield gaps greater than 25%, helping ensure global food security (Cassman, 1999).

In this research, we aim to understand and quantify the partial contribution of major management factors in a systems-approach to wheat yield when grown under FP versus Y_w management, including enhanced fertilization and crop nutrition practices, as well as crop production components.

Enhanced fertilization and crop nutrition practices

Nitrogen

Winter wheat production relies heavily on the supply of N either from the soil or fertilizer produced commercially from the energy-demanding Haber-Bosch procedure. Globally, N fertilizer production increased from 10 million metric tons in 1960 to 87 million metric tons in 2000 (Tilman et al., 2001), helping meet the global demand, which was approximately 110 million metric tons in 2014, with approximately 78 million metric tons consumed as urea (FAO, 2014b). In 2011, the United States consumed 11.5 million metric tons of N fertilizer with 1.5 million metric tons (or 13%) applied to wheat fields. In Kansas, over 94% of the wheat area received N fertilizer for a total of 206,000 metric tons, representing 2% of the total N fertilizer consumed by the United States (USDA-NASS, 2013).

Nitrogen availability for a given crop is affected by the environment (e.g. temperature regime, moisture availability) and soil (e.g. pH, organic matter content, indigenous N content, texture), and world's N use efficiency for cereal crops is extremely low and averages 33% (Raun and Johnson, 1999). Wheat production in Europe and United States can achieve greater N use efficiency [i.e. 50-60% (Powlson et al., 1992; Blankenau and Kuhlmann, 2000; Leikam et al., 2003)]; however, N is highly susceptible to losses by denitrification, volatilization, and leaching. Thus, proper management of N is required to maximize yields and maintain environmental stewardship (Morris et al., 1989).

Nitrogen recommendations for wheat in Kansas are based on yield goal and N use efficiency, and credits are provided for soil organic matter content, residual soil nitrate-N, previous crop, and tillage practice (Leikam et al., 2003). According to these recommendations, 40 kg N ha^{-1} are required for every one Mg ha^{-1} of wheat yield goal (Eq. 1-1). Nitrogen credits include 11.2 kg N ha^{-1} for each percent organic matter, full credits for each kg ha^{-1} of nitrate-N in the soil profile at sowing, an additional 22.4 kg N ha^{-1} required if under no-tillage practices, and variable credits depending on previous crop. As a consequence, hard red winter wheat with a yield goal of 4.7 Mg ha^{-1} on soils with 2% organic matter will require 132 kg N ha^{-1}; however, a yield goal of 4.7 Mg ha^{-1} with soil organic of 4% will require 110 kg N ha^{-1}.

Equation 1-1.

1 Mg ha^{-1}of wheat 12.5% protein= 125 kg protein ha^{-1} * 16 % (% N in a kg of protein) / 50 % N Use Efficiency=40 kg of N ha^{-1}*

Winter wheat producers in the state of Kansas typically apply N all in the fall prior to or during sowing, or it is split between sowing and early spring (Feekes GS 4) (Large, 1954). The production system, whether dual-purpose (grazed and grain) or grain only, will affect the timing and rate of N applied for that growing season (Boman et al., 1995; Kelly, 1995). Grazed systems are generally sown earlier and have greater fall N requirements to increase the production of biomass for cattle grazing during winter and early spring. Most grain-only producers, on the other hand, perform a split N application to decrease the risks for N losses from leaching or denitrification. Also, high N rates applied in the fall typically result in excess tillering which can be detrimental to the wheat crop in the spring as most water would be used unproductively early during the growing season, intensifying the effects of any possible late-season drought stress (McLeod et al., 1996).

Research has shown that application of N at Feekes GS 5-6 meets the greatest uptake of N by the crop (Baethgen and Alley, 1989). In Europe, Spiertz (1983) indicated that a split application of N between tillering and jointing increased wheat yields by 13% as compared to applying only at tillering, and Blankenau et al. (2002) found that an additional split in N timing to include a stem elongation application increased yields by 2.8% as compared to having the higher rate applied all at tillering. Thus, split applications of N help increase nitrogen use efficiency (NUE) of wheat and decrease the environmental risks when compared to single applications.

Wheat grain protein concentration is another important characteristic for wheat commercialization as it affects the milling industry and can affect the price received for the product. While restricted to years characterized by overall low protein contents, producers within Oklahoma, Kansas, and Nebraska can receive a premium when delivering wheat with protein levels greater than 12-13.5%, depending on growing season. However, more often, producers can suffer a penalty if protein levels are less than 11.5%. Additionally, Goos et al. (1982) found that grain protein concentration below 11.5% was an indicative that N was a limiting factor to grain yields. Managing protein concentration can be challenging as generally there is an inverse relationship between grain yield and protein concentration, and the response is variety-specific (Fowler, 2003). Grain protein concentration is determined early in the grain filling process, starting approximately 10 days after flowering and accumulating approximately 50% in the following 10 days (Daigger et al., 1976; Dupont et al., 2006). One solution to increase protein concentration is to apply N later in the growing season, between flag leaf emergence and anthesis. If soil-applied, it is important that the N is in the root zone prior to anthesis as only 10-20% of the N in the grain is up-taken after anthesis (Heitholt et al. 1990). Otherwise, foliar N applied later in the growing season can be an alternative although rates needed to improve protein concentration can cause leaf burn (Cruppe et al., 2017). Still, protein concentration was increased when N was foliar-applied after boot (Feekes GS 10) (Ellen and Spertz, 1980), before flowering (Feekes GS 10.5) (Woolfolk et al., 2002), or after flowering (Feekes GS 10.5.4) (Bly and Woodard, 2003; Cruppe et al., 2017). Even though protein concentration can be increased with later applications of N, it is not a common practice for producers as it is not always economical (Dick et al., 2016); thus optimizing N source and rate early during the growing season (Feekes GS 3 to 5) is still the preferred route to increase wheat yields while sustaining minimum required protein levels.

Several sources of N are available for wheat producers in Kansas, and their decision is often made based on product availability, distance from the product source to their operation, and price per unit N. The lack of preference for a particular source arises from a lack of consistent response of wheat yields to N source. For instance, Christensen and Meints (1982) evaluated two N sources; urea ammonium nitrate (UAN) and urea resulted in the same yield for winter wheat when applied in the spring. Urea applied at cooler temperatures and on moist or snow packed soils is susceptible to volatilization and N losses can occur up to 30-40%; however, that process can be reduced if a rainfall event of 18-25 mm is received immediately following urea application (Engel et al., 2011). Pre-plant urea can be converted to nitrate in 7-10 days and can be leached out of the soil profile (Boyer et al., 2012). However, Boyer et al. (2012) found topdressing UAN increased NUE by 19% as compared to pre-plant urea. Edwards et al. (2009) measured a grain yield increase of 0.34 Mg ha^{-1} when applying UAN as compared to urea in season.

Sulfur

Sulfur plays a variety of roles within the plant, from the synthesis of amino acids to the formation of compounds such as disulfide linkages, glucoside oils (Coleman, 1966), and chlorophyll (Duke et al., 1986). Liebig and Blyth in (1859) first discovered S as a limiting nutrient, and it is the fourth most important element behind N, P, and K among the 17 essential elements which crops need to complete their life cycle (Tabatabai, 1984). Sulfur is supplied to plants in three ways: rainfall, organic matter mineralization, or as part of organic or mineral fertilizers. Agronomic crops have shown a response to S fertilization in the past and these cases are becoming more prevalent in recent years. The two main reasons for the increase in S responses are the decline in organic matter in cultivated soils as compared to native vegetation (Lollato et al., 2012) and decrease in sulfur dioxide in the rainfall. In 1970, the Clean Air Act required that coal fired plants to use scrubbers to remove the sulfate from emissions; thus, a 30% decline in S emissions was measured from 1970 to 1993 (Ceccotti, 1996). As a consequence, sulfur deposition levels from rainfall dropped from 13.5-19 kg ha^{-1} in 1980 (Barrie, 1984) to only 4 kg ha^{-1} in 2014 (National Atmospheric Deposition, 2014).

Organic matter plays a very important role in supplying plants with nutrients, especially N and S. Organic matter contains a ratio of 8N:1S (Stewart and Whitfield, 1965), and wheat takes up approximately 80% of the sulfur before anthesis (Hocking, 1994). However, mineralization of organic matter is slow in the spring when temperatures are cool (Camberato and Casteel, 2010), which might result in a mismatch between crop needs and S availability from organic matter mineralization. In a long-term study conducted in western Kansas, Hobbs and Brown (1957) found organic matter to lose 50% of its N in 40 years of intensified farming. The fact that S is not regularly applied to agricultural soils also suggests that S availability has decreased at even greater rates recently than in the past. Currently, many types of S fertilizers are available. The most common are ammonium sulfate (21-0-0-24S), ammonium thiosulfate (12-0-0-26S), elemental sulfur (90-95% S), and gypsum (18.6% S). Wheat responds differently to S fertilizer source, with ammonium sulfate increasing yields by 36% over the control with no additional S (Riley et al., 2000). Likewise, in Oklahoma on a sandy, low organic matter soil, a grain yield response to S was experienced in 43% of the studied seasons (6 out of 14 site years), and gypsum provided more consistent responses as compared to elemental S (Girma et al., 2005). The reasoning behind this response is that plants can only take up sulfate (SO_4^{-2}) (Kopriva et al., 2015), thus, elemental S has to be oxidized before it can become plant available (Mahler and Maples, 1987), and the time required for S oxidation might actually be longer than a winter wheat growing season (Riley et al., 2000).

Approximately 10% of soils in Kansas test less than 3 ppm sulfate-S at a depth of 0-60 cm (Murrell et al., 2015). Sulfur recommendations for wheat in Kansas are based on yield goal, credits are provided for soil organic matter content, and residual soil sulfate-S (Leikam et al., 2003). According to these recommendations, 10 kg S ha^{-1} are required for every 1 Mg ha^{-1} yield goal. Sulfur credits include 2.8 kg S ha^{-1} for each percent organic matter, full credits for each kg ha^{-1} of sulfate-S at sowing. As a consequence, hard red winter wheat with a yield goal of 4.7 Mg ha^{-1} on soils with 2% organic matter and profile sample of 24 kg S ha^{-1} will require 17 kg S ha^{-1}; however, a yield goal of 4.7 Mg ha^{-1} with soil organic of 2% and a profile sample of 48 kg S ha^{-1} will require no additional sulfur fertilizer.

To ensure S is non-limiting, a ratio of 15N:1S is needed to for optimal wheat growth from the results of a tissue analysis (Rasmussen et al., 1975; Flæte et al., 2005). Additionally, Rasmussen et al. (1975) found the critical plant S to be 0.09% in above ground biomass at harvest and 0.12% in the harvestable grain in soft white wheat. In other words, a wheat crop yielding 4 Mg ha^{-1} will remove 9 kg ha^{-1} of S in the grain (Duke et al., 1986). Wheat is less efficient in moving S from the vegetative parts to the developing grains as compared to other key nutrients like N and P. For instance, only about 40% of the S is remobilized as compared to approximately 70% for N and P (Hocking, 1994). Thus, the majority of S is taken up before anthesis and only a small amount of the S is remobilized to the grain, resulting in a low amount of crop removal.

Wheat grain protein can be divided into three classes; albumins (22%), gluten (65%), and globulins (15%). Gluten can be sub divided into two storage proteins: gliadin and glutenin, which contribute to about 80% of the storage protein in the wheat grain (Satorre and Slafer, 1999). Gliadin is the protein that gives the dough the ability to stretch, whereas the glutenin is the protein that gives the dough its strength (Branlard and Dardevet, 1985; Gupta et al., 1993). Glutenin can be further classified into low-molecular weight (LMW) and high-molecular weight (HMW) sub units (Zhao et al., 1999). The ratio of the gliadin/glutenin are important for the baking quality of wheat (Simmonds, 1989). The primary role of S is the reduction to cysteine (Zhao et al., 1999) which holds the glutenin together (Satorre and Slafer, 1999), thus allows for the production of high quality flour (Byers et al., 1987). Sulfur deficiencies will result in the production of HMW proteins which offset the ratio of HMW/LMW, resulting in low loaf bread volume (Zhao et al., 1999). Zhao et al. (1999) concluded that S applications were less effective in increasing grain yield, but more effective in increasing bread making quality.

Chloride

Boyer et al. (1954) determined Cl to be an essential micronutrient to plants due to its many physiologic roles, ranging from osmotic regulation (Kafkafi and XU, 2002) to disease suppression (Scheyer et al., 1987). Chloride application suppressed stripe rust (*Puccinia striiformis* f.sp. *Tritici)* in susceptible wheat varieties and take all root rot (*Gaeumannomyces graminis*) in several wheat varieties (Scheyer et al., 1987). Chloride is applied to agricultural soils in many ways, but the two most important are i) rainfall, which deposits relatively low rates ranging from 0 to 1 kg ha^{-1} yr^{-1} (National Atmospheric Deposition, 2014); and ii) potash fertilizer. A survey conducted in Kansas indicated that only 19% of soils tested less than the soil critical K level (Fixen et al., 2010); thus, producers are often not required to apply Cl containing fertilizers (e.g. potassium chloride). However, symptoms of Cl deficiency are increasingly more common in Kansas wheat production fields.

In Kansas, an application of Cl is recommended when a soil test value is below 6 mg kg^{-1} or if leaf concentrations are below 0.10-0.12% (Lamond and Leikam, 2002). Approximately 40% of the soil samples evaluated by Fixen et al. (2010) tested less than 4 mg kg^{-1} Cl in Kansas (Fixen et al., 2010). Likewise, in Montana, a total of 33 kg ha^{-1} Cl (soil test + fertilizer) was needed at a depth of 0-60 cm in the soil to bring the wheat whole plant Cl concentration above the critical level of 4 g kg^{-1} at Feekes GS 10.5 to prevent yield limitations (Engel et al., 1998). However, research on yield response to Cl fertilizer can be challenging as it is a micronutrient and thus needed in very small quantities in the plant. Thus, yield responses are often inconsistent and many times dependent on soil type or disease pressure. In Oklahoma, Freeman et al. (2005) indicated a 9% yield increase when Cl was applied at high rate of 67.2 kg ha^{-1} to wheat grown in a sandy loam soil. Similarly, a more recent meta-analysis indicated that wheat yields increased by 8% due to Cl application (Ruiz Diaz et al., 2012). Test weight was also significantly increased by Cl application (Scheyer et al., 1987; Engel et al., 1994). In a long term study, Mengel et al. (2009) suggested that wheat yields increased 0.22 Mg ha^{-1} due to application of 11.12 kg Cl ha^{-1}. Another study in Kansas found that Cl applied at 22 kg Cl ha^{-1} increased wheat yields by 1.28 Mg ha^{-1}; however, this yield increase was variety-specific and restricted to very low Cl testing soils (Lamond et al., 1999).

Crop production components

Fungicide

The environment in Kansas is highly variable between- and within-growing seasons, resulting in a wide array of biotic and abiotic stresses, including many different diseases and disease pressures. Major fungal foliar diseases found in Kansas are leaf (*Puccinia triticina*) and stripe rust (*Puccinia striiformis* f.sp. *Tritici),* tan spot (*Pyrenophora tritici-repentis*), powdery mildew (*Blumeria graminis f. sp. tritici*)*,* and septoria tritici blotch (*Septoria tritici*). Historically, leaf rust has been the most common disease in Kansas; however, recently stripe rust has been the state’s highest yield limiting disease (USDA-ARS, 2015).

Stripe rust was first recorded in the United States in 1915, and recorded in Kansas in 1957 (Pady et al., 1957). This pathogen will form yellow lesions on the leaf and continue to grow along the veins to form “stripes.” Stripe rust is an early spring disease favored by cool temperatures (9-13°C) and moist weather conditions (Roelfs et al., 1992). If conditions are favorable, stripe rust can continue to spread through wheat heads, causing yield reductions of as much as 50% (Roelfs et al., 1992). In Kansas, stripe rust caused 15.4, 9.1, and 8% yield reductions in 2015, 2016, and 2017, with a 5 year average reduction in wheat yield of 6% (Hollandbeck et al., 2016, 2017).

Leaf rust is the most common rust disease in North America, and the first epidemic in Kansas was recorded in 1938 (Roelfs and Bushnell, 1985). The disease will form reddish-orange lesions on the leaf. Unlike stripe rust, leaf rust has larger pustules and does not follow the veins of the leaf, resulting in a more random infection pattern. Leaf rust is a late spring disease, as its development is favored by warmer temperatures (20°C) In Kansas, leaf rust caused 1.3% yield reductions in 2016 and the 5 year average yield reduction was 0.56% (Hollandbeck et al., 2016), but yield reductions of 10% or more have been reported (Roelfs et al., 1992).

Tools available for leaf and stripe rust management include in-season foliar fungicide or variety genetic resistance. The timing of a fungicide treatment application can greatly affect crop response and the efficacy of the product applied. Foliar fungicides will only protect the leaves present at time of application, and the product's efficacy will decrease after 20-30 days, depending on active ingredient. Thus, early applications of foliar fungicide might result in decreased efficacy at later stages of crop growth, when leaf rust time of infection prevails. On the other hand, late foliar fungicide applications may not benefit the crop, as chances exist that stripe rust disease may have already established and caused a significant yield reduction. Classes of fungicides commonly used are strobilurin or triazole, which were introduced in the 1990s and 1970s, respectively (Russell, 2005). A strobilurin fungicide kills the fungus by stopping the production of adenosine triphosphate (ATP) by halting mitochondrial respiration (Bartlett et al., 2002). A triazole fungicide kills the fungus by degrading cell membranes, which is triggered by the inhibition of sterol biosynthesis (Fishel, 2005). Thus, a combination of these fungicides is the preferred management practice.

Green leaf area, which is responsible for over 70% of the photosynthates produced after wheat heading under favorable weather conditions, can be preserved by applying a foliar fungicide after the flag leaf emerges. The flag leaf is the closest leaf to the wheat head and the last leaf to senesce, and is most important leaf contributing to carbohydrate production and grain fill. Under optimal conditions, as much as 60-70% of the carbohydrates produced after heading are synthesized by the flag leaf and its sheath (Rawson et al., 1983; Miller, 1992). However, under unfavorable growing conditions such as heat or drought stress, wheat has a great capacity to mobilize water soluble carbohydrates from the stem, and as much as 50% of its stored carbohydrates can help contribute to grain yield (Gent, 1994). Unlike carbohydrates, N uptake occurs mostly prior to anthesis (i.e. approximately 70-90%), and wheat can remobilize as much as 75% of leaf and stem N to the grain; thus, maintaining green leaf area after heading is important to allow for those nutrients to be transferred to the seed and maximize grain yield and protein concentration (Hocking, 1994).

Often, greater profitability results from applying a foliar fungicide after flag leaf emergence (Feekes GS 9) as compared to applications earlier in the growing season (Wegulo et al., 2011). Fungicide application can increase grain test weight due to the extended grain filling period resulting from the greener leaf area (Kelley, 2001), and as much as 70-90% of the carbohydrates produced after anthesis are used to determine final grain weight (Frederick and Bauer, 1999). Likewise, in the southern Great Plains, Edwards et al. (2012) found fungicide application to increase test weight, which resulted in a 10% yield increase in susceptible varieties, and Morris et al. (1989b) found when N was applied multiple times during the growing season with a fungicide, yields were increased by 10%. In Europe, where winter wheat is intensively managed to capitalize on the high environmental yield potential. Varga et al. (2005) found test weight and grain yield to increase significantly when winter wheat received a fungicide application. However, using a crop model, Weisz et al. (2011) found that applying a fungicide when disease pressure was low to a soft red winter wheat solely on maintaining optimal plant health was not economical in Virginia and North Carolina.

Planting Density

Winter wheat grain yield is determined by the yield components i) grains per spike, ii) spikes per unit area, and iii) individual grain weight (Slafer et al., 2014). A high number of grains per unit area can be sustained either by optimal plant populations or by increased tiller survival. Plant population density is among the main causes defining the crop's capability to capture resources such as water, nutrients, and solar radiation (Satorre and Slafer, 1999). The response of wheat to plant population density is a function of competition for resources with neighboring plants (Satorre and Slafer, 1999), and increased competition can reduce tiller survival, dry matter production, and grain yield of individual wheat plants (Satorre, 1988). Wheat plants subjected to high density generally have fewer tillers and grains than widely spaced plants (Rana et al., 1995). On the other hand, too widely spaced plants can result in fewer grains per unit area, explaining the typical parabolic response of grain yield to plant density (Holliday, 1960). Consequently, appropriate management of population density may allow maximum yields per unit area to be achieved (Satorre and Slafer, 1999).

Guitard et al. (1961) found that wheat yield components were greatly affected by different seeding rates. While plants per hectare increased with increasing planting density, yield per hectare increased with increased planting density up to a seeding rate of 100 kg ha^{-1}, plateauing with further increases in seeding rate (Guitard et al., 1961). Donald (1968) suggested that wheat be planted at a high density so there is no tillering and only one spike per plant which would result in high shoot survival, which was later proven to be a key component in predicting wheat grain yield (Shanahan et al., 1985). Darwinkel et al. (1977) found main shoots and early tillers to produce the highest yield in both low (80 kg ha^{-1}) and high (160 kg ha^{-1}) planting densities. In the same study, they found the high plant populations to increase yield by approximately 20-30%. Geleta et al. (2002) found the optimal wheat seeding rate to achieve high test weight was 64 kg ha^{-1}, whereas 118 kg ha^{-1} resulted in optimum grain yields in eastern Nebraska. Increased planting density resulted in an increase of spikes m^{-2} and had greater effects in grain yield than in grain test weight (Blue et al., 1990). The greater relationship between wheat yields and spikes m^{-2} than test weight is an indicative that wheat is often sink-limited and not source-limited (Shanahan et al., 1985; Borrás et al., 2004).

Increased within-canopy competition may also lead to other challenges, such as uneven tiller maturity at harvest time. Geleta et al. (2002) found that an increased planting rate (130 kg ha^{-1}) decreased the time to flowering by two days as compared to ultra-low planting rates (16 kg ha^{-1}). Likewise, Darwinkel (1978) found that only the main shoot survived when wheat was seeded at 800 plants m^{-2}, while tiller survival increased with a decrease in seeding rate so that at 200 plants m^{-2} the first, second, and third tillers survived at rates of 90%, 55%, and 10% to produce grain-bearing spikes. When wheat was sown at an extremely low density (16.8 kg ha^{-1}), yield and biomass were significantly reduced by 40%, whereas harvest index remained constant (Sharma and Smith, 1987).

At high plant populations, individual plants cannot support as many grains as under lower plant populations because there is increased plant-to-plant competition for resources such as for nutrients, solar radiation, and water, which might result in lower test weights and fewer and smaller spikes per plant (Darwinkel, 1978). Spikes per plant, grains per head, and 1000 kernel weight all decreased with increasing planting rate (Guitard et al., 1961; Holen et al., 2001). Geleta et al. (2002) found wheat quality also to be affected by planting density, as flour protein and mixing tolerance decreased with increasing planting densities to a rate of 65 kg ha^{-1} and grain protein concentration decreased with increasing planting densities of 50 to 100 seeds m^{-2} (Gooding et al., 2002). However, flour mixing time increased with increasing plant population from 16 to 65 kg ha^{-1} (Geleta et al., 2002). Decreasing plant populations, on the other hand, might not result in similar yield reductions due to the high tillering capacity and plasticity of the wheat plant. For instance, decreasing a winter wheat stand by 35% did not result in significant differences in yield when compared to the optimal seeding rate (Fowler et al., 1976; Holen et al., 2001).

Finally, wheat response to plant population needs to be discussed within the context of planting date and fertility level. Earlier planting dates will allow for more tillering and might justify reduced plant populations unless the crop is intended for graze-out or dual-purpose (Edwards et al., 2006), while recommendations are to increase plant population when planting is delayed within or past the optimum window due to reduced fall tillering potential (Staggenborg et al., 2003), which results in greater wheat tillering (Lollato et al., 2013), is essential when reducing plant populations to support the additional tillers, which results in more spikes per unit area, and in-return, sustaining or increasing in grain yield (Satorre and Slafer, 1999).

Plant Growth Regulator

Lodging, caused by stem failure or by mechanical root displacement will consequently cause the plant to fall over (Pinthus, 1974), is a reoccurring issue in high-fertility, high-moisture systems (Lollato and Edwards, 2015). Following anthesis, the risk of lodging of the wheat crop increases (Pinthus, 1974) and, by the time senescence is achieved, the stem has to support many heads which increases the risk of lodging. Lodging can be worsened by particular management strategies, such as increased rate of N fertilizer (Robins and Domingo, 1962; Harris, 1979), high seeding rates (Easson et al., 1993), and decreased row spacing (Stapper and Fischer, 1990); and cause yield reduction, delays in harvest, and delayed grain drying (Berry et al., 2004).

Lodging caused yield losses of as much as 1.7 Mg ha^{-1} in Australian spring wheat (Peake et al., 2014), and as much as 40% yield reduction in bread wheat, which tends to yield less than soft wheat due to greater quality (Kelbert et al., 2004). Berry and Spink (2012) used a crop model to predict that crop losses could potentially surpass 60% when the crop is completely lying on the ground. Thus, field studies concluded that lodging losses were reduced from 30 to 10% when lodging occurred at crop maturity versus when it occurred between heading and hard dough (Weibel and Pendleton, 1964). The use of PGR can help decrease wheat height, potentially decreasing lodging potential and avoiding some of the damaging effects of lodging.

Gibberellic acid (GA), a plant hormone, promotes internode elongation in plants (Taiz and Zeiger, 2006); thus, plant height can be reduced by regulation of GA (Hedden and Phillips, 2000). The most commonly used PGR to reduce plant height are ethephon (De Wilde, 1971), chlormequat chloride (CCC) ((2-Chloro-ethyl) trimethylammonium chloride) (Cathey, 1964), and trinexapac-ethyl (Rademacher, 2000). Chlormequat chloride reduces stem elongation by reducing the activity of the subapical meristematic tissue (Cathey, 1964) and blocking GA from reaching the cell tissue (Lockhart, 1962). Trinexapac-ethyl, which is a new formulation of a PGR, is a GA inhibitor but it affects the plant later in the biosynthetic pathway (Rademacher, 2000). Ethephon can be supplied externally to the plant and will be absorbed by the leaf cells (Cooke, 1968), thus releasing ethylene in the leaf cell and resulting in growth inhibition (Burg, 1973). A simplified diagram in which ethephon is broken down into ethylene can be found in the review by Morgan (1980).

In the 1970s and early 1980s, PGRs were extensively used by producers in Europe with the objective of reducing the lodging of wheat plants as intensified cropping was becoming a common practice (Dicks, 1976). Research on the effects of growth regulators on wheat height, lodging, and yield have been relatively inconsistent and appear to depend on weather conditions. Gooding et al. (2002), for instance, found that in the absence of lodging, growth regulator had no effect on wheat yield. When lodging occurred, a study also demonstrated no significant effect of PGR on winter wheat yield and grain protein concentration (Mohamed et al., 1990). While plant height was reduced by the reduced growth of the peduncle and third internode when a PGR was applied at the Feekes GS 7-8 growth stage (Matysiak, 2006; Swoish and Steinke, 2017), the effects of PGR on wheat yield and plant height were inconsistent in a study conducted in Kentucky (Knott et al., 2016). Some inconsistencies might derive from the different active ingredients as well, as a CCC application increased soft red winter wheat yields 4.5% while ethephon decreased wheat yields by 9% in one year of a two-year study (Knapp et al., 1987). Matysiak (2006) found in high rainfall years, application of trinexapac-ethyl increased winter wheat yields by 8%; however, in low rainfall years, there was no yield response to PGR. Swoish and Steinke (2017) found 5% greater wheat grain yield when a PGR was applied to a taller soft white winter wheat by reducing the negative effects of lodging. The authors concluded that PGR application should be based on plant height and lodging susceptibility instead of N application.

Chapter 2 - Plant population and fungicide economically reduce winter wheat yield gap in Kansas

Introduction

Yield potential is the yield attained by an adapted cultivar grown under best management practices (e.g. optimum sowing date and rate, weed-, insect-, disease-, and water-stress-free), and only limited by solar radiation and temperature (Van Ittersum et al., 2013). For non-irrigated systems, such as the majority of the wheat grown in the central Great Plains (i.e. Kansas, Colorado, Nebraska, and Oklahoma), water-deficit stress decreases yield potential in most growing seasons and therefore the water-limited yield [(Y_w, or the yield potential limited by water deficit stress; Van Ittersum et al. (2013)], becomes a more relevant benchmark to calculate YG and set goals for sustainable intensification. For non-irrigated conditions, a YG can be defined as the difference between Y_w and average yield for that location-year (Neumann et al., 2010). Despite the importance of Kansas in the U.S. wheat production scenario [e.g. approximately 10.2 million metric tons of wheat produced yearly from an area of about 4 million hectares, corresponding to 26% of the total U.S. wheat production (USDA-NASS, 2017b)], the central portion of the state is characterized a YG ranging between 2.7-3.1 Mg ha^{-1}, or in other words, current yields are 54% of the Y_w (Lollato et al., 2017). In these rainfed environments, crop yields can be economically improved to as much as 75% of the Y_w (Lobell et al., 2009). Thus, wheat yields in Kansas can potentially be economically improved by as much as 25% through improved agronomic management. Fulfilling this large YG can help meet future food demand from a growing global population.

Recent research has been conducted to evaluate agronomic management strategies to reduce the YG in maize (Grassini et al., 2014; Ruffo et al., 2015), soybeans (Grassini et al., 2015), and rice (Laborte et al., 2012); however, limited information is available using a systems approach to maximize yields for modern wheat varieties. Lollato and Edwards (2015) used an intensified management approach to maximize Y_w in the U.S. southern Great Plains; however, did not attempt to decipher combinations of management practices to economically reduce YG. Mohamed et al. (1990) studied combinations of management practices affecting wheat yields, but results from irrigated wheat in California likely does not directly translate into applicable information for non-irrigated wheat production in Kansas. The majority of the additional literature focuses on single management factors at a time (i.e. nutrient management, plant population, pest management, etc.), failing to optimize the entire production system. Agronomic intensification has to be economical to be adopted by producers; thus, defining which combination of management factors have the greatest effect on yield can help economically reduce the YG in modern day agriculture (Dobermann 2003).

Proper nutrient management is essential to maximize winter wheat yields in the southern Great Plains (Lollato and Edwards, 2015). Winter wheat grain yield and quality relies on nitrogen fertilizer (Byers et al., 1987), which increases tiller and grain number (Weisz et al. 2001) as well as grain protein concentration (Dick et al., 2016). In Kansas, producers typically apply N exclusively in the fall prior to or during sowing, or split the application between sowing and early spring (Feekes GS 4) (Large, 1954). Despite evidence suggesting a better nitrogen use efficiency (NUE) and possibly better yields (Alley et al., 2009) resulting from split applications of N fertilizer in the spring (e.g. partial fertilization at Feekes GS 3-4 and the remaining at Feekes GS 5-6), this practice is rarely used in the region and its role in maximizing yields in a systems approach have not been evaluated. Sulfur is another important secondary nutrient for wheat production, and S deficiencies have become more prevalent in recent years (Camberato and Casteel, 2010). The two main reasons for the increase in S responses are the decline in organic matter (OM) in cultivated soils as compared to native vegetation (Lollato et al., 2012) and a decrease in S dioxide in the rainfall as a result from a 30% decline in S emissions since 1970 due to the Clean Air Act (Ceccotti, 1996). Sulfur is not only important for wheat yield, but also affects wheat grain quality, which is necessary in the baking and milling industry (Byers et al., 1987; Zhao et al., 1999). Another micronutrient contributing to winter wheat yield is Cl. Chloride deficiency in winter wheat is not uncommon in Kansas (Lamond et al., 1995, 1999). Two most common ways Cl is applied to crops are rainfall (National Atmospheric Deposition, 2014) and potassium chloride (KCl) fertilizer. A survey conducted in the Great Plains indicated that the median potassium levels in 2,000 fields to be approximately 270 ppm (Fixen et al., 2010), which is considerably higher than the critical value for most crops grown in Kansas (Leikam et al., 2003). Therefore, producers rarely apply Cl-containing fertilizers (e.g. KCl). Still, a meta-analysis of wheat yield response to Cl indicated that Cl application increased wheat yield on average by 8% across site-years in Kansas (Ruiz Diaz et al., 2012), warranting further exploration on wheat grain yield response to Cl in intensified systems.

Plant population density defines the crop's capability to capture resources such as water, nutrients, and solar radiation (Satorre and Slafer, 1999). Wheat plants subject to high population density generally have fewer tillers and grains than widely spaced plants (Rana et al., 1995). On the other hand, too widely spaced plants can result in fewer plants per unit area and consequently fewer grains per unit area, explaining the typical parabolic response of grain yield to plant density (Holliday, 1960). Definition of optimum population density for wheat is challenging not only because of the high plant plasticity and compensation capacity through tillering (Darwinkel et al., 1977; Darwinkel, 1978), but also because it interacts with sowing date (Darwinkel et al., 1977), fertility levels (Alley et al., 2009), and tillage practice (Halvorson et al., 1999; Staggenborg et al., 2003). More information is needed to define optimum population densities to maximize yields per unit area and minimize winter wheat YG (Satorre and Slafer, 1999).

Another major yield-limiting factor in the majority of the winter wheat growing regions of the world is the incidence of fungal pathogens. Major fungal foliar diseases found in Kansas are leaf (*Puccinia triticina*) and stripe rust (*Puccinia striiformis* Westend. f. sp. *tritici* Eriks.), tan spot (*Pyrenophora tritici-repentis*), powdery mildew (*Blumeria graminis f. sp. tritici*), and septoria tritici blotch (*Septoria tritici*). Leaf and stripe rusts alone have caused production losses as great as 25% or more at state level in recent years (USDA-ARS, 2017). While genetic resistance can protect winter wheat cultivars from fungal pathogens, different diseases tend to breakdown genetic resistance within a few years from variety release leading to variety withdraw from the market (Perronne et al., 2017). The aforementioned fungal diseases can be controlled by strobilurin and triazole classes of fungicide, helping the crop reach its yield potential by avoiding yield losses resulting from diseases (DeWolf, 2017). Most fungicide applications to winter wheat aim to protect the flag leaf, which can account for over 60% of the photosynthates translocated to grains during grain fill under favorable weather conditions (Rawson et al., 1983; Miller, 1992). A long-term study suggested that fungicide-treated resistant varieties had approximately 10% greater grain yields, and yield gains in susceptible varieties were even greater (DeWolf et al., 2013; Thompson et al., 2014). However, foliar fungicides are not always economical (Weisz et al., 2011) and their role on decreasing YG within a systems approach is yet to be explored.

Plant lodging is a major concern when wheat is grown under intensive management (Lollato and Edwards, 2015). Lodging, caused by either stem failure or root displacement, which causes plant to fall over (Pinthus, 1974) and can lead to wheat yield losses as great as 60% or more depending on timing and severity of lodging (Berry and Spink, 2012). In addition to yield reduction, lodging also decreases agronomic efficiency of the system by delaying grain drying and harvest (Berry et al., 2004). Plant growth regulators can be an alternative to reduce lodging in these systems (Nafziger et al., 1986). The most commonly used PGR are ethephon (De Wilde, 1971), chlormequat chloride (Cathey, 1964), and trinexapac-ethyl (Rademacher, 2000). While the use of PGR can decrease plant height and reduce the damaging effects of lodging in many years (Nafziger et al., 1986; Mohamed et al., 1990), its effects on grain yield (Knott et al., 2016; Mohamed et al., 1990) and grain protein concentration (Mohamed et al., 1990) are inconsistent and many times nonexistent. While PGR might be a promising management practice especially in intensively managed wheat systems, more research is needed to identify whether its inconsistent yield results will render it economical.

The majority of previous research has focused either on the effects of individual management practices or the combination of two management factors at a time on wheat yield. Little research has investigated the combination of different management factors and their effects on economically reducing YG using a systems approach. Thus, our objective was to quantify the individual contribution of different management factors to maximizing wheat yield and minimizing wheat YG, when added to a low-input, standard control (hereafter referred to as 'Farmer Practice', FP) or removed from a high-input, kitchen sink control (hereafter referred to as 'Water limited yield', Y_w). Specific objectives were to: i) understand how fertilization, pest management, and crop production practices, and their combination, affect wheat yield and yield components; and ii) identify agronomic practices or their combination which resulted in greater return over investment for producers whose objectives are to maximize wheat yield and profitability.

Materials and Methods

Site Description

Field studies were conducted at three locations in Kansas during the 2015-16 and 2016-17 winter wheat growing seasons. Experiments were established at the Kansas State University (KSU) North-Central Experiment Field in Belleville (39°48' N, 97°48' W, alt. 450 m) on a moderately well-drained Crete silt loam, 0 to 1 percent slope, loess plains and breaks, at the KSU South-Central Experiment Field in Hutchinson (37°55' N, 98°1' W, alt. 530 m), on a well-drained Ost loam, 0 to 1 percent slope, and at the KSU North Agronomy Farm in Manhattan (39°12' N, 96°35' W, alt. 350 m) on a well-drained Kahola silt loam, 0 to 1 percent slope, and rarely flooded (USDA-NRCS, 2015) for a total of six site-years. All site-years were conducted under rainfed conditions and located within 16 kilometers from a Kansas Mesonet network which provided rainfall (mm) and average daily temperatures (T_{ave}, °C). These locations were selected to capture the environmental variability (i.e. weather and soils) and different yield potential levels throughout Kansas.

Experimental design and treatments

Experimental design

Fourteen treatments were established in an incomplete factorial treatment structure conducted in a randomized complete block design with six replications, similar to the approach suggested by Ruffo et al (2015). The incomplete factorial design was developed to evaluate the individual effect of six different agronomic practices compared against two control treatments: a FP and Y_w. Yield goals on the control treatments were used to determine N fertilization rates for the different treatments (Leikam et al., 2003) and were 4.7 Mg ha^{-1} and 8.1 Mg ha^{-1}, respectively. The other twelve treatments consisted of six agronomic management practices individually added to the FP or removed from the Y_w, structure also referred to as supplemented versus withheld (Ruffo et al., 2015).

Agronomic practices evaluated consisted of (i) seeding rate, (ii) N rate, (iii) S, (iv) Cl, (v) foliar fungicide, and (vi) PGR. Each management practice consisted of a low level and a high level. Seeding rates used were 84 kg ha^{-1} and 123 kg seed ha^{-1} at the low and high levels, respectively. Nitrogen was top-dressed at Feekes GS 3 for a yield goal of 4.7 Mg ha^{-1} in the low-level treatment, while the high level consisted of the same N regime with an additional 134 kg N ha^{-1} application at Feekes GS 5 for a yield goal of 8.1 Mg ha^{-1}. Sulfur or Cl were either absent (low level) or applied at Feekes GS 5 at 45 kg ha^{-1} (high level). Similarly, foliar fungicide was either absent (low level) or applied two times during the growing season, the first at Feekes GS 6 and the second at GS 10.5 (high level). The PGR treatment also consisted of absence (low level) versus one application at Feekes GS 6 (high level). The FP consisted of the combination of all low input levels above: 84.1 kg seed ha^{-1}, N applied at planting and top-dressed at Feekes GS 3 for a yield goal of 4.71 Mg ha^{-1}, and none of the additional management factors. The next six treatments consisted of each of the previous six management practices individually added to the FP. Individual practices were not cumulatively added, so that the partial contribution of each practice could be evaluated. The Y_w consisted of all high-level practices combined: 123.3 kg seed ha^{-1}, N applied at planting and split top-dressed at Feekes GS 3 and 5 for a yield goal of 8.1 Mg ha^{-1}, 45 kg ha^{-1} of S and of Cl, two fungicide applications, and a PGR application. Conversely, the six consecutive treatments consisted of each of the aforementioned management practices individually removed from the Y_w. Treatments and treatment structure are detailed in Table 2-2.

Treatments

Nitrogen fertilizer was applied as urea (46-0-0) at rate needed to meet each individual yield goal, according to Kansas State University recommendations (Leikam et al., 2003). Final N rates based on these recommendations were calculated based on yield goal and taking into consideration soil organic matter (O.M) in 0 – 15 cm depth soil layer, nitrate N (NO_3-N) in the 0 – 60 cm soil profile, as well as tillage practice, N credits from the previous crop, and N credits from starter fertilizer placed with the seed. Because soils at each studied site-year differed in N profile characteristics, different N rates were required at each location to meet the 4.7 Mg ha^{-1} yield goal in the low-input treatments. Final N rates are presented in Table 2-1. A one and half meter, push-type Gandy spreader was used to apply urea at Feekes GS 3 and the variable rate dial present on the spreader helped ensure the correct amount of fertilizer was applied. Urea was weighed and applied by hand spreading at Feekes GS 6 for the high input treatments.

Sulfur and Cl fertilizers were applied as gypsum (160 g kg^{-1} S) and potassium chloride (450 g kg^{-1} Cl). Based on the meta-analysis by Ruiz Diaz et al. (2012) which indicates that applying 45 kg ha^{-1} would achieve approximately 90-95 % relative grain yield of wheat in Kansas. Therefore, Cl was applied at a rate of 45 kg ha^{-1} to allow for the greatest opportunity to measure a yield response if Cl was yield limiting. Timing of application can be found in Table 2-1. Sulfur and Cl were weighed and applied by hand spreading during Feekes GS 6 similarly to N in the high input treatments.

A foliar fungicide was applied at two different growth stages throughout the growing season. At jointing (Feekes GS 6), 66 mL ha^{-1} Picoxystrobin-Class 11 (full description of active ingredients used across this manuscript can be found at Table 2-5) was sprayed as the early fungicide, and this application was complemented with a second fungicide application with a mixed mode of action at heading (Feekes GS 10.5) at a rate of 92 mL ha^{-1} Picoxystrobin- Class

11, and 37 mL ha^{-1} Cyproconazole- Class 3. Along with each fungicide application, a non-ionic surfactant (NIS) was applied at a rate of 847 mL 380 L^{-1}. A backpack sprayer with a 1.5 m hand boom was used to make the application on each individual plot. The CO_2 tank had a regulator to ensure a specific pressure was being applied to the hand boom and TEEJET yellow flat fan nozzles (11002VS) were used to ensure a thorough coverage of leaf area, needed due to the lack of product translocation (DeWolf et al., 2013).

A PGR, which will decrease plant height and reduce the damaging effects of lodging (Nafziger et al., 1986; Mohamed et al., 1990) was another factor evaluated in the study, as lodging can be a common concern in high-management wheat production in the southern Great Plains (Lollato and Edwards, 2015). A rate of 130 mL ha^{-1} trinexapac-ethyl (Palisade EC-Syngenta) was used as PGR, also applied with the same rate of NIS used for foliar fungicide application. PGR treatment was applied at Feekes GS 6 with the backpack sprayer and hand boom system.

Crop management

The winter wheat variety Everest was sown at all locations for being the most widely planted variety in the state of Kansas (USDA-NASS, 2017a). To ensure that early season fungal diseases and insect pests were not limiting factors, seeds were treated with fungicide and insecticide seed treatment (full description of active ingredients used across this manuscript can be found at Table 2-5). Pre-plant fertilization was applied to the entire experiment area to ensure adequate soil fertility and early season growth at all site-years as 67.2 kg ha^{-1} diammonium phosphate (18-46-0) in-furrow with the seed at sowing. Phosphorus and potassium levels were greater than 20 and 130 ppm at all locations, indicating that base fertilization ensured 100% sufficiency levels for these nutrients (Leikam et al., 2003). In Belleville, 89.6 kg N ha^{-1} and 33.6

kg P ha^{-1} was broadcast and incorporated before sowing in the form of urea ammonium nitrate (32-0-0) and ammonium polyphosphate (10-34-0). However, Hutchinson and Manhattan did not receive any pre-plant fertilizer other than the in-furrow DAP fertilizer, Belleville and Hutchinson were sown using conventional tillage practices following a wheat crop, and Manhattan was sown using no-tillage (nine years in no-till) practices following maize (*Zea mays* L.). Conventional tillage was done by a 1.9 m, three point mount rotary tiller with 48 blades at Belleville and by a field cultivator with a total of 20 shanks in a seven-six-seven shank configuration with a drag sweep on the back at Hutchinson. Soil depth incorporation consisted of the top eight cm by each implement to ensure good seed bed conditions at the time of planting.

Weeds were controlled throughout the experiment to ensure these were not limiting factors by a pre- and post-emergent herbicide application. Application dates are shown in Table 2-1, and full complete name and description of active ingredients are provided in Table 2-5. Insect pressure was not experienced in either growing season; therefore, no in-season insecticide was applied.

Plot size varied with experimental location and depended on land availability and drill size. The trial at Manhattan during the 2015-16 and 2016-17 growing seasons, and the trial at Belleville during the 2016-17 growing season, were sown with a 7-row Great Plains 506 drill. In 2015-16, the trial was sown with an 8-row 1950 Oliver drill in Belleville. All aforementioned site-years were sown with a row-spacing of 19.1 cm. In Hutchinson, a 6-row Hege 1000 drill with a row spacing of 25.4 cm was used for trial establishment both growing seasons. The wider row spacing is justified in western Kansas locations of this study because it is the typical practice producers use to optimize crop water use in the western portion of the southern Great Plains (Winter and Welch, 1987). Plot dimensions for Belleville, Hutchinson, and Manhattan were 1.71

m x 9.14 m, 1.78 m x 9.14 m, and 1.52 m x 9.75 m, respectively. In 2015-16, plots were harvested using a 3300 John Deere small plot combine in Manhattan, a Gleaner E in Belleville, and a Hege 140 in Hutchinson. Meanwhile, a Hege 140 harvested all the plots at all locations in 2016-17. Grain moisture was determined at harvest time and corrected to 135 g kg^{-1} water basis. Sowing and harvest dates are presented in Table 2-1.

Agronomic measurements

Soil characteristics

Composite soil samples were taken at sowing from the trial area at each location for soil nutrient analysis (Table 2-3). Samples were taken using a 2.54 cm diameter hand probe from two depths, 0 – 15 cm and 15 – 45 cm in 2015-16 and 0 – 15 cm and 15 – 60 cm in 2016-17. A total of 15 cores were collected per depth and combined to represent a composite sample at each location. A routine soil analysis was performed by KSU Soil Testing Lab for pH, buffer pH, ammonium, nitrate, Mehlich III P, K, calcium, magnesium, sodium, O.M., cation exchange capacity, Cl, and sulfate-sulfur, and results were used to determine N rates for the different yield goals. The lab procedures used are described by Nathan and Gelderman (2012).

Plant growth, development, and yield measurements

Plant measurements included stand count, percent green canopy cover, disease incidence, plant height, lodging score, above-ground biomass, yield components [spikes m^{-2}, harvest index (HI), 1000-grain weight, and number of grains per spike], and grain yield. Stand count was conducted three to four weeks after planting by counting the number of emerged plants in one linear meter in the middle rows at two different locations in each plot; the average of the two measurements determined the final stand establishment. Percent green canopy cover was measured using a methodology similar to the one described by Purcell (2000), where digital photographs are taken in different stages of crop development. The camera (model ELPH13015, Canon, Japan) was mounted on a monopod attached to a polyvinyl chloride pipe (PVC) placed approximately one meter above the ground, which encompassed approximately one meter square of the plot area. The camera was inclined to ensure PVC pipe was not included in the frame of the picture. One downward-facing picture was taken at random within each plot. Pictures were then analyzed for percent green canopy cover using Canopeo (Patrignani and Ochsner, 2015). Canopy cover measurements were taken a few times prior to jointing (Feekes GS 6), and on a bi-weekly basis from jointing until physiological maturity (Feekes GS 11.4). Disease ratings were taken 14-20 days after fungicide application, and evaluated for stripe and leaf rust severity. Plots were given a percent leaf area affected by each disease throughout the plant canopy. Lodging scores were taken on the day of harvest for each experimental unit, and scored for percent lodging from 0-100%. Zero percent lodging reflected wheat standing perpendicular to the ground while 100% lodging consisted of the wheat lying completely flat on the ground.

Plant height, final above-ground biomass, and yield components were measured immediately prior to harvest. Plant height was measured from the soil surface to the tip of the wheat awns at three different locations within each experimental unit using a meter stick, and the average of the three sub-samples was used as plot mean height. Above-ground biomass was determined by clipping a one linear meter from the middle row of each plot, avoiding edge effect, and oven drying the samples at 50°C to a constant weight. Yield components were determined from the above-ground biomass samples. Spikes m^{-2} were estimated from each sample prior to sample threshing, which was performed using a bucket and drill system. The grains from each sample were weighed, and the quotient of grain weight over total sample weight was used as the HI. A grain sub-sample was used to measure 1000-grain weight and average number of grains per spike. Grain yield was determined by combine harvesting the entire experimental unit.

Grain samples were retrieved from each experimental unit by mechanically harvesting the entire plot, and were cleaned to remove foreign material using an air-blast seed cleaner (Alma, Co SABSCIC, Nevada, IA). Grain protein concentration (g kg^{-1}) and test weight (kg m^{-3}) were measured from these samples using a near-infrared reflectance spectroscopy technique with a Perten DA 7200 and both are reported on a 135 g kg^{-1} water basis.

Economic Analysis

Our economic analysis was performed over the variable costs that were considered treatments; thus, the values reported are going to be inflated as compared to a real life situation where other variable (i.e. weed, insect, and machinery) or fixed (i.e. land payment or taxes) costs are considered. Variable input costs included N, S, Cl, plant population, fungicide, and PGR, and a breakdown of individual prices can be found at Table 2-19. Wheat grain price of \$142 Mg^{-1}, which reflects actual grain price, from Cargill in Salina, KS on July 27, 2017. This location was selected for grain price as this was a central location where producers from the research sites could realistic deliver grain, if necessary, avoiding bias as producers who harvest grain early might have a higher or lower price at the end of harvest. A net income value was determined by summing each variable input costs associated with each individual management strategy, and were calculated by block to allow for statistical analysis. This economic analysis allows to determine which management strategies are economically reducing the winter wheat yield gap in Kansas.

Yield Gap Analysis

Percent YP was determined for each individual management strategy at each particular site-year, using the Y_w as reference for water-limited yield and was calculated by block to allow for statistical analysis (Equation 2-1). The Y_w was chosen as the threshold as it was the most intensively managed treatment, receiving all other individual management practices and no signs of yield limiting factors were observed (e.g. diseases, lodging, insects, etc.), thus being representative of the potential yield for each site-year (Van Ittersum et al., 2013). By using the Y_w as the threshold, we were able to measure how far the current farmer practice yields were from the water-limited potential yields, and to quantify the individual contribution of each management practice in economically reducing the yield gap.

Equation 2-1.

$$\textit{Yield Gap \%} = \frac{(\mathbf{Yw}-\textbf{Individual Managment Strategy})}{\mathbf{Yw}}$$

Statistical Analysis

The effects of different treatments on vegetative growth parameters (i.e. percent green canopy cover, disease incidence, and above-ground biomass), grain yield, yield components (i.e. spikes m^{-2}, grains per spike, 1000-grain weight), grain protein concentration, yield gap, and net income were analyzed with a linear mixed model using the PROC MIXED procedure of SAS Version 9.4 (SAS Institute Inc, 2009). Analyses of variance followed a hierarchical structure at two different levels. First, treatment effect was evaluated at each individual site-year considering treatment as fixed effects and blocks as random effects. Second, site-years were combined based on the tillage practice adopted in each locations, as previous literature indicated that management strategies needed to maximize wheat grain yield are different according to tillage adopted (Staggenborg et al., 2003), low or high stripe rust pressure measured during the growing season, and growing region within the state of Kansas (eastern or central). Thus, the two site-years conducted in Manhattan (2015-16 and 2016-17) were combined under a no-till level, which had low levels of stripe rust and located in eastern Kansas (hereafter be referred as no-till throughout this publication). Likewise, the four remaining site-years (Hutchinson and Belleville, 2015-16 and 2016-17) were combined under a conventional-till level, which had high levels of stripe rust and located in central Kansas (hereafter be referred as conventional till throughout this publication). For the combined analysis, treatments were considered as fixed effects, and locations, years, and blocks were considered random effects, locations nested within year and blocks nested within location and year. At all hierarchical levels adopted, a one-way analysis of variance was used due to the incomplete nature of the factorial structure adopted, and degrees of freedom were computed using the approximation described by Kenward and Roger (1997). A pre-planned set of orthogonal contrasts was used to evaluate the significance of the difference in least square means estimates between specific factors across treatments at the 0.05 probability level. Orthogonal contrasts were constructed to evaluate the effect of FP versus Y_w across all individual treatment additions or removals, as well as the effect of each individual factor across both FP and Y_w. For instance, the FP was compared to the FP plus fungicide, and the Y_w was compared to the Y_w minus fungicide. Likewise, to evaluate whether fungicide was a significant factor across management levels, orthogonal contrasts were specified to compare both FP and the Y_w minus fungicide (both treatments with no added fungicide, across management levels) versus both FP with additional fungicide and the Y_w treatment (both treatments with added fungicide, across management levels). Linear regression analysis was used to evaluate the relationship between yield and yield components (spikes m^{-1}, kernels $spike^{-1}$, and kernel weight), and the relationship between yield components (spikes m^{-1}, kernels $spike^{-1}$, and kernel weight).

Results

Weather Conditions

The weather conditions at all six site-years followed similar trends, except for slightly lower precipitation totals in 2016-17. Overall, all locations received adequate moisture at planting for good seedling emergence and stand establishment in both seasons, except that a day after sowing Belleville in 2016-17, over 25 mm precipitation created a crust on the soil surface that hindered seedling emergence, resulting in below optimum stand establishment. Still, due to the high compensation capacity of wheat, yields were likely not affected (Table 2-7). During both seasons, the winter and early spring had above normal temperatures and below normal precipitation (late Feb/Early March, Table 2-4), and the spring consisted of above average rainfall and below average temperatures (Table 2-4), allowing for increased disease pressure (USDA-ARS, 2016a) and yield potential (Lingenfelser et al., 2016). During 2015-16, the dry winter prolonged until mid-April at all locations, hindering tillering capacity and precluding early season fertilizer from being dissolved into the soil profile, likely affecting tiller survival and the establishment of potential kernels per spike. However, spring precipitation started in mid-March in 2016-17 and the early fertilizer application, applied in a timely manner and all locations, received precipitation within days after application and dissolved into the root zone. This allowed for increased tillering and potential of spikelets per spike. June was warmer and drier than normal for both seasons, which allowed for excellent harvest conditions (Table 2-4).

Grain Yield

Overview

Across growing seasons, average grain yield was greater in 2016-17 than in 2015-16 (Table 2-7). In 2015-16, above average rainfall in Belleville during the spring allowed for adequate grain filling conditions resulting in above average yields ranging from 3.45 to 6.68 Mg ha^{-1}. Hutchinson followed the same weather pattern; however, sowing towards the late end of the optimum window hindered fall tillering and reduced kernels m^{-2}, consequently decreasing yield levels (2.14-3.92 Mg ha^{-1}). The entire plot area in Manhattan experienced severe geese grazing in January 2016, reducing yields to 3.13-3.86 Mg ha $^{-1}$, which are still above the ten year average for that region (2.3 Mg ha $^{-1}$) (Lollato et al., 2017). In 2016-17, all locations received 400-700 mm in rainfall during the growing season, which is considered greater than needed for maximum wheat yields (Patrignani et al., 2014). In addition, below average temperature during May and early June resulted in grain yields as high as 6.38, 6.85, and 5.46 Mg ha^{-1} at Belleville, Hutchinson, and Manhattan, respectively.

Treatment effects on grain yield by site-year

There was a significant treatment effect on grain yields at all site-years (Table 2-6). In Belleville 2015-16, 2016-17, and Hutchinson 2015-16, grain yields only responded to foliar fungicide; meanwhile, in Hutchinson 2016-17, foliar fungicides and split-N affected grain yields. All aforementioned sites, conducted under conventional tillage, were centrally located in the state and experienced greater disease pressure in both seasons than the Manhattan location. The disease pressure at these locations significantly decreased percent green leaf area early following anthesis (Figure 2-1). For instance, the absence of foliar fungicides reduced green canopy cover from approximately 84% to 39% at Belleville 2016-17, and similar trends were observed at the other locations (Figure 2-1). Although wheat is not usually source-limited during grain fill (Borrás et al., 2004), the reduced leaf area early during the grain filling period likely led to some extent of source limitation, reducing wheat yields.

In Belleville 2015-16, adding foliar fungicide to the FP increased yields from 4.04 Mg ha $^{-1}$ to 6.21 Mg ha $^{-1}$, and removing fungicide from the Y_w decreased yields from 6.52 Mg ha $^{-1}$ to 4.27 Mg ha $^{-1}$ (Table 2-7). Orthogonal contrasts at this site-year indicated that yields were significantly increased by 2.14 Mg ha $^{-1}$ due to the Y_w and by 2.21 Mg ha $^{-1}$ due to fungicide alone. Similarly, in Hutchinson 2015-16, the addition of fungicide significantly increased yields from 2.55 Mg ha^{-1} in the FP to 3.36 Mg ha $^{-1}$ and removal of fungicide from the Y_w reduced yields from 3.45 Mg ha $^{-1}$ to 2.19 Mg ha $^{-1}$ (Table 2-7). Orthogonal contrasts indicated the yields were increased by 0.67 Mg ha $^{-1}$ due to the Y_w and by 1.03 Mg ha $^{-1}$ due to fungicide. In Belleville 2016-17, adding foliar fungicide to the FP control did not significantly increase grain yield (5.20 Mg ha $^{-1}$, Table 2-7) but removing fungicide from the Y_w reduced grain yield from 6.05 Mg ha $^{-1}$ to 4.74 Mg ha $^{-1}$. Orthogonal contrasts indicated that the Y_w and fungicide increased yields by 0.73 and 0.94 Mg ha $^{-1}$, respectively. In Hutchinson 2016-17, grain yields significantly responded to fungicide and split-N treatments. The FP yielded 4.95 Mg ha $^{-1}$ and increased to 6.06 Mg ha $^{-1}$ due to the addition of fungicide. Meanwhile, the Y_w yielded 6.77 Mg ha $^{-1}$ and yields were significantly reduced by the removal of split-N (6.03 Mg ha $^{-1}$) and fungicide (4.78 Mg ha $^{-1}$). Orthogonal contrasts indicated that yields were significantly increased by 1.23 Mg ha $^{-1}$ due to the Y_w, by 0.41 Mg ha $^{-1}$ due to split-N, and by 1.55 Mg ha $^{-1}$ due to fungicide.

In the eastern location, Manhattan, which was conducted under no-till and experienced low disease pressure, grain yields responded to split-N, S, and increased plant population both growing seasons, and to foliar fungicide in 2015-16. Interestingly, during the first studied season, no addition of treatments significantly increased yields from the FP (3.19 Mg ha $^{-1}$, Table 2-7). However, the Y_w yielded 3.86 Mg ha $^{-1}$, and yields were significantly reduced by the removal of split-N (3.30 Mg ha $^{-1}$), S (3.57 Mg ha $^{-1}$), decreasing plant population (3.52 Mg ha $^{-1}$), and fungicide (3.57 Mg ha $^{-1}$). Orthogonal contrasts indicated that 2015-16 yields were increased by the F_w (0.36 Mg ha $^{-1}$), split-N (0.25 Mg ha $^{-1}$), and increased plant population (0.29 Mg ha $^{-1}$). During 2016-17, the FP yielded 4.90 Mg ha $^{-1}$, and increasing plant population significantly increased yields to 5.28 Mg ha $^{-1}$. Meanwhile, the Y_w yielded 5.66 Mg ha $^{-1}$, and yields were significantly reduced by the removal of split-N (5.00 Mg ha $^{-1}$), S (4.99 Mg ha $^{-1}$), and increased plant population (5.17 Mg ha $^{-1}$). Orthogonal contrasts indicated that yields were increased by 0.38 Mg ha $^{-1}$ due to Y_w, by 0.30 Mg ha $^{-1}$ due to extra split-N, by 0.36 Mg ha $^{-1}$ due to increasing S, and by 0.43 Mg ha $^{-1}$ due to increasing plant population.

Treatment effects on grain yield pooled for no-till and conventional till

Across locations and years, average grain yields were greater in the conventional till as compared to the no-till (Table 2-7). In the conventional till, fungicide was the only significant treatment affecting grain yield. This was likely an unplanned consequence of all four site-years being centrally located, where greater disease pressure was experienced. The FP yield increased from 4.18 Mg ha $^{-1}$ to 5.34 Mg ha $^{-1}$ due to the addition of fungicide, and removing fungicide from the Y_w reduced yield from 5.70 to 3.99 Mg ha $^{-1}$. This significant yield effect can be attributed to the FP yields being increased by fungicide in three out of the four site-years (Belleville 2015-16 and Hutchinson 2015-16 and 2016-17), and Y_w yields being reduced in all four site-years by the removal of the fungicide (Table 2-7). Orthogonal contrasts indicated that yields were increased by the Y_w (1.18 Mg ha $^{-1}$), and fungicide (1.44 Mg ha $^{-1}$) in the conventional till analysis.

Across site-years under no-till, the FP yielded 4.05 Mg ha $^{-1}$ and only the addition of plant population increased yields to 4.35 Mg ha $^{-1}$. No other individual treatment addition significantly affected grain yield. The Y_w treatment increased grain yield to 4.76 Mg ha $^{-1}$, and the removal of split-N reduced yields to 4.15 Mg ha $^{-1}$, of S reduced yields to 4.25 Mg ha $^{-1}$, of plant population reduced yields to 4.34 Mg ha $^{-1}$, and of foliar fungicide reduced yield to 4.44 Mg ha $^{-1}$. Orthogonal contrasts indicated that yields were increased by the Y_w (+0.37 Mg ha $^{-1}$), split-N (+0.28 Mg ha $^{-1}$), S (+0.26 Mg ha $^{-1}$), increased plant population (+0.36 Mg ha^{-1}), and fungicide (+0.18 Mg ha $^{-1}$).

Yield Gap

Yield gaps were measured by block using as reference the yield obtained in the Y_w treatment. The treatment most commonly affecting YG was foliar fungicide that coincidently had high disease pressure, especially the in conventional tilled and central locations. The largest YG across all six site-years was measured in Belleville during 2015-16 (Table 2-8), where the addition of fungicide decreased the YG from 37% in the FP to 3%. Likewise, removing foliar fungicide from the Y_w increased the YG to 33%. Orthogonal contrasts indicate that the YG was reduced by 33% due to the Y_w and by 34% due to fungicide. In Hutchinson 2015-16, treatment effects on YG followed the same trend as in Belleville and a measured YG of 25% in the FP and decreased to 2% due to the addition of fungicide while the YG increased to 37% due to the removal of fungicide from the Y_w. Orthogonal contrasts indicate that the Y_w reduced the YG by 19%, and fungicide reduced the yield gap by 30%. In Belleville 2016-17, a YG of 14% in the FP decreased to 9% due to increased plant population and to 5% due to foliar fungicide. Likewise, the removal of fungicide from the Y_w increased the YG to 22%. Orthogonal contrasts indicate that the YG was reduced by 12 % due to $Y_{w,}$ and by 16% due to fungicide. In Hutchinson 2016-17, the YG was 27% in the FP, and the addition of fungicide decreased the yield gap to 11%. When the split-N and fungicide were removed from the Y_w, the YG increased to 11% and 29%, respectively. Orthogonal contrasts indicate that the YP was reduced by the Y_w (18%), split-N (6%), and fungicide (23%).

In Manhattan during both growing seasons, multiple treatments affected the YG (Table 2-8). In 2015-16, the YG was 19% in the FP and was not affected by the addition of treatment applications; however, removing split-N from the Y_w increased YG to 16%, decreased plant population increased YG to 10%, and foliar fungicide increased YG to 9%. Orthogonal contrasts indicated that more treatments affected the YG (Table 2-8): the Y_w reduced the YG by 9%, and split-N and increased plant population reduced the YG by 6% and 7%, respectively. In 2016-17, the YG was decreased from 13% in the FP to 6% due to increased plant population, and increased by the removal of split-N (11%), S (11%), and increased plant population (8%) from the Y_w (Table 2-8). Orthogonal contrasts indicated that the Y_w reduced the YG by 7%, S reduced it by 6%, and increased plant population by 8%.

The analyses pooled across site-years by tillage practice indicated a significant treatment effect on YG for both conventional and no-till systems (Table 2-6). Overall, the conventional till had larger YG than the no-till system (Table 2-8). In the no-till and low disease pressure, the YG of the FP was 16%; and increasing plant population reduced the YG to 9%. Meanwhile, the YG for the Y_w was increased to 13% by removing split-N, to 10% by removing S, to 9% by decreasing plant population, and to 7 % by removing fungicide. Orthogonal contrasts indicated that the YG was reduced from FP by 8% due to the Y_w, by 6% due to split-N, by 5% due to S, by 3% due to Cl, by 8% due to increased plant population, and by 4% due to fungicide. Meanwhile in the conventional till and high disease pressure, the YG was reduced to 5% when fungicide was added to the FP, and the YG increased to 30% when fungicide was removed from the Y_w. No other treatment applications reduced or increased the YG. Orthogonal contrasts indicate that the

YG was reduced from the FP by 20% due to the Y_w and by 25% due to the fungicide in conventional till and high disease pressure.

Grain Protein Concentration

Despite some site-specific variability, the extra N applied as a split application seemed to be the most consistent factor affecting grain protein concentration in most site-years. In Belleville 2015-16 and 2016-17, Manhattan 2015-16 and 2016-17, and Hutchinson 2016-17, grain protein concentration was affected by split-N (Table 2-9). For instance, in Belleville 2015-16, the addition of split-N increased protein to 121 g kg^{-1} compared to 116 g kg^{-1} of the FP, whereas removing split-N decreased protein from 123 g kg^{-1} in the Y_w to 116 g kg^{-1}. Orthogonal contrasts indicate that grain protein concentration was increased by 5 g kg^{-1} due to Y_w, by 6 g kg^{-1} due to split-N. In Belleville 2016-17, grain protein increased from 110 g kg^{-1} in the FP to 118 g kg^{-1} due to addition of split-N and to 115 g kg^{-1} due to fungicide. On the other hand, grain protein decreased from 130 g kg^{-1} in the Y_w to 120 g kg^{-1} due to the removal of split-N and to 123 g kg^{-1} when fungicide was removed. Orthogonal contrasts indicated that grain protein was increased by the Y_w (14 g kg^{-1}), split-N (9 g kg^{-1}), fungicide (6 g kg^{-1}), and PGR (5 g kg^{-1}). In Manhattan 2015-16, the addition of split-N increased protein concentration to 119 g kg^{-1} from 110 g kg^{-1} of the FP. Likewise, the removal of split-N from the Y_w decreased the grain protein from 121 g kg^{-1} to 111 g kg^{-1}. Orthogonal contrasts indicated that grain protein concentration increased by 8 g kg^{-1} due to the Y_w, and by 10 g kg^{-1} due to split-N. In Manhattan 2016-17, the FP grain protein was 119 g kg^{-1} and increased by split-N to 127 g kg^{-1}. Likewise, grain protein was reduced from 131 g kg^{-1} in the Y_w to 122 g kg^{-1} due to the removal of split-N. Orthogonal contrasts indicated that grain protein was increased by the Y_w (10 g kg^{-1}) and split-N (8 g kg^{-1}). In Hutchinson 2015-16, there was no effect of split-N on grain protein concentration; instead, grain protein increased from 124 g kg^{-1} in the Y_w to 133 g kg^{-1} due to the addition of fungicide, and the Y_w was unaffected by the removal of treatments. Orthogonal contrasts indicate that grain protein was increased by the Y_w (10 g kg^{-1}), split-N (3 g kg^{-1}), and fungicide (6 g kg^{-1}). During 2016-17, however, the addition of split-N and PGR increased the FP grain protein from 93 g kg^{-1} to 119 and 96 g kg^{-1}, respectively, in Hutchinson. Likewise, the removal of split-N decreased protein to 93 g kg^{-1} compared to the 123 g kg^{-1} of the Y_w. Orthogonal contrasts indicated that grain protein increased by 21 g kg^{-1} due to the Y_w and by 28 g kg^{-1} due to split-N.

Pooled across locations and years based on tillage practice, analysis of variance indicated a significant treatment effect on grain protein concentration for both the conventional and no-till systems (Table 2-6), and only the split-N treatment affected protein at both tillage systems (Table 2-9). In the no-till, FP grain protein increased from 114 g kg^{-1} to 123 g kg^{-1} from the addition of split-N, and decreased from 126 g kg^{-1} in the Y_w to 117 g kg^{-1} when split-N was removed. Orthogonal contrasts indicate that grain protein increased by 9 g kg^{-1} due to both of the Y_w and split-N treatments in the no-till. Likewise, the FP grain protein increased from 111 g kg^{-1} to 121 g kg^{-1} from the additional split-N, and the Y_w grain protein decreased from 128 g kg^{-1} to 116 g kg^{-1} from the removal of split-N in the conventional till. Similarly, orthogonal contrasts indicated that grain protein increased by 12 g kg^{-1} for both of the Y_w and split-N treatments in the conventional till.

Test Weight

A large variation in grain test weight occurred in 2015-16, ranging from 661 to 785 kg m^{-3} (Table 2-10). In Belleville, increasing plant population decreased test weight from 766 kg m^{-3} in the Y_w to 747 kg m^{-3}; meanwhile, adding fungicide increased test weight to 784 kg m^{-3}. Likewise, test weight decreased from 776 kg m^{-3} in the Y_w to 758 kg m^{-3} due to the removal of fungicide. Orthogonal contrasts indicated that the Y_w increased test weight by 12 kg m^{-3}, and fungicide by 18 kg m^{-3}. Meanwhile, the increased plant population and PGR decreased test weight by 11 kg m^{-3} and 8 kg m^{-3}, respectively. In Hutchinson 2015-16, test weight increased from 679 to 735 kg m^{-3} when fungicide was added to the Y_w, and adding PGR decreased to test weight to 637 kg m^{-3}. Removal of fungicide from the Y_w decreased test weight from 744 to 667 kg m^{-3}. Orthogonal contrasts indicated that test weight increased by 47 kg m^{-3} due to the Y_w, by 16 kg m^{-3} due to increased plant population, and by 67 kg m^{-3} due to fungicide. Meanwhile, the application of PGR decreased test weight by 20 kg m^{-3}. In Manhattan, test weight did not respond to treatment application (Table 2-10). Grain test weights were more consistent in 2016-17 as compared to 2015-16, ranging from 763 to794 kg m^{-3} (Table 2-10). Following the same trend as that observed during 2015-16, the addition of fungicide increased test weight from 790 to 797 kg m^{-3} and addition of split-N reduced test weight from 790 to 780 kg m^{-3} in Belleville. Removal of fungicide reduced test weight from 792 kg m^{-3} in the Y_w to 781 kg m^{-3}. These trends were confirmed by the orthogonal contrasts, which indicated that test weight increased by 2 kg m^{-3} due to the Y_w and by 9 kg m^{-3} due to fungicide, whereas split-N decreased test weight by 6 kg m^{-3}. Similar results were measured in Hutchinson, where test weight decreased from 779 kg m^{-3} to 763 kg m^{-3} due to the addition of split-N, and from 777 kg m^{-3} in the Y_w to 760 kg m^{-3} due to the removal of fungicide. Orthogonal contrasts indicated that test weight decreased by 2 kg m^{-3} and 8 kg m^{-3} from the Y_w and split-N, respectively; however, fungicide increased test weight by 8 kg m^{-3}. In Manhattan, removing S from the Y_w increased test weight from 784 to 791 kg m^{-3}. Orthogonal contrasts indicate that test weight was decreased by 5 kg m^{-3} due to S across management strategies.

Analysis of variance pooled across environments by tillage practice indicated no treatment effect for either tillage practice (Table 2-6). These results are likely attributed to the large range of test weights measured across locations (Table 2-10). However, trends in the individual site-year analyses support that increased split-N reduced test weight (three site-years), while the Y_w (three site-years) and fungicide (four site-years) increased test weight.

Economics

Net income followed similar trends to those observed on grain yield. In Belleville 2015-16, net income of the FP was \$436 ha^{-1} and was reduced to approximately \$265 ha^{-1} by each addition of split-N and PGR; meanwhile, fungicide application increased net income to \$612 ha^{-1}. Likewise, the removal of split-N from the Y_w increased net income to \$534 ha^{-1} as compared to \$407 ha^{-1}; however, the removal of fungicide decreased the net income to \$199 ha^{-1}. Orthogonal contrasts indicate net income was reduced by split-N (-\$151 ha^{-1}), Cl (-\$88 ha^{-1}), and PGR (-\$122 ha^{-1}), and increased by fungicide (+\$192 ha^{-1}). Following the same trend as Belleville, the FP had a net income of \$262 ha^{-1} and was reduced to \$148 ha^{-1} from the additional split-N and to \$139 ha^{-1} from the PGR in Hutchinson 2015-16. The Y_w had a net income of \$54 ha^{-1}, and the removal of split-N increased the net income to \$225 ha^{-1} and the removal of fungicide decreased the net income to a negative \$39 ha^{-1}. Orthogonal contrasts indicated net income was reduced by the Y_w (-\$135 ha^{-1}), split-N (-\$139 ha^{-1}), Cl (-\$55 ha^{-1}), and PGR (-\$86 ha^{-1}), and increased by fungicide (+\$51 ha^{-1}). In Belleville 2016-17, the treatments did not increase or decrease the net income for either of the FP (\$565 ha^{-1}) or Y_w (\$441 ha^{-1}). Orthogonal contrasts indicated that the net income was reduced by Y_w (-\$92 ha^{-1}) and PGR (-\$109 ha^{-1}). In Hutchinson 2016-17, the FP had a net income of \$588 ha^{-1} and it was reduced to \$480 ha^{-1} due to split-N and to \$515 ha^{-1} due to increased plant population; meanwhile, the removal of fungicide from the Y_w decreased net income to \$319 ha^{-1} from \$517 ha^{-1}. Orthogonal contrasts indicate that the net income was reduced by Y_w (-\$54 ha^{-1}), split-N (-\$53 ha^{-1}), PGR (-\$64 ha^{-1}) and increased by fungicide (+\$125 ha^{-1}).

In Manhattan 2015-16, the addition of split-N and fungicide decreased net income to \$179 ha^{-1} and 211 \$ ha^{-1}, respectively when compared to the FP (\$307 ha^{-1}). Meanwhile, the Y_w was not significantly affected by the removal of any individual treatment. Orthogonal contrasts indicated that net income was decreased by the Y_w (-\$179 ha^{-1}), split-N (-\$76 ha^{-1}), and fungicide (-\$70 ha^{-1}). In Manhattan 2016-17, net income for the FP was \$598 ha^{-1} and was reduced to a range of \$418-531 ha^{-1} from the addition of split-N, fungicide, and PGR. However, the Y_w had a net income of \$402 ha^{-1}, and it was reduced from the removal of S to \$294 ha^{-1}, and increased to \$452 ha^{-1} from the removal of fungicide. Orthogonal contrasts indicated that the net income was reduced by Y_w (-\$171 ha^{-1}), split-N (-\$76 ha^{-1}), and fungicide (-\$108 ha^{-1}), and increased by increased plant population (+47 \$ ha^{-1}).

Analysis of variance pooled across site-years by tillage practice indicated that there was a significant treatment effect for both the no-till which had low disease pressure and conventional till which had high disease pressure systems (Table 2-6). In the no-till system and low disease pressure, the FP net income was reduced from \$452 ha^{-1} by the additional split-N (\$326 ha^{-1}), Cl (\$414 ha^{-1}), fungicide (\$334 ha^{-1}), and PGR (\$388 ha^{-1}). Likewise, the Y_w net income was reduced from \$225 ha^{-1} by the removal of S and increased plant population to \$169 ha^{-1} and \$180 ha^{-1}, respectively, and the fungicide increased net income to \$284 ha^{-1}. Orthogonal contrasts indicated that net income was reduced by Y_w (-\$175 ha^{-1}), split-N (-\$76 ha^{-1}), Cl (-\$25 ha^{-1}), fungicide (-\$89 ha^{-1}), and PGR (-\$35 ha^{-1}). Meanwhile, the increased plant population increased net income by \$37 ha^{-1} in the no-till system. The net income of the conventional till and high disease pressure was affected by the split-N, PGR, and fungicide (Table 2-11). The net income of the FP was reduced to \$335 ha^{-1} from the split-N and \$342 ha^{-1} from the PGR. Likewise, the Y_w had a net income of \$356 ha^{-1} but it was reduced to \$197 ha^{-1} when the fungicide was removed. For the conventional till system, the orthogonal contrasts indicated that the net income was reduced by Y_w (-\$56 ha^{-1}), split-N (-\$106 ha^{-1}), and PGR (-\$95 ha^{-1}); however, the fungicide increased net income by \$107 ha^{-1}.

Plants m^{-2}

As expected, there was a significant treatment effect ($p<0.001$) for plant population at each individual site-year (Table 2-6). The individual addition of increased plant population to the FP increased plant stand establishment, and the individual removal of increased plant population from the Y_w reduced plant stands in all individual site-locations in 2015-16 and 2016-17 (Table 2-12). Similarly, orthogonal contrasts indicated that plant population was the only treatment affecting plant stands across management levels. In our pooled analysis, there was a significant treatment effect on final plant stand ($p<0.001$) for both the conventional and no-till systems. Average plant stand was 188 plants m^{-2} in no-till and 212 plants m^{-2} in conventional till, and increased by 27% and 48% due to increased plant population, respectively. There was no other significant treatment effect affecting plants stands. Across treatments and locations, orthogonal contrasts indicated that plant population was the only treatment that affected plant stands (Table 2-12), as would be expected, indicating that plant stands can be increased with increased seeding rates.

Plant Height

There was a significant treatment effect ($p<0.001$) on plant height at each individual site-year both growing seasons (Table 2-6). Average plant height was variable within location and treatment in 2015-16 (Table 2-13). In Belleville 2015-16, plant height was affected by plant population, split-N, and fungicide. Plant height increased from 83 cm in the FP to 91 cm due to increased plant population. The Y_w had an average plant height of 89 cm, and the individual removal of split-N and fungicide decreased plant height to 80 and 75 cm, respectively. Orthogonal contrasts indicate that fungicide increased plant height by 8 cm. In Hutchinson, plant height significantly responded to the PGR and fungicide treatments (Table 2-13), reducing from 77 cm in the FP to 60 cm due to PGR and from 67 cm in the Y_w to 55 cm when fungicide was removed. Orthogonal contrasts indicate that the Y_w decreased plant height by 4 cm, and PGR application decreased plant height by 12 cm. In Manhattan, plant height was significantly affected by increased plant population and PGR (Table 2-13). Increasing plant population increased plant height from 76 cm in the FP to 79 cm, and removing PGR from the Y_w increased plant height from 76 cm to 79 cm. Orthogonal contrasts indicate PGR decreased plant height by 2 cm in this location-year.

Treatment effect on plant height was more consistent in 2016-17 (Table 2-13). In Belleville, plant height was 93 cm in the FP treatment and reduced to 82 cm due to addition of PGR, while Y_w plant height increased from 87 cm to 98 cm when PGR was removed. Orthogonal contrasts indicate that the Y_w and PGR significantly decreased plant height by 4 cm and 12 cm, respectively. In Hutchinson, FP plant height was 87 cm; however, the addition of S increased plant height to 90 cm, and PGR decreased plant height to 75 cm. The removal of fungicide increased plant height of the Y_w from 79 cm to 88 cm, likely due to a fungicide interaction with PGR. Orthogonal contrasts indicated that Cl (+2 cm), fungicide (+4 cm), and split-N (+2 cm) increased plant height, whereas PGR (-7 cm) decreased plant height at this location (Table 2-13). In Manhattan, plant height decreased from 97 cm in the FP to 78 cm as a result of the PGR application. Likewise, the removal of split-N and S from the Y_w reduced plant height from 83 cm to 79 and 78 cm, respectively. The removal of PGR significantly increased plant height from the Y_w to 98 cm. Orthogonal contrasts indicated that plant height decreased due to the Y_w treatment (-11 cm) and PGR (-17 cm), and increased by S (+3 cm).

Average plant height was affected by treatment application across both tillage practices (Table 2-13). In our analysis pooled across no-till locations, plant height at the FP treatment was 86 cm and 80 cm in the Y_w treatment; however, no individual additional or removal of treatments affected plant height. In the conventional till pooled analysis, plant height in the FP treatment was 85 cm as compared to 83 cm in the Y_w treatment. Plant height decreased to 73 cm from FP due to addition of PGR. Likewise, plant height was decreased to 74 cm from the Y_w due to the removal of fungicide and increased to 88 cm from the Y_w due to the removal of PGR. Orthogonal contrasts indicate that plant height increased by 4 cm due to fungicide, and deceased by 8 cm due to PGR.

Aboveground Dry Matter

In Belleville and Manhattan during the 2015-16 growing season, aboveground dry matter (DM) was not affected by individual treatment application (Table 2-14). However, orthogonal contrasts indicated that the Y_w increased DM in 3.09 Mg ha^{-1} and fungicide by 2.1 Mg ha^{-1} in Belleville. In Hutchinson, the removal of fungicide reduced DM from 10.44 Mg ha^{-1} in the Y_w to 7.53 Mg ha^{-1}. Orthogonal contrasts indicated that the Y_w increased DM by 1.6 Mg ha^{-1} and foliar fungicide increased DM by 2.11 Mg ha^{-1}. Following the same trend in 2015-16, total aboveground DM was not affected by individual treatment application in Belleville and Manhattan (Table 2-14). In Hutchinson, foliar fungicide increased DM from 13.07 Mg ha^{-1} in the FP to 16.10 Mg ha^{-1}. Likewise, removal of fungicide from the Y_w reduced DM from 19.97 to

15.4 Mg ha^{-1}, and removal of split-N reduced it to 15.9 Mg ha^{-1}. Orthogonal contrasts indicated that aboveground DM was increased by Y_w (+3.6 Mg ha^{-1}), split-N (+2.4 Mg ha^{-1}), Cl (+2.4 Mg ha^{-1}), and fungicide (+3.2 Mg ha^{-1}). Analysis of variance pooled across tillage practices suggested a significant treatment effect on aboveground DM for both no-till and conventional till (Table 2-6). In no-till, increased plant population increased DM from 11.09 Mg ha^{-1} in the FP to 12.8 Mg ha^{-1}, and the removal of treatments did not affect the Y_w. Orthogonal contrasts indicate the Y_w increased DM by 0.94 Mg ha^{-1} in no-till. In the conventional till, the addition of each individual treatment resulted in similar DM to the FP; however, total DM decreased from 15.3 Mg ha^{-1} in the Y_w to 13.4 Mg ha^{-1} due to the removal of fungicide. Orthogonal contrasts indicated that Y_w increased DM by 2.2 Mg ha^{-1} and fungicide by 1.9 Mg ha^{-1}.

Harvest Index

In Belleville and Manhattan, 2015-16, the addition or removal of treatments did not significantly affect HI from their respective control. However, in Hutchinson, the addition of fungicide increased HI from 0.35 in the FP to 0.41, and removal of fungicide from the Y_w reduced HI from 0.39 to 0.35. Orthogonal contrasts indicated that the Y_w increased HI in 0.01, and fungicide increased HI in 0.05 during 2015-16. In 2016-17, HI was unaffected by the addition of each treatment in Belleville as compared to the FP. However, removing PGR decreased HI from 0.37 in the Y_w to 0.27. Orthogonal contrasts indicated that the PGR increased HI by 0.06 in this site-year. In Hutchinson, 2016-17, addition of split-N reduced HI from 0.45 in the FP to 0.41, and the Y_w was unaffected by the removal of treatments. Orthogonal contrasts indicated that the split-N (-0.03) and S (-0.02) reduced HI in this site-year. In Manhattan 2016-17, both Y_w and FP were unaffected by addition and removal of treatments when compared to their respective control, with no treatment response measured. Analysis of variance pooled across locations based on tillage practice indicated no treatment effect on HI for both no-till and conventional till (Table 2-6), with HI values ranging from 0.35 to 0.40 for all treatment applications and controls.

Spikes m^{-2}

In Manhattan 2015-16, spikes m^{-2} increased from 773 in the FP to 910 due to increased plant population, while removal of treatments from the Y_w had no significant effect. Orthogonal contrasts indicated that Y_w increased the spikes m^{-2} by 101 and by 114 due to increased plant population. In Belleville and Hutchinson, 2015-16, the addition or removal of treatments did not affect spikes m^{-2} when compared to their respective control. Orthogonal contrasts indicated that Y_w increased spikes m^{-2} by 152 in Belleville and 91 in Hutchinson. Similarly, the addition or removal of treatments from its respective control had no effect on spikes m^{-2} in Belleville or Manhattan during 2016-17 (Table 2-16). Orthogonal contrasts indicated that spikes m^{-2} increased by 132 due to the Y_w in Manhattan, but no single treatment consistently led to this increase. In Hutchinson, however, spikes m^{-2} decreased from 1,433 in the Y_w when split-N (1,026), plant population (1,228), or foliar fungicide (1,179) were removed. Orthogonal contrasts indicated that the Y_w increased spikes m^{-2} in 327 and split-N in 262. Our pooled analysis across tillage practices indicated a significant treatment effect in both conventional and no-till systems (Table 2-6). In the no-till system, increased plant population increased spikes m^{-2} from 731 in the FP to 880, and removal of foliar fungicide decreased spikes m^{-2} from 941 in the FP to 830. Likewise, orthogonal contrasts indicated the Y_w increased spikes m^{-2} by 110 and increased plant population by 105 in the no-till system. In the conventional till, spikes m^{-2} was not increased from the addition of each treatment to the FP, and the removing split-N reduced spikes m^{-2} from 1,057 in the Y_w to 907. Orthogonal contrasts indicate that the Y_w increased spikes m^{-2} by 148 but no consistent individual treatment effect occurred.

Kernels m^{-2}

In Belleville 2015-16, decreasing plant population from the Y_w increased kernels m^{-2} from 18,400 to 22,500, and no addition of individual treatments affected the FP. Orthogonal contrasts indicated that the Y_w treatment increased kernels m^{-2} by 2,600 as compared to the FP. Similarly, the FP did not respond to the addition of treatments in Manhattan 2015-16. However, removal of fungicide reduced kernels m^{-2} from 21,000 in the Y_w to 17,900. Orthogonal contrasts indicated that the Y_w increased grains m^{-2} by 2,200 in Manhattan. In Hutchinson during the same growing season, both the FP and Y_w were unresponsive to the addition and removal of treatments, and orthogonal contrasts indicated that there was no treatment effect on kernels m^{-2}. During 2016-17, kernels m^{-2} were unaffected by treatment application in Manhattan and Belleville (Table 2-17). In Hutchinson, removing split-N reduced kernels m^{-2} from 20,500 in the Y_w to 17,200 (Table 2-17). Addition of individual treatments did not increase kernels m^{-2} from the FP. Orthogonal contrasts indicated that the Y_w increased grains m^{-2} in 3,600. Our analysis of variance pooled across locations based on tillage practice indicated a significant treatment effect for no-till but not for conventional till (Table 2-6). In the no-till, addition of individual treatments to the FP did not increase kernels m^{-2}; however, removing fungicide from the Y_w reduced kernels m^{-2} from 22,900 to 19,500. Orthogonal contrasts indicated that grains m^{-2} were increased in 2,500 due to the Y_w.

1000-Kernel Weight

During the 2015-16 growing season in Belleville, foliar fungicide increased 1000-kernel weight from 21.6 g in the FP treatment to 25.5 g, and increased plant population and PGR decreased it to 18.8 g and 19.3 g, respectively (Table 2-18). The Y_w resulted in 1000-kernel weight of 23.4 g, which was increased by the removal of split-N to 26.3 g and removal of S to 25.7 g. However, removing foliar fungicide decreased it to 18.7 g. Orthogonal contrasts indicated that the Y_w increased 1000-kernel weight by 3.0 g and fungicide increased it by 4.3 g. Meanwhile, 1000-kernel weight was decreased by 2.5 g by extra split-N, by 1.7 g when S was provided, by 1.7g by increased plant population, and by 1.7 g when PGR was added in Belleville. In Hutchinson, 1000-kernel weight increased from 18.7 g in the FP to 20.6 g due to extra split-N, to 21 g due to increased plant population, and to 24.7 g due to foliar fungicide. Removal of fungicide from the Y_w was the only treatment to reduce 1000-kernel weight (from 24.4 g to 18.3 g). Orthogonal contrasts indicated that 1000-kernel weight was increased due to the Y_w and fungicide by 3.6 and 6.1g, respectively. In Manhattan, 1000-kernel weight was unaffected by the FP, Y_w, or the individual treatments (Table 2-18). In 2016-17, there was no significant treatment effect on 1000-kernel weight in Belleville or Manhattan (Table 2-18). However, in Hutchinson, 1000-kernel weight decreased from 30.6 g in the FP treatment to 25.2 g due to the addition split-N, and from 31.3 g in the Y_w treatment to 27.0 and 25.5 g due to the removal of Cl and of fungicide, respectively. Orthogonal contrasts indicated that fungicide was the only treatment to increase 1000-kernel weight (3.9 g) in Hutchinson.

Analysis of variance pooled across locations based on tillage practice indicated a significant treatment effect for the conventional till but not for the no-till system (Table 2-6), the latter resulting in very similar 1000-kernel weight between FP (23.2 g) and Y_w (22.1 g) (Table 2-18). Meanwhile, 1000-kernel weight decreased from 26.8 g to 21.5 g by the removal of fungicide in the conventional-till. Orthogonal contrasts indicated that 1000-kernel weight increased by 2 g due to Y_w, and by 4 g due to foliar fungicide.

Discussion

Yield and Yield Components

Conventional Till

Average grain yield increased by foliar fungicide in four site-years (Belleville and Hutchinson, 2015-16 and 2016-17), which can be attributed to the severe stripe rust infestations experienced during both growing seasons in central Kansas (USDA-ARS, 2016b, 2017). Under optimum conditions, over 60% of photosynthates translocated to developing wheat grains are produced by the flag leaf during grain filling; thus, the fungicide application protected the flag leaf from diseases and allowed photosynthates to be produced and translocated to the grain (Rawson et al., 1983; Miller, 1992). As a consequence, in the presence of disease pressure, foliar fungicide applications typically increase wheat yields in susceptible wheat varieties (Thompson et al. 2014). In the Great Plains, Edwards et al. (2012) measured a yield increase of over 20% from fungicide application in the presence of disease.

Fungicide significantly increased 1000-kernel weight three out of four site-years (Belleville 2015-16, and Hutchinson 2015-16 and 2016-17). During these growing seasons, severe stripe rust was present during grain fill, and the fungicide prolonged the grain filling period, which was measured by percent canopy coverage dynamics (Figure 2-1). Likewise, Cruppe et al. (2017) indicated that 1000-kernel weight increased due to foliar fungicide; however, this increase was only measured in high yielding environments. In other wheat growing regions, a reduction in 1000-kernel weight resulted in yield losses from stripe rust infestations (Akanda and Mundt, 1997; Afzal et al., 2008).

Wheat is generally sink limited, and as a consequence, kernels m^{-2} is often more correlated to grain yield than 1000-kernel weight (Borrás et al., 2004). Slafer et al. (2014)

indicated that kernels m^{-2} act as course regulators and are main drivers for wheat grain yield, whereas 1000-kernel weight act as fine regulators and have a smaller effect on increases in grain yield. However, in our results, treatments did not significantly affect kernels m^{-2} (Table 2-17) as consistently as they affected 1000-kernel weight (Table 2-18). As a consequence, correlations between grain yield and 1000-kernel weight ($r^2 = 0.32$, $p < 0.0001$) were greater than those between grain yield and kernels m^{-2} ($r^2 = 0.24$, $p < 0.0001$), suggesting that grain yield was more source- (kernel weight) than sink- (grains m^{-2}) limited. Similarly, Lollato and Edwards, (2015) found kernel weight to play a significant role in increasing wheat grain yield in the U.S. southern Great Plains. Although the authors reported drought as the yield limiting factor instead of disease, the leaf area lost to water-deficit stress likely had similar negative effect reducing source availability. Our experiment adds empirical evidence to support the fact that winter wheat in the U.S. southern Great Plains may be co-limited by source (photosynthates) and sink (potential grains m^{-2}) many growing seasons. Similar co-limitation was reported by Lynch et al. (2017), who indicated kernel weight increased wheat grain yields in one out of nine years. Additionally, Slafer et al. (2014) suggested that increases in kernels m^{-2} were mostly a result of increased spikes m^{-2} rather than kernels spike^{-1}. Our results, however, suggest similar proportion of the variability in kernels m^{-2} explained by kernels spike^{-1} ($r^2 = 0.29$, $p < 0.0001$) and spikes m^{-2} ($r^2 = 0.28$, $p < 0.0001$), likely because spring tillering was compromised by drought and lack of fertilizer dissolution into the root zone in half of the studied site-years (2015-16 growing season). As a consequence, the 2015-16 season resulted in less spikes m^{-2} and grain yield determination relied to a greater extent on kernels spike^{-1}.

Across both locations and growing seasons, aboveground DM, which is highly correlated with grain yields (Calderini et al., 1999), ranged from 7.5 Mg ha^{-1} to 23.3 Mg ha^{-1}. Aboveground

DM greater than 15 Mg ha^{-1} have been reported in the U.S. southern Great Plains, conditions which resulted in yields greater than 5 Mg ha^{-1} (Lollato and Edwards, 2015). Likewise, total aboveground DM greater than 20 Mg ha^{-1} was measured in Belleville, which resulted in yields over 5 Mg ha^{-1}. Also, aboveground DM was unaffected by seeding rate, indicating that the lowest seeding rate studied (i.e. 2.7 million seeds ha^{-1}) would have been sufficient for maximum biomass yield. The response of wheat to plant population density is a function of competition for resources with neighboring plants (Satorre and Slafer, 1999), and increased competition can reduce survival, dry matter production, and grain yield of individual wheat plants (Satorre, 1988). The fact that total biomass production was unaffected by seeding rate, and that kernels m^{-2} increased by kernels spike^{-1}, suggests that 2.7 million seeds ha^{-1} was sufficient for maximum yields in a conventional tilled system in central Kansas.

Harvest index was variable across growing seasons, increasing in three out of six site-years (Table 2-15) mostly due to foliar fungicide added to the FP treatment, and decreasing in one site-year when foliar fungicide was removed from the Y_w treatment. This variability in results led to no significant differences when the data was pooled based on tillage practice (Table 2-6). Similar variability has been reported in the U.S. southern Great Plains, as HI was variable across locations (Lollato and Edwards, 2015) and varieties (Edwards et al., 2012). Likewise, HI was also was affected by a fungicide application when varieties had different levels of disease resistance (Edwards et al., 2012). This experiment and those aforementioned support the fact that HI was affected by year and treatments.

Previous research indicated that the long-term Y_w in the southern Great Plains lies between 5.2 Mg ha^{-1} (Lollato et al., 2017) and 6.7 Mg ha^{-1} (Patrignani et al., 2014). These long-term Y_w are not greater due to environmental variability and hot and dry conditions during the grain filling period as compared to other wheat producing regions (Patrignani et al., 2014; Lollato and Edwards, 2015). However, environmental conditions were optimal in our experiment (above average precipitation and below average spring temperatures) and still, the pooled analysis of four site-years in our research indicated that grain yield in the FP plus fungicide was 5.3 Mg ha^{-1}, and grain yield measured in the Y_w was 5.7 Mg ha^{-1}. These results support the fact that maximizing yields past 5.2 Mg ha^{-1} is highly unlikely in the U.S. southern Great Plains.

No-Till

In a no-till system, average grain yield was affected by split-N, S, increased plant population, and fungicide (Table 2-7), suggesting that a more comprehensive approach is needed to maximize yields. Increased plant population and N rates are generally recommended for wheat grown in a no-till situation to help eliminate the negative effects of heavy residue left on the soil surface (Staggenborg et al., 2003; Whitney and Staggenborg, 2008). Staggenborg et al. (2003) found seeding rates should be increased to 134 kg ha $^{-1}$ when wheat follows sorghum or maize, crops which will produce a large amount of residue. Heavy residue can be problematic as seed placement and establishment can be difficult; thus, increasing seeding rates is justified. Indeed, our results suggested a decreased stand establishment under no-till (240 plants m^{-2}) as compared to conventional till (315 plants m^{-2}). Likewise, Whitney and Staggenborg, (2008) found N rates should be increased by 22.4 kg N ha^{-1} in a no-till cropping system. The justification for this recommendation also lies in the increased residue on the soil surface in no-till, which might immobilize a large portion of the applied N, especially in high C:N ratio residues (Doran, 1980).

The preplant soil S analysis indicated adequate S levels in the soil profile for a yield goal of 4.7 Mg ha^{-1} (i.e. 36 mg S kg^{-1}, Table 2-3) (Leikam et al., 2003). However, as the yield goal was increased to 8.1 Mg ha^{-1} in the Y_w, the soil was deficient in S and warranted S fertilizer application (Leikam et al., 2003). Likewise, an additional 13 mg S kg^{-1}, which includes the 36 mg S kg^{-1} from the preplant soil S analysis, would need to be applied to sustain this Y_w yield goal. Thus, the removal of S from the Y_w resulted in a yield reduction (Table 2-7). Additionally, S availability is lower in early spring time as mineralization of O.M. is low due to cooler temperatures (Camberato and Casteel, 2010). Meanwhile, the majority of S is taken up before anthesis (Hocking, 1994), and by the time organic mineralization increased to levels high enough to meet crop demand, the wheat plant has already taken up the majority of its required S. Thus, S applied to winter wheat in the southern Great Plains results in yield gains many years (Girma et al., 2005). In Kansas, Gardner and Ruiz Diaz (2017) also found wheat to respond to S applications; however, the results were inconsistent (one out of three site-years).

Leaf and stripe rust pressures were low in both growing seasons in Manhattan; however, removing foliar fungicide from the Y_w significantly reduced grain yield in the 2016-17 growing season. This decreased grain yield was mostly led by reduced kernels m^{-2}, likely due to early season disease reducing potential kernels spike^{-1} or less survival of secondary tillers in the absence of fungicide. The determination of potential kernels m^{-2} occurs between Feekes 4 and 6 in wheat, and any plant stresses during this period can reduce the potential kernel number (Slafer et al., 1990). Kernels m^{-2} might also result from abortion of secondary tillers in the absence of fungicide. Thus, application of fungicide during the growing season protects the potential number of kernels m^{-2}, which was one of the main drivers of increased yields in no-till system (Table 2-17).

The relationship between yield components and grain yield in the no-till analyses were slightly different than those in the conventional till (Table 2-18, Table 2-17). These differences are attributed to the environment and tillage practice. In these site-years, kernels m^{-2} and 1000-

kernel weight had similar correlations with grain yield ($r^2 = 0.39$ and 0.37, $p < 0.0001$). This indicated a slightly greater sink limitation than that observed in the central Kansas sites, where source limitation was stronger. Additionally, kernels m^{-2} had a stronger correlation to spikes m^{-2} than kernels spike^{-1}, agreeing with Slafer et al. (2014). Wheat is generally sink limited and grains m^{-2} (course regulation) plays a larger role in increasing grain yields (Slafer et al., 2014), which was true in our no-till analyses where increased seeding rate increased spikes m^{-2}. These results also suggest that seeding rates possibly need to be increased further in a no-till system following maize. This experiment in eastern Kansas suggests that there might be a larger yield potential in this environment than central Kansas as grains m^{-2} (course regulation) was the main effect in increasing yields, not 1000-kernel weight (fine regulation). However, the management strategy or strategies leading to further reductions on this YG have yet be discovered.

Overall, the FP or Y_w yield components (grain number, spike m^{-2}, and grain weight) were not consistently affected by the addition or removal of treatments, other than the number of spikes increased from increased plant population; grains m^{-2} and total biomass increased by the Y_w, and 1000-kernel weight were unaffected by any of the treatments.

Economically Reducing Yield Gaps

In the conventional till, FP treatment resulted in a yield gap of 20% and the addition of foliar fungicide reduced the YG to 5%. Simultaneously, the net income was only increased from the fungicide application (\$106 ha^{-1}), with no other treatments or the Y_w resulting positive returns (Table 2-11). These results support the findings of Lobell et al. (2009), who suggested that YG greater than 20% in rainfed systems can be economically reduced. Our results quantify winter wheat YG in Kansas, as well as management strategies to economically maintain these YG at less than 20% for conventional till systems in central KS. However, our results apply for growing seasons with high Y_w and disease pressure. Further research is needed to examine the YG and the management practices that can reduce it when disease pressure is low.

The no-till system did not follow the same trend as the conventional till. The YG was 8% in the FP treatment, and was reduced by split-N (6%), S (5%), Cl (3%), increased plant population (8%), and fungicide (4%). However, the only treatment which resulted in positive net return was increased plant population (\$37 ha^{-1}). Lobell et al. (2009) described that YG cannot economically be decreased past 20%, which is largely confirmed by our results with the exception of plant population, which allowed for the production system to economically produce 92% of the Y_w. Likewise, Grassini et al. (2015) found commercial soybean production systems achieving as high as 90% of their Y_w.

Grain Protein Concentration

Nitrogen is a key input to maximize protein concentration in the wheat grain (Ellen and Spertz, 1980; Woolfolk et al., 2002; Bly and Woodard, 2003; Cruppe et al., 2017). Grain protein concentration starts to be determined 10 days after anthesis, and by day 20 following anthesis about 50% of the grain protein has accumulated (Daigger et al., 1976; Dupont et al., 2006). In our study, the additional split-N applied at a rate of 134 kg N ha^{-1} at jointing (Feekes 6) increased grain protein concentration in 9 g kg^{-1} in our pooled analysis across sites for no-till, and in 12 g kg^{-1} in conventional till (Table 2-7). In no-till, the split-N also increased yields by 0.28 Mg ha^{-1}, which did not happen in the conventional till. These findings indicate that applications of N late in the vegetative period can increase grain protein concentration, but due to the greater N requirement in no-till, this protein gain might be diluted due to increased grain yields as compared to same N rates in conventional tillage systems. These findings also support that wheat may need additional N above what is applied for the yield goal to maximize grain protein concentration. While the split-N application increased protein concentration; it resulted in a net loss of \$106 ha^{-1} in conventional till and \$76 ha^{-1} in no-till. Producers in the southern Great Plains rarely receive a premium for high protein wheat (>125 $g\ kg^{-1}$), and this premium is year dependent. Thus, these results support the finding of Dick et al, (2016), who found it was not economical to maximize grain protein concentration in the southern Great Plains.

Test Weight

Grain test weight was highly variable across growing seasons, and the analysis of variance suggested no significant differences when the data was pooled (Table 2-6), although foliar fungicide increased grain test weight in four site-years due to the high disease pressure (Table 2-10). Grain weight is the last yield component determined in wheat (i.e. spikes m^{-1}, kernels $spike^{-1}$, kernels m^{-1}, and kernel weight); thus, leaf area is essential to provide the photosynthates to fill the wheat grain, justifying the significant effect of fungicide on wheat test weight. Likewise, Paul et al. (2010) measured an approximately 3% grain test weight increase from fungicide application. In an increased nitrogen and fungicide experiment, Cruppe et al. (2017) found test weight only responded to fungicide and not to additional nitrogen in specific environments. Likewise, Edwards et al. (2012) found grain test weight to increase in one site-year due to foliar fungicides for susceptible wheat varieties. Thus, the results from this experiment and those aforementioned indicate that grain test weight responses from fungicide are dependent on the environment and disease pressure experienced during the growing season.

Plant Height

Plant height was significantly affected by PGR application in five out of six site-years (Table 2-13). At maturity, plant height was unaffected in the no-till; however, it decreased by 8 cm in the conventional till. These results agree with other research where PGR application reduced wheat plant height, conducted in Michigan (Swoish and Steinke, 2017), California (Mohamed et al., 1990), and Illinois (Nafziger et al., 1986), but not with results found in Kentucky (Knott et al., 2016), where researchers reported that plant height was not consistently affected by the PGR application. Plant height reduction from PGR usually occurs by the inhibition of gibberellic acid, which prevents plant stems from elongating (Hedden and Phillips, 2000). In Michigan, Swoish and Steinke (2017) also reported a yield increase resulting from PGR, which was not measured in our experiment (Table 2-7), in Kentucky (Knott et al., 2016), or in California (Mohamed et al., 1990). Our results also support that environmental conditions have a great effect on results obtained from PGR applications, as plant height was unaffected in some site-years and in others, it was significantly reduced which agree with previous research (Nafziger et al., 1986; Cox and Otis, 1989; Mohamed et al., 1990).

In two site-years within our experiments, fungicide application increased plant height (Table 2-13). This result has not been reported in the literature, and we hypothesize that this increase in plant height is actually resultant from a synergism between the PGR and fungicide rather than a direct effect from fungicides on plant height. We speculate that the fungicide is alleviating some of the plant height reduction effects caused by the PGR, once the early application of PGR and fungicide were tank mixed. We observed that plant height was decreased to a greater extent when PGR was applied with no tank-mixed fungicides (Table 2-13); and as a consequence of the nature of our statistical approach, orthogonal contrasts indicated that fungicide increased plant height by 4 cm, when in fact it was mostly reducing the effects of the PGR which decreased plant height by 8 cm.

Everest, the variety sown in this experiment, has a robust straw strength, thus, lodging was expected to be minimal (DeWolf et al., 2017). Due to a neutral yield response, a PGR application is not economically justified as it resulted in a negative net income return for both the no-till (-\$35 ha^{-1}) and conventional till (-\$95 ha^{-1}) analyses. In other wheat producing regions within the U.S., PGR applications are suggested to have either beneficial or negative effects on net income. While no economic analyses were performed in the following experiments, they capture the variability in results from PGR applications: in Kentucky, yield and plant height reduction were inconsistent suggesting a negative net income return from PGR (Knott et al., 2016); in California (Mohamed et al., 1990) and Illinois (Nafziger et al., 1986), only lodging results were consistent suggesting a partial net income return from PGR as the negative effects of lodging were decreased; and in Michigan, Swoish and Steinke (2017) measured a plant height reduction and yield increase by 5% suggesting PGR applications could result in a positive net income. Likewise, in Europe, region characterized by greater yield potential, the use of PGR applications are economically viable as they further enhance net income (Baylis, 1990). In light of our results and available literature, PGR applications should only be considered in regions where lodging is major concern.

Conclusions

Across all site-years studied, intensifying wheat production using an aggressive “kitchen-sink” approach was never economical, as net returns were consistently lower in the Y_w as compared to the FP. Instead, different management practices were required to economically reduce winter wheat YG according to tillage practice and environmental conditions. Individual management strategies that economically reduced the YG in the seasons studied were foliar fungicides in high disease-pressure site-years (in this manuscript coincidently conducted under conventional tillage practices), and increased plant population in no-till. Our results also indicate that split-N, S, and fungicides may help reduce the YG in a no-till system, although these were not economical. The lack of net return from these operations in our study might be a consequence of the low price of wheat for both growing seasons, and an increase in price might allow for the economical application of these treatments.

Grain protein concentration was significantly increased by the application of split-N in both growing seasons and tillage practices. However, producers of the southern Great Plains rarely receive premiums for increased grain protein concentration; thus, it was not economical to apply the extra split-N solely with the objective of increasing grain protein concentration. In the future, if premiums are consistently paid to producers for high protein wheat, this split-N application may be justified. In this experiment, no yield response was measured from the application of Cl or PGR. All pre-plant soil analysis measured adequate levels of Cl before planting; thus, a yield response to Cl was not expected. These results reinforce the need for soil sampling at time of wheat sowing so that more informed decisions regarding fertilizer application are made, improving the system's profitability, sustainability, and reducing footprint of agriculture associated with over fertilization. Likewise, due to the excellent straw strength of Everest, a yield response from the PGR application was not expected, as lodging and its negative effects were minimal. However, had the experiment been conducted with a variety with below-average straw strength, a PGR application could possibly help eliminate these negative effects, as plant height reduction due to PGR was measured in this experiment. Thus, our results support the idea of an integrated pest management approach to maximize winter wheat profitability, considering conditions experienced in the current growing season instead of performing a high-input based system where pesticide applications are performed.

This project also provides empirical evidence to support that in regions where wheat grain yield is often limited by weather conditions during grain fill that decrease kernel weight (e.g. heat and drought stresses, or high disease pressure), individual kernel weight which is otherwise considered a fine regulator of grain yield, plays an important role in increasing wheat yield in addition to number of kernels m^{-2}, indicating a co-limitation between source and sink.

Figures

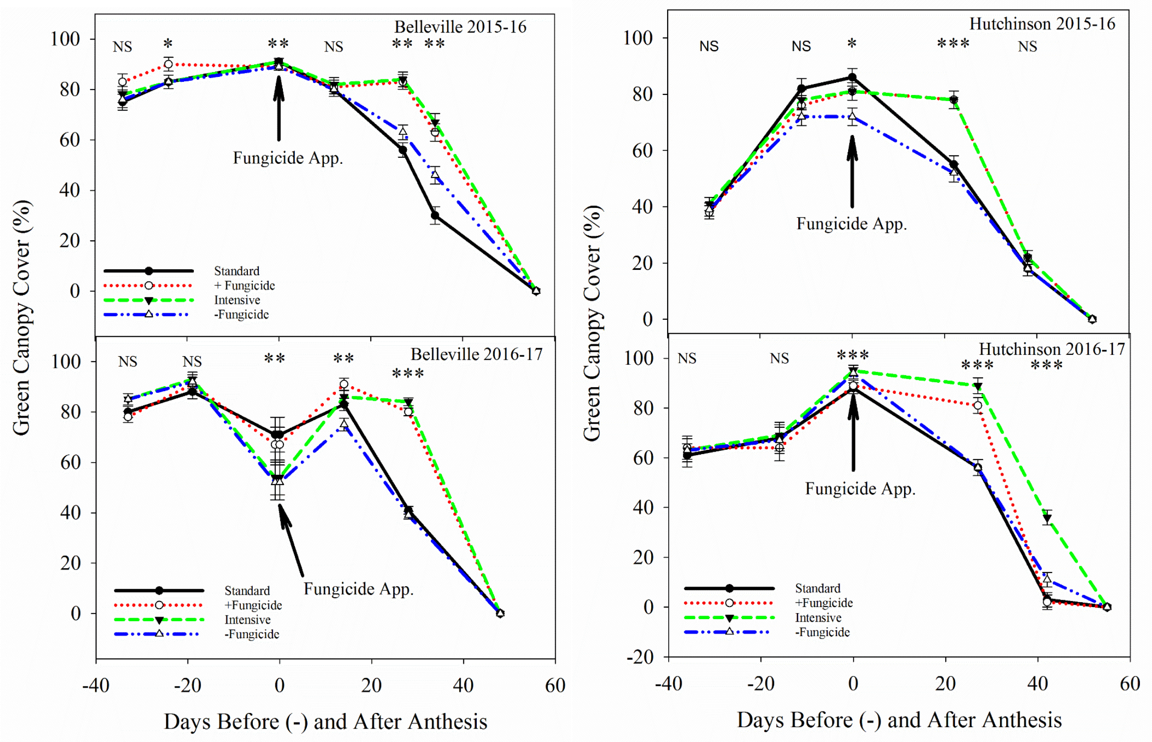

Figure 2-1. Treatment application effects on percent green canopy coverage at Belleville 2015-16 (top-left panel) and 2016-17 (lower-left panel) and at Hutchinson 2015-16 (top-right panel) and 2016-17 (lower-right panel). The arrow represents date when the later fungicide was applied during the growing season. On the x-axis, (0) represents the day anthesis occurred, negative numbers are days before anthesis, and positive numbers are days after anthesis.

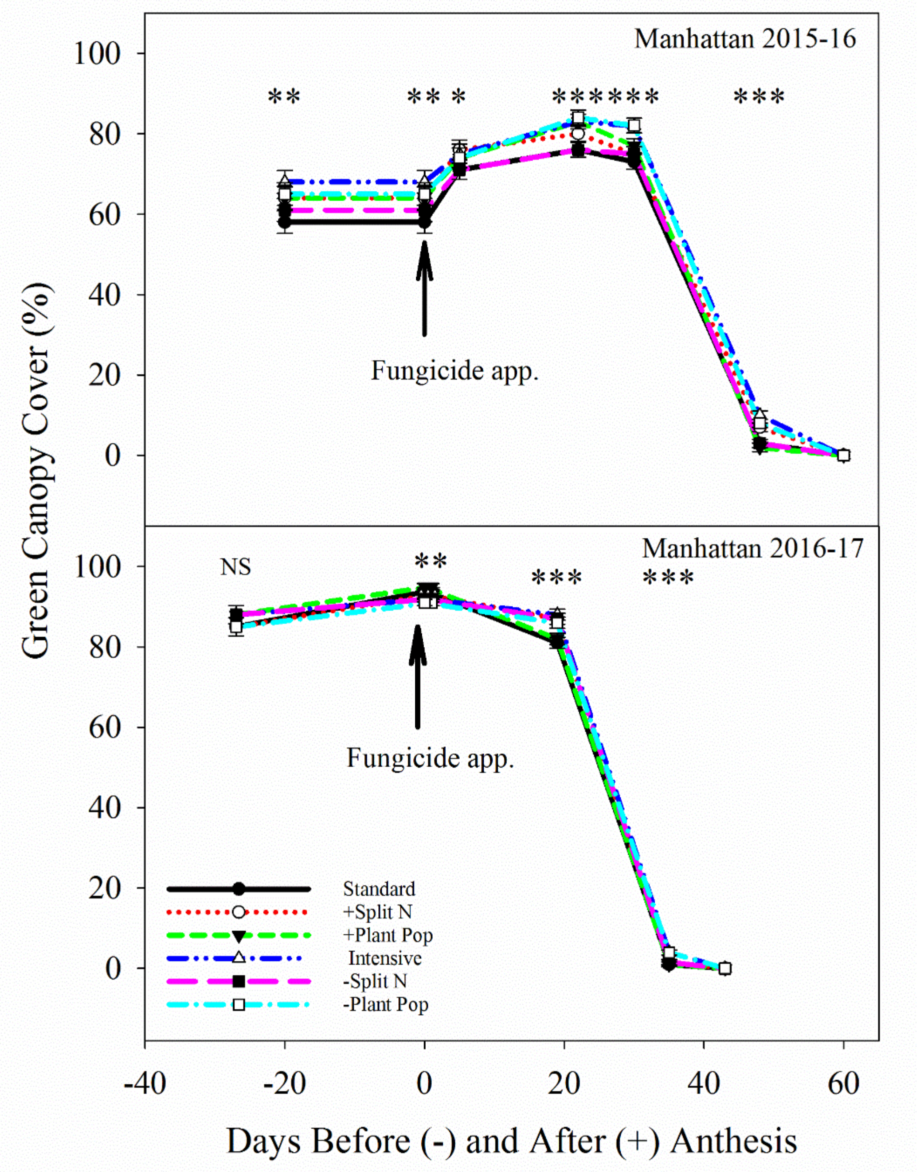

Figure 2-2. Treatment application effects on percent green canopy coverage at Manhattan 2015-16 (top panel) and 2016-17 (lower panel). The arrow represents date when the later fungicide was applied during the growing season. On the x-axis, (0) represents the day anthesis occurred, negative numbers are days before anthesis, and positive numbers are days after anthesis.

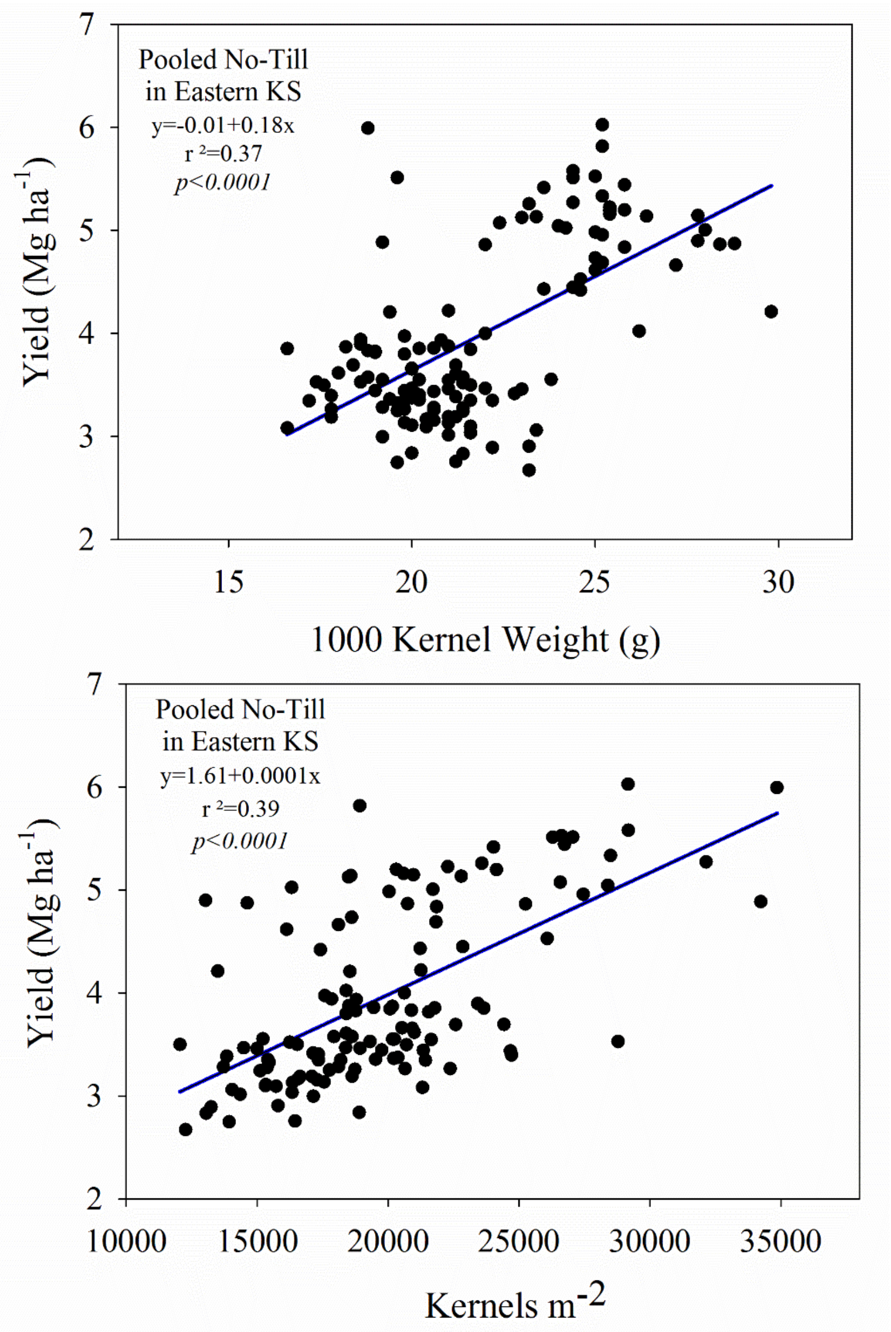

Figure 2-3. Linear relationships between 1000-kernel weight and grain yield (Mg ha^{-1}) (top panel), and linear relationship between grain m^{-2} and grain yield (Mg ha^{-1}) in the no-till system (bottom panel). Data included are the results of the addition or removal of each management strategy across both growing seasons of 2015-16 and 2016-17 for the no-till system in eastern Kansas.

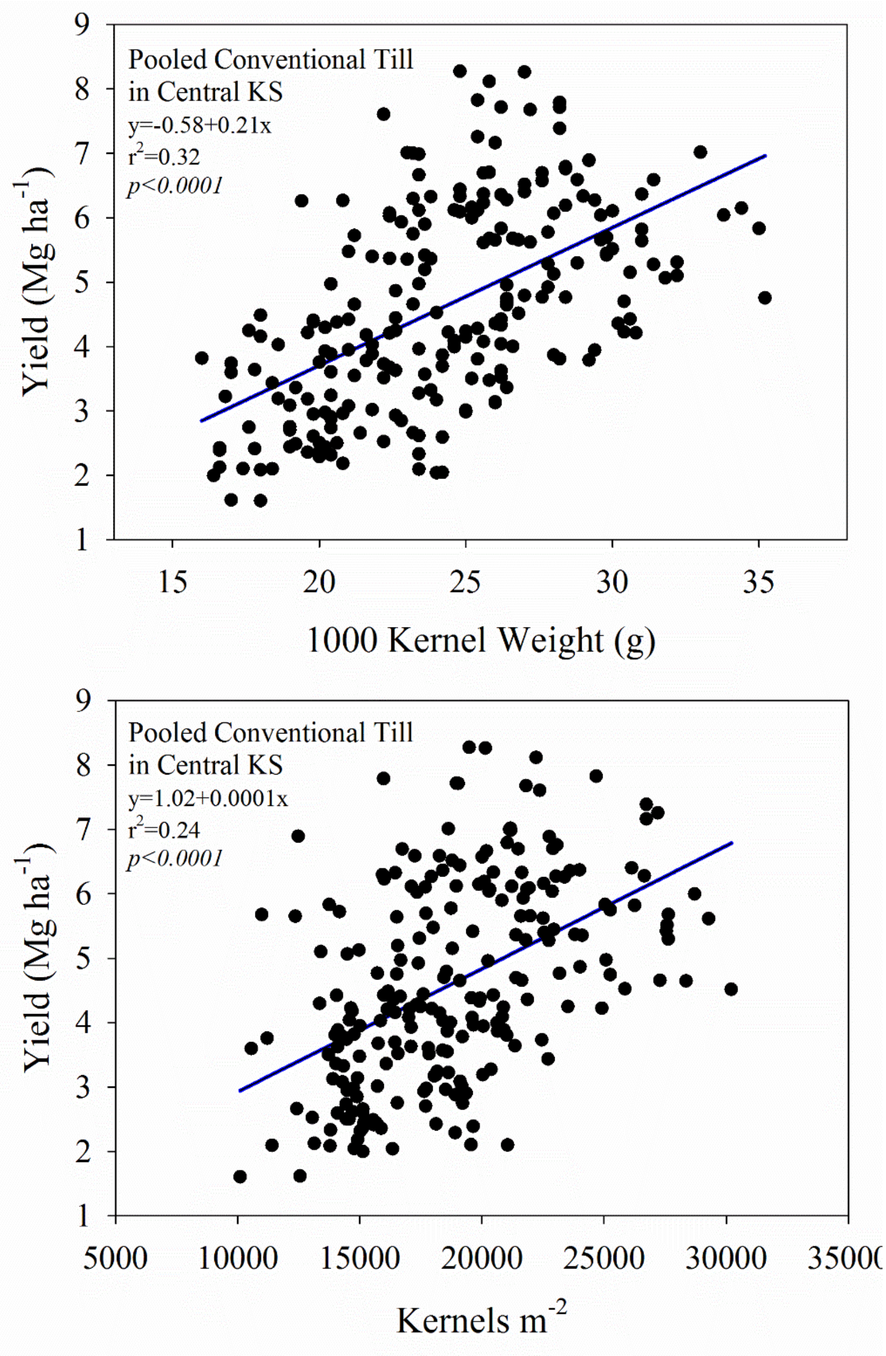

Figure 2-4. Linear relationships between 1000-kernel weight and grain yield (Mg ha^{-1}) (top panel), and linear relationship between grain m^{-2} and grain yield (Mg ha^{-1}) in the conventional till system (bottom panel). Data included are the results of the addition or removal of each management strategy across both growing seasons of 2015-16 and 2016-17 for the conventional system in central Kansas.

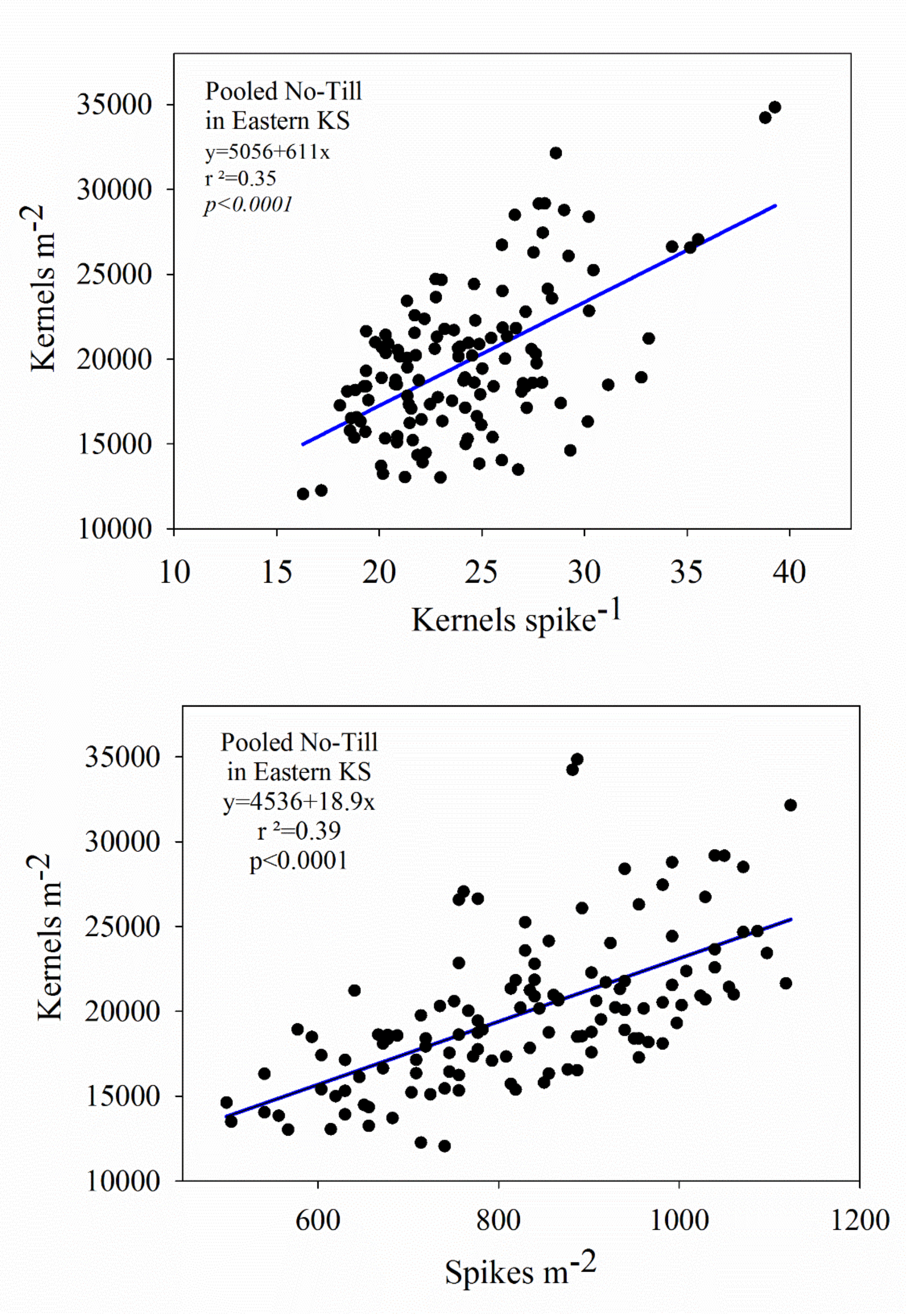

Figure 2-5. Linear relationships between grains spike^{-1} and grain m^{-2} (top panel), and linear relationship between spikes m^{-1} and grains m^{-2} (bottom panel). Data included are the results of the addition or removal of each management strategy across both growing seasons of 2015-16 and 2016-17 for the no-till system in eastern Kansas (Manhattan).

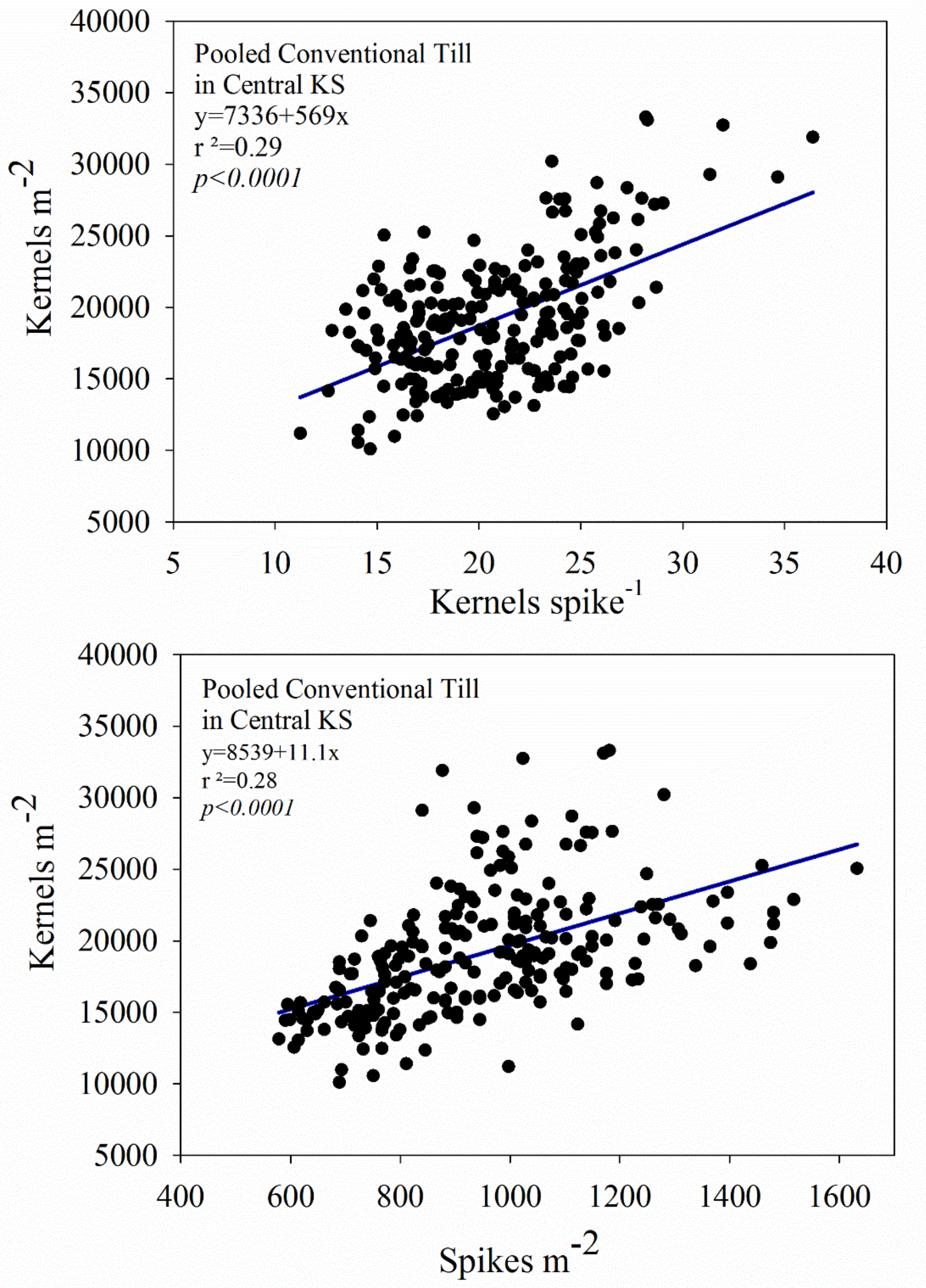

Figure 2-6. Linear relationships between grains spike^{-1} and grains m^{-2} (top panel), linear relationship between spikes m^{-1} and grains m^{-2} (bottom panel). Data included are the results of the addition or removal of each management strategy across both growing seasons of 2015-16 and 2016-17 for the conventional till system in central Kansas (Belleville and Hutchinson).

Tables

Table 2-1. Sowing date, date of treatment application (unless otherwise specified) for top-dress and split top-dress nitrogen (N), sulfur (S), chloride (Cl), herbicide, early and late fungicide, plant growth regulator, and harvest dates for Manhattan, Hutchinson, and Belleville, Kansas, for the 2015-16 and 2016-17 growing seasons.

Field Operation	Manhattan	Hutchinson	Belleville
	2015-16		
Sowing	10/09/2015	10/29/2015	10/02/2015
Topdress N Rate	147 kg N ha^{-1}	90 kg N ha^{-1}	34 kg N ha^{-1}
Topdress N	02/17/2016	02/16/2016	2/19/2016
Split- Topdress N (134 kg N ha^{-1})	3/18/2016	3/15/2016	3/17/2016
Topdress S or Cl (45 kg S or Cl ha^{-1})	3/18/2016	3/15/2016	3/17/2016
Herbicide	03/10/2016	02/19/2016	03/09/2016
Plant Growth Regulator (Palisade) (1022 mL ha^{-1})	04/11/2016	03/25/2016	04/04/2016
Early Fungicide (Approach) (292 mL ha^{-1})	04/11/2016	03/25/2016	04/04/2016
Late Fungicide (Approach Prima) (496 mL ha^{-1})	04/28/2016	4/25/2016	05/05/2016
Harvest	06/27/2016	06/16/2016	06/30/2016
	2016-17		
Sowing	10/17/2016	10/12/2016	10/3/2016
Topdress N Rate	74 kg N ha^{-1}	93 kg N ha^{-1}	41 kg N ha^{-1}
Topdress N	02/21/2017	02/17/2017	2/21/2017
Split- Topdress N (134 kg N ha^{-1})	3/22/2017	3/20/2017	3/22/2017
Topdress S or Cl (45 kg S or Cl ha^{-1})	3/22/2017	3/20/2017	3/22/2017
Herbicide	3/8/2017	11/15/2016	11/14/2016
Plant Growth Regulator (Palisade) (1022 mL ha^{-1})	4/6/2017	4/3/2017	4/11/2017
Early Fungicide (Approach) (292 mL ha^{-1})	4/6/2017	4/3/2017	4/11/2017
Late Fungicide (Approach Prima) (496 mL ha^{-1})	5/5/2017	4/25/2017	5/10/2017
Harvest	6/17/2017	6/19/2017	6/27/2017

Table 2-2. Treatment description. Each management strategy included a FP and an Y_w control, and six inputs (N, S, Cl, plant population, fungicide, and PGR) were added (+) or removed (-) from their respective control.

Management	Yield Goal (Mg ha^{-1})	Exception	Nitrogen	Sulfur	Cl	Plant Population (seeds ha^{-1} *10^{6})	Fungicide	Plant Growth Regulator
FP	4.7	None	Base + Top-dress	None	None	2.7	None	None
Standard	8.1	+N	Base + Split Topd.	None	None	2.7	None	None
Standard	4.7	+S	Base + Top-dress	+S	None	2.7	None	None
Standard	4.7	+Cl	Base + Top-dress	None	+Cl	2.7	None	None
Standard	4.7	+Population	Base + Top-dress	None	None	4.0	None	None
Standard	4.7	+Fungicide	Base + Top-dress	None	None	2.7	With	None
Standard	4.7	+PGR	Base + Top-dress	None	None	2.7	None	With
Y_w	8.1	None	Base + Split Topd.	+S	+Cl	4.0	With	With
Intensive	4.7	-N	Base + Top-dress	+S	+Cl	4.0	With	With
Intensive	8.1	-S	Base + Split Topd.	None	+Cl	4.0	With	With
Intensive	8.1	-Cl	Base + Split Topd.	+S	None	4.0	With	With
Intensive	8.1	-Population	Base + Split Topd.	+S	+Cl	2.7	With	With
Intensive	8.1	-Fungicide	Base + Split Topd.	+S	+Cl	4.0	None	With
Intensive	8.1	-PGR	Base + Split Topd.	+S	+Cl	4.0	With	None

Table 2-3. Initial soil fertility levels at Belleville, Hutchinson, and Manhattan, Kansas, for the 2015-16 and 2016-17 growing seasons. Fertility level include soil pH, buffer pH, Mehlich-3 extractable phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sodium (Na), ammonium-(NH_4-N) and nitrate- (NO_3-N) nitrogen, chloride (Cl), sulfate-sulfur (SO_4-S), organic matter (O.M.) and cation exchange capacity (CEC). Sampling depths were 0-15 cm and 15-45 cm in 2015-16 and 0-15 cm and 15-60 cm in 2016-17.

Location	Sample Depth	pH	Mehlich P	K	Ca	Mg	Na	NH_4-N	$N0_3$-N	Cl^-	$S0_4$-S	O.M.	CEC
	cm					mg kg^{-1}						%	Meq 100g^{-1}
						2015-16							
Belleville	0-15	5.07	51.7	423	1594	233	22.6	4.0	22.9	13.0	5.60	2.48	16.0
	15-45	5.72	12.6	337	3001	419	66.2	4.2	12.0	9.4	4.95	1.89	22.8
Hutchinson	0-15	4.9	95.4	273	1692	275	25.3	28.6	54.6	9.3	8.4	2.3	16.6
	15-45	7.2	11.0	203	4127	320	77.6	9.7	15.6	5.5	4.2	2.1	18.6
Manhattan	0-15	6.60	39.8	210	4045	311	22.8	29.7	9.7	4.8	7.0	3.9	26.8
	15-45	7.04	15.3	227	5383	279	23.9	12.7	3.5	3.3	4.4	3.3	23.1
						2016-17							
Belleville	0-15	4.78	64.8	492	1217	176	14.21	15.86	21.34	13.04	7.43	2.75	24.59
	15-60	5.9	27.2	354	2620	364	60.99	10.04	10.23	7.60	5.03	2.58	26.31
Hutchinson	0-15	7.48	57.9	318	3850	172	15.34	17.07	7.08	3.34	5.37	2.61	21.57
	15-60	7.95	37.8	287	4724	173	16.48	19.12	6.14	3.36	4.97	2.66	25.88
Manhattan	0-15	7.47	28.8	268	4245	220	12.34	34.62	9.61	6.88	8.77	4.04	23.80
	15-60	7.85	25.9	291	5609	281	16.83	15.75	10.15	4.12	5.26	3.31	31.21

Table 2-4. Average monthly temperature (T_{ave}), precipitation (Precip), and 30 year average (1981-2010) during the 2015-16 and 2016-17 growing seasons at Belleville, Hutchinson, and Manhattan, Kansas. Data shown as a mm and °C of the 30-yr normal [1980-2010, National Oceanic and Atmospheric Administration, Arguez et al., (2012)].

Month	Location								
	Belleville			Hutchinson			Manhattan		
	2015-16	2016-17	30-yr	2015-16	2016-17	30-yr	2015-16	2016-17	30-yr
	Precip.								
	mm								
October	34	49	68	25	15	59	18	55	68
November	42	19	44	95	11	34	114	11	44
December	52	23	27	64	21	26	70	19	27
January	16	26	16	16	56	18	14	34	16
February	10	5	27	14	4	27	9	12	27
March	11	35	63	25	88	65	9	101	63
April	112	59	80	116	138	69	202	115	80
May	158	131	129	167	109	113	151	92	129
June	24	80	145	102	48	123	32	74	145
Total	461	426	500	623	491	534	619	513	600
	T_{ave}								
	°C								
October	14	15	13	16	17	14	16	17	14
November	7	8	5	9	10	6	10	11	6
December	1	-3	-2	4	0	0	4	0	0
January	-2	-1	-2	0	1	-1	-1	1	-2
February	2	4	0	5	7	2	5	6	1
March	8	7	6	10	9	7	11	9	6
April	13	12	12	14	13	12	15	14	13
May	17	16	17	17	18	18	18	18	18
June	26	23	22	26	25	24	27	25	24

†Winter wheat growing season in Kansas (October-June)

Table 2-5. Description of trade name, active ingredient, chemical name, and percent active ingredient of chemical for seed treatment, foliar fungicide, plant growth regulator (PGR), and herbicide using during the experiment years of 2015-16 and 2016-17 in Belleville, Hutchinson, and Manhattan, Kansas.

Management	Trade Name	A.I.†	Chemical Name	% A.I‡
Seed Treatment	Sativa IMF Max	Imidacloprid	1-[(6-Chloro-3-pyridinyl)methyl]-N-nitro-2-imidazolidinimine	11.6
		Metalaxyl	N-(2,6-dimethylphenyl)-N-(methoxyacetyl)alanine methyl ester	0.60
		Tebuconazole	Alpha-[2-4(chlorophenyl)ethyl]-alpha-(1,1-dimethyl-ethyl)-1H-1,2,4-triazole-1-ethanol	0.45
		Fludioxonil	4-(2,2-Difluoro-1,3-benzodioxol-4-yl)-1H-pyrolle-3-carbonitrile	0.36
Foliar Fungicide	Aproach	Picoxystrobin	Methyl [E]-3-methoxy-2-{2-[[[6-(trifluoromethyl)pyridin-2-yl]-oxy]methyl]phenyl}acrylate	22.5
	Aproach Prima	Picoxystrobin		17.94
		Cyproconazole	α-(4-chlorophenyl)-α-(1-cyclopropylethyl)-1H-1,2,4-triazole-1-ethanol	7.17
PGR	Palisade	Trinexapac-ethyl	4-(Cyclopropyl-a-hydroxymethylene)-3,5-dioxo-cyclohexanecarboxylic acidethylester	12.0
Herbicide	Powerflex	pyroxsulam	N-(5,7-dimethoxy[1,2,4]triazolo[1,5-a]pyrimidin-2-yl)-2-methoxy-4-(trifluoromethyl)-3-pyridinesulfonamide	7.5
	MCPA Ester	MCPA	2-ethylhexyl ester of 2-methyl-4-chlorophenoxyacetic acid	69.3
	Harmony Extra	Thifensulfuron-methyl	Methyl 3-[[[[(4-methoxy-6-methyl-1,3,5-triazin-2-yl) amino]carbonyl]amino]sulfonyl]-2-thiophenecarboxylate	33.3
		Tribenuron-methyl	Methyl 2-[[[[N-(4-methoxy-6-methyl-1,3,5-triazin-2-yl)methylamino]carbonyl]amino]sulfonyl]benzoate	16.67
	Roundup PowerMax	glyphosate	N-(phosphonomethyl)glycine, in the form of its potassium salt	48.7
	2,4-D Amine	2,4-D	Dimethylamine salt of 2,4-Dichlorophenoxyacetic acid	47.3
	Gramoxone SL	Paraquat	(1,1'-dimethyl-4,4'-bipyridinium dichloride)	30.1
	Preference	NA§	Alkylphenol ethoxylate, sodium salts of soya fatty acids, isopropyl alcohol	89.5
	AMS	NA	Ammonium Salts, Polyacrylamide polymer, and Siloxane	100

† Active Ingredient

‡ Percent Active Ingredient

§ Not Available

Table 2-6. Significance of the analysis of variance for treatment effect on plants m^{-2}, plant height, aboveground dry matter at maturity (DM), harvest index (HI), grain yield, grain test weight, grain protein concentration, yield gap (YG), yield components (1000-kernel weight, spikes m^{-2}, and grains m^{-2}), and net income for the 2015-16 and 2016-17 growing seasons at Belleville, Hutchinson, and Manhattan, Kansas, as well as for the analysis across locations pooled by tillage practice (No-till, consisting of Manhattan 2015-16 and 2016-17, and conventional-till consisting of Belleville 2015-16 and 2016-17, and Hutchinson 2015-16 and 2016-17).

Source of Variation	2015-16			2016-17			2015-16 & 2016-17	
	Belleville	Hutchinson	Manhattan	Belleville	Hutchinson	Manhattan	No-Till	Conventional Till
Grain Yield	***	***	***	***	***	***	***	***
YG	***	***	***	***	***	***	***	***
Protein Concentration	***	***	***	***	***	***	***	**
Test Weight	**	***	*	***	***	*	NS	NS
Net Income	***	***	***	**	***	***	***	***
Plants m^{-2}	***	***	***	***	***	***	***	***
Height	***	***	**	***	***	***	NS	***
DM	***	***	NS	NS	***	NS	NS	NS
HI	NS	***	NS	*	**	NS	NS	NS
Spikes m^{-2}	**	*	**	NS	***	NS	***	**
Kernels m^{-2}	*	NS	**	NS	***	NS	***	NS
1000-kernel weight	***	***	*	NS	*	NS	NS	**

*, **, *** indicate significance at the 0.05, 0.01, 0.0001 probability, respectively.

† NS, nonsignificant

Table 2-7. Average winter wheat grain yield as affected by management strategy and by addition or removal of individual treatments from the FP and Y_w controls, respectively, for the 2015-16 and 2016-17 growing seasons in Belleville, Hutchinson, Manhattan, Kansas, and for the pooled analysis across no-till (Manhattan, 2015-16 and 2016-17) and conventional till (Belleville, 2015-16 and 2016-17; and Hutchinson, 2015-16 and 2016-17) site-years.

Treatment		2015-16			2016-17			2015-16 & 2016-17	
Mgmt. Strat.	Exception	Belleville	Hutchinson	Manhattan	Belleville	Hutchinson	Manhattan	No-Till	Conventional Till
					Mg ha^{-1}				
FP	None	4.04	2.55	3.19	5.20	4.95	4.90	4.05	4.18
Standard	+Split Nitrogen	3.52	2.64	3.13	4.86	5.03	4.85	3.99	4.00
Standard	+Sulfur	3.93	2.48	3.22	5.06	5.27	4.95	4.09	4.19
Standard	+Chloride	3.64	2.56	3.37	5.20	5.24	4.93	4.15	4.16
Standard	+Plant Population	3.96	2.68	3.42	5.50‡	4.55	5.28‡	4.35†	4.17
Standard	+Fungicide	6.21†‡	3.36†	3.25	5.76‡	6.06†	4.92	4.09	5.34†‡
Standard	+Plant Growth Regulator	3.45	2.14	3.17	4.90	4.72	4.57	3.87	3.80
Y_w	None	6.52	3.45	3.86	6.05	6.77	5.66	4.76	5.70
Intensive	-Split Nitrogen	6.51	3.92	3.3†‡	6.28	6.03†	5.00†‡	4.15†‡	5.69
Intensive	-Sulfur	6.68	3.12	3.57†	6.38	6.85	4.99†‡	4.28†‡	5.77
Intensive	-Chloride	6.59	3.59	3.67	5.98	6.66	5.46	4.57	5.71
Intensive	- Plant Population	6.61	3.28	3.52†	5.60‡	6.75	5.17†‡	4.34†	5.57
Intensive	- Fungicide	4.27†‡	2.19†‡	3.57†	4.74†‡	4.78†‡	5.31	4.44†	3.99†‡
Intensive	- Plant Growth Regulator	6.59	3.57	3.75	6.53	6.75	5.57	4.66	5.87
Significance of single degree of freedom orthogonal contrasts									
Y_w vs FP		-2.14***	-0.67***	-0.36***	-0.73***	-1.23***	-0.38***	0.37***	1.18***
Split Nitrogen vs. No Split Nitrogen		0.26	0.2	-0.25*	0.29	-0.41*	-0.30*	0.28**	-0.08
Sulfur vs. No Sulfur		0.14	-0.13	-0.16	0.23	-0.12	-0.36*	0.26**	-0.03
Chloride vs. No Chloride		0.23	0.06	-0.19	-0.03	-0.20	-.11	0.15	-0.02
High Population vs. Low Population		0.09	-0.15	-0.29**	-0.38	0.20	-0.43**	0.36***	0.06
Fungicide vs. No Fungicide		-2.21***	-1.03***	-0.18	-0.94***	-1.55***	-0.18	0.18*	1.44***
PGR vs. No PGR§		0.34	0.27	-0.04	0.39	0.11	0.12	0.04	-0.27

*, **, *** indicate significance at the 0.05, 0.01, 0.0001 probability, respectively.

NS-nonsignificant

† Indicates treatment was significantly different from the respective management strategy control at α<0.05 (individual treatment additions to the standard control compared to the standard control, and individual treatment removal from the intensive control compared to the intensive control).

‡ Indicates treatment was not significantly different from the alternative management strategy control at α<0.05 (individual treatment additions to the standard control compared to the intensive control, and individual treatment removal from the intensive control compared to the standard control).

§PGR, Plant Growth Regulator

Table 2-8. Percent winter wheat yield gap relative to the Y_w control as affected by management strategy and by addition or removal of individual treatments from the FP and Y_w controls, respectively, for the 2015-16 and 2016-17 growing seasons in Belleville, Hutchinson, Manhattan, Kansas, and for the pooled analysis across no-till (Manhattan, 2015-16 and 2016-17), and conventional till (Belleville, 2015-16 and 2016-17; and Hutchinson, 2015-16 and 2016-17) site-years.

Treatment		2015-16			2016-17			2015-16 & 2016-17	
Mgmt. Strat.	Exception	Belleville	Hutchinson	Manhattan	Belleville	Hutchinson	Manhattan	No-Till	Conventional Till
						%			
FP	None	37	25	19	14	27	13	16	26
Standard	+Split Nitrogen	46	22	20	20	25	14	17	28
Standard	+Sulfur	39	27	18	16	22	12	15	26
Standard	+Chloride	44	24	14	14	22	12	13	26
Standard	+Plant Population	39	22	13	9‡	33	6†‡	9†	26
Standard	+Fungicide	3†‡	2†‡	17	5‡	11†	13	15	5†‡
Standard	+Plant Growth Regulator	47	38	19	19	30	19	19	33
Y_w	None	0	0	0	0	0	0	0	0
Intensive	-Split Nitrogen	-1	-15	16†‡	-4	11†	11†‡	13†‡	-2
Intensive	-Sulfur	-3	10	8.5	-6	-1	11†‡	10†	0
Intensive	-Chloride	-3	-6	6	0	2	3	5	-2
Intensive	- Plant Population	-2	6.2	10†	7‡	0	8†‡	9†	3
Intensive	- Fungicide	33†‡	37†‡	9†	22†‡	29†‡	6	7†	30†‡
Intensive	- Plant Growth Regulator	-3	-2	4	-8	0	1	3	-3
Significance of single degree of freedom orthogonal contrasts									
Y_w vs FP		-33***	-19***	-9***	-12***	-18***	-7***	-8***	-20***
Split Nitrogen vs. No Split Nitrogen		5	6	-6*	5	-6**	-5	-6**	2
Sulfur vs. No Sulfur		2	-4	-3	4.2	-2	-6*	-5**	0
Chloride vs. No Chloride		5	3	-4	0	-3	-2	-3*	1
High Population vs. Low Population		2	-5	-7**	-6	3	-8**	-8***	-1
Fungicide vs. No Fungicide		-34***	-30***	-5	-16***	-23***	-3	-4*	-25***
PGR vs. No PGR§		6	7	-1	6.8	2	2	0	5

*, **, *** indicate significance at the 0.05, 0.01, 0.0001 probability, respectively.

NS-nonsignificant

† Indicates treatment was significantly different from the respective management strategy control at $\alpha<0.05$ (individual treatment additions to the standard control compared to the standard control, and individual treatment removal from the intensive control compared to the intensive control).

‡ Indicates treatment was not significantly different from the alternative management strategy control at $\alpha<0.05$ (individual treatment additions to the standard control compared to the intensive control, and individual treatment removal from the intensive control compared to the standard control).

§ PGR, Plant Growth Regulator

Table 2-9. Average winter wheat grain protein concentration as affected by management strategy and by addition or removal of individual treatments from the FP and Y_w controls, respectively, for the 2015-16 and 2016-17 growing seasons in Belleville, Hutchinson, Manhattan, Kansas, as well as for the pooled analysis across no-till (Manhattan, 2015-16 and 2016-17) and conventional till (Belleville, 2015-16 and 2016-17; and Hutchinson, 2015-16 and 2016-17) site-years.

Treatment		2015-16			2016-17			2015-16 & 2016-17	
Mgmt. Strat.	Exception	Belleville	Hutchinson	Manhattan	Belleville	Hutchinson	Manhattan	No-Till	Conventional Till
						g kg^{-1}			
FP	None	116	124	110	110	93	119	114	111
Standard	+Split Nitrogen	121†‡	127	119†	118†	119†	127†‡	123†‡	121†‡
Standard	+Sulfur	117	124	110	112	93	115	113	112
Standard	+Chloride	115	123	111	111	93	117	114	111
Standard	+Plant Population	118	126	110	109	93	116	113	112
Standard	+Fungicide	118	133†‡	111	115†	93	119	115	115
Standard	+Plant Growth Regulator	120†‡	128	112	117	96†	117	115	115
Y_w	None	123	138	121	130	123	131	126	128
Intensive	-Split Nitrogen	116†‡	134	111†‡	120†	93†	122†‡	117†	116†‡
Intensive	-Sulfur	124	139	122	131	123	130	126	129
Intensive	-Chloride	123	137	120	130	124	128	124	129
Intensive	- Plant Population	124	136	122	131	123	132	127	129
Intensive	- Fungicide	125	135	119	123†	120	131	125	126
Intensive	- Plant Growth Regulator	125	136	121	127	122	130	125	127
Significance of single degree of freedom orthogonal contrasts									
Y_w vs FP		5***	10***	8***	14***	21***	10***	9***	12***
Split Nitrogen vs. No Split Nitrogen		6***	3*	10***	9***	28***	8**	9***	12**
Sulfur vs. No Sulfur		0	-1	0	0	0	-1	-1	0
Chloride vs. No Chloride		0	0	2		-1	1	1	0
High Population vs. Low Population		0	2	0	-1	0	-2	-1	0
Fungicide vs. No Fungicide		0	6**	2	6**	1	0	1	3
PGR vs. No PGR§		2	3	1	5**	2	0	1	3

*, **, *** indicate significance at the 0.05, 0.01, 0.0001 probability, respectively.

NS-nonsignificant

† Indicates treatment was significantly different from the respective management strategy control at α<0.05 (individual treatment additions to the standard control compared to the standard control, and individual treatment removal from the intensive control compared to the intensive control).

‡ Indicates treatment was not significantly different from the alternative management strategy control at α<0.05 (individual treatment additions to the standard control compared to the intensive control, and individual treatment removal from the intensive control compared to the standard control).

§ PGR, Plant Growth Regulator

Table 2-10. Average winter wheat grain test weight as affected by management strategy and by addition or removal of individual treatments from the FP and Y_w controls, respectively, for the 2015-16 and 2016-17 growing seasons in Belleville, Hutchinson, Manhattan, Kansas, and for the pooled analysis across no-till (Manhattan, 2015-16 and 2016-17) and conventional till (Belleville, 2015-16 and 2016-17; and Hutchinson, 2015-16 and 2016-17) site-years.

Treatment		2015-16			2016-17			2015-16 & 2016-17	
Mgmt. Strat.	Exception	Belleville	Hutchinson	Manhattan	Belleville	Hutchinson	Manhattan	No-Till	Conventional Till
		kg m^{-3}							
FP	None	766	679	761	790	779	788	774	753
Standard	+Split Nitrogen	764	670	757‡	780†	763†	784‡	771	745
Standard	+Sulfur	762	661	764‡	787‡	775‡	785‡	775	749
Standard	+Chloride	771‡	683	760‡	788‡	782	786‡	773	756
Standard	+Plant Population	747†	697	764‡	792‡	775‡	791	777	753
Standard	+Fungicide	784†‡	732†‡	763‡	797†‡	778‡	789‡	776	773
Standard	+Plant Growth Regulator	751†	637†	762‡	789‡	780‡	784‡	773	737
Y_w	None	776	744	760	792	777	784	772	772
Intensive	-Split Nitrogen	785	724	764‡	794	777‡	788‡	776	770
Intensive	-Sulfur	778	745	759‡	794‡	778‡	791†‡	775	774
Intensive	-Chloride	780	730	756‡	794‡	774	788‡	772	769
Intensive	- Plant Population	778	734	759	790‡	777‡	780	769	770
Intensive	- Fungicide	758†‡	667†‡	758‡	781†‡	760†	786‡	772	741
Intensive	- Plant Growth Regulator	777	734	762‡	793‡	773	788‡	775	769
Significance of single degree of freedom orthogonal contrasts									
Y_w vs FP		12***	46***	-2*	2	-2**	-0	-1	14
Split Nitrogen vs. No Split Nitrogen		-6	8	-4*	-6*	-8***	-4	-4	-3
Sulfur vs. No Sulfur		-3	-3	2	-2	-3	-5*	-1	-36
Chloride vs. No Chloride		0	-11	2	-2	3	-3	-1	3
High Population vs. Low Population		-11**	16*	2	2	2	4	3	1
Fungicide vs. No Fungicide		18***	67***	2	9***	8***	0	-1	25
PGR vs. No PGR§		-8*	-20*	0	-1	3	-4	-2	-7

*, **, *** indicate significance at the 0.05, 0.01, 0.0001 probability, respectively.

NS-nonsignificant

† Indicates treatment was significantly different from the respective management strategy control at $\alpha<0.05$ (individual treatment additions to the standard control compared to the standard control, and individual treatment removal from the intensive control compared to the intensive control).

‡ Indicates treatment was not significantly different from the alternative management strategy control at $\alpha<0.05$ (individual treatment additions to the standard control compared to the intensive control, and individual treatment removal from the intensive control compared to the standard control).

§ PGR, Plant Growth Regulator

Table 2-11. Average net income (\$ ha^{-1} based on a price from Cargill in Salina on 7-27-2017 for \$141 Mg^{-1}) of winter wheat affected by management strategy and by addition or removal of individual treatments from the FP and Y_w controls, respectively for the 2015-16 and 2016-17 growing seasons in Belleville, Hutchinson, Manhattan, Kansas, as well as for the pooled analysis across no-till (Manhattan, 2015-16 and 2016-17) and conventional till (Belleville, 2015-16 and 2016-17; and Hutchinson, 2015-16 and 2016-17) site-years.

Treatment		2015-16			2016-17			2015-16 & 2016-17	
Mgmt. Strat.	Exception	Belleville	Hutchinson	Manhattan	Belleville	Hutchinson	Manhattan	No-Till	Conventional Till
						$ ha^{-1}			
FP	None	436	256	307	565	588	598	453	461
Standard	+Split Nitrogen	263†	148†	179†	457‡	480†‡	472†	326†	335†‡
Standard	+Sulfur	397‡	218	282	517‡	605	578	430	434‡
Standard	+Chloride	335‡	204	278	511‡	575‡	549	414†	406‡
Standard	+Plant Population	413‡	259	325	594	515†‡	638	482	445
Standard	+Fungicide	612†	266	211†	540‡	641	458†	334†	515
Standard	+Plant Growth Regulator	267†	139†	245	464‡	497†	531	388†	342†‡
Y_w	None	406	54	73	441	517	376	225	356
Intensive	-Split Nitrogen	535†‡	225†‡	97	494‡	515	402	250	442‡
Intensive	-Sulfur	469‡	21	45	417	541‡	294†	169†	364
Intensive	-Chloride	481‡	113	84	386	541‡	388	236	381‡
Intensive	- Plant Population	460‡	45	39	389	529‡	322	180†	357
Intensive	- Fungicide	199†	-39†	117	310	319†	452†	284†	197†
Intensive	- Plant Growth Regulator	481‡	110	97	557‡	554‡	364	230	427‡
Significance of single degree of freedom orthogonal contrasts									
Y_w vs FP		43	-135***	-179***	-92**	-54***	-171***	-175***	-58**
Split Nitrogen vs. No Split Nitrogen		-152**	-139***	-76*	-80	-53*	-76**	-76***	-106**
Sulfur vs. No Sulfur		-51	-2	2	-12	-4	31	16	-17
Chloride vs. No Chloride		-88**	-55*	-20	0	-18	-30	-25*	-40
High Population vs. Low Population		-38	6	26	41	-42	47*	37**	-9
Fungicide vs. No Fungicide		192***	51*	-70*	53	125***	-108***	-89***	107**
PGR vs. No PGR§		-122**	-87**	-43	-109*	-64	-28	-35**	-95**

*, **, *** indicate significance at the 0.05, 0.01, 0.0001 probability, respectively.

NS-nonsignificant

† Indicates treatment was significantly different from the respective management strategy control at α<0.05 (individual treatment additions to the standard control compared to the standard control, and individual treatment removal from the intensive control compared to the intensive control).

‡ Indicates treatment was not significantly different from the alternative management strategy control at α<0.05 (individual treatment additions to the standard control compared to the intensive control, and individual treatment removal from the intensive control compared to the standard control).

§ PGR, Plant Growth Regulator

Table 2-12. Average winter wheat stand (plants m^{-2}) measured three weeks as affected by management strategy and by addition or removal of individual treatments from the FP and Y_w controls, respectively, for the 2015-16 and 2016-17 growing seasons in Belleville, Hutchinson, Manhattan, Kansas, as well as for the pooled analysis for no-till (Manhattan, 2015-16 and 2016-17), and conventional till (Belleville, 2015-16 and 2016-17; and Hutchinson, 2015-16 and 2016-17) site-years.

Treatment		2015-16			2016-17			2015-16 & 2016-17	
Mgmt. Strat.	Exception	Belleville	Hutchinson	Manhattan	Belleville	Hutchinson	Manhattan	No-Till	Conventional Till
		Plants m^{-2}							
FP	None	200	210	190	190	250	190	190	210
Standard	+Split Nitrogen	210	230	180	190	240	160†	170	220
Standard	+Sulfur	200	230	190	180	240	180	180	210
Standard	+Chloride	200	210	191	180	240	170	180	210
Standard	+Plant Population	320†‡	290†‡	240†‡	290†‡	340†‡	250†‡	250†‡	310†‡
Standard	+Fungicide	180	200	180	190	250	190	180	200
Standard	+Plant Growth Regulator	200	210	180	210	230	180	180	210
Y_w	None	340	300	230	270	340	260	240	320
Intensive	-Split Nitrogen	330	310	260†	260	340	260	260	310
Intensive	-Sulfur	320	300	220	260	320	230†	220	300
Intensive	-Chloride	320	300	230	250	340	230	230	300
Intensive	- Plant Population	210†‡	220†‡	180†‡	180†‡	250†‡	190†‡	180†‡	210†‡
Intensive	- Fungicide	320	310	220	260	340	230†	220	310
Intensive	- Plant Growth Regulator	340	310	230	270	340	240	230	320
Significance of single degree of freedom orthogonal contrasts									
Y_w vs FP		100***	70***	30***	50***	70***	40***	40***	70***
Split Nitrogen vs. No Split Nitrogen		10	0	-20*	10	10	-10	-20*	0
Sulfur vs. No Sulfur		10	10	0	0	-10	10	10	10
Chloride vs. No Chloride		10	-10	0	0	0	0	0	0
High Population vs. Low Population		130***	90***	-50***	100***	90***	70***	60***	100***
Fungicide vs. No Fungicide		0	10	0	0	0	10	10	0
PGR vs. No PGR§		0	-10	-10	10	-10	0	0	0

*, **, *** indicate significance at the 0.05, 0.01, 0.0001 probability, respectively.

NS-nonsignificant

† Indicates treatment was significantly different from the respective management strategy control at α<0.05 (individual treatment additions to the standard control compared to the standard control, and individual treatment removal from the intensive control compared to the intensive control).

‡ Indicates treatment was not significantly different from the alternative management strategy control at α<0.05 (individual treatment additions to the standard control compared to the intensive control, and individual treatment removal from the intensive control compared to the standard control).

§ PGR, Plant Growth Regulator

Table 2-13. Average winter wheat plant height as affected by management strategy and by addition or removal of individual treatments from the FP and Y_w controls, respectively, for the 2015-16 and 2016-17 growing seasons in Belleville, Hutchinson, Manhattan, Kansas, and for the pooled analysis across no-till (Manhattan, 2015-16 and 2016-17), and conventional till (Belleville, 2015-16 and 2016-17; and Hutchinson, 2015-16 and 2016-17) site-years.

Treatment		2015-16			2016-17			2015-16 & 2016-17	
Mgmt. Strat.	Exception	Belleville	Hutchinson	Manhattan	Belleville	Hutchinson	Manhattan	No-Till	Conventional Till
						cm			
FP	None	83	77	76	93	87	97	86	85
Standard	+Split Nitrogen	82	74‡	76‡	92	90‡	96	86	84‡
Standard	+Sulfur	85‡	74‡	77‡	93	90†‡	97	87	86‡
Standard	+Chloride	80	75‡	77‡	94	90‡	98	88	85‡
Standard	+Plant Population	91†‡	74‡	79†	95	86‡	98	89	87‡
Standard	+Fungicide	86‡	73‡	74‡	94	87‡	96	85	85‡
Standard	+Plant Growth Regulator	77	60†	74‡	82†	75†	78†	76	73†
Y_w	None	89	67	76	87	88	83	80	83
Intensive	-Split Nitrogen	80†‡	71‡	75‡	85	86‡	79†	77	81
Intensive	-Sulfur	87‡	68	77‡	87	88‡	78†	78	82‡
Intensive	-Chloride	87‡	70‡	77‡	88	86‡	82	80	83‡
Intensive	- Plant Population	89‡	68	78‡	85	88‡	82	80	82‡
Intensive	- Fungicide	75†	55†	76‡	86	79†	83	79	74†
Intensive	- Plant Growth Regulator	90‡	75‡	79†	98†	90‡	98†‡	89	88†‡
Significance of single degree of freedom orthogonal contrasts									
Y_w vs FP		2	-4**	1	-3.9***	0	-11***	-5	-2
Split Nitrogen vs. No Split Nitrogen		4	-3	1	0	2*	2	1	1
Sulfur vs. No Sulfur		2	-1	0	0	2	3***	1	1
Chloride vs. No Chloride		-1	-2	0	0	2*	1	1	0
High Population vs. Low Population		4	-1	1	2	0	1	1	1
Fungicide vs. No Fungicide		8**	5	-1	1	4***	0	0	4**
PGR vs. No PGR§		-4	-12***	-2*	-12***	-7***	-17***	-10	-8***

*, **, *** indicate significance at the 0.05, 0.01, 0.0001 probability, respectively.

NS-nonsignificant

† Indicates treatment was significantly different from the respective management strategy control at α<0.05 (individual treatment additions to the standard control compared to the standard control, and individual treatment removal from the intensive control compared to the intensive control).

‡ Indicates treatment was not significantly different from the alternative management strategy control at α<0.05 (individual treatment additions to the standard control compared to the intensive control, and individual treatment removal from the intensive control compared to the standard control).

§ PGR, Plant Growth Regulator

Table 2-14. Average winter wheat aboveground dry matter measured at physiological maturity as affected by management strategy and by addition or removal of individual treatments from the FP and Y_w controls, respectively, for the 2015-16 and 2016-17 growing seasons in Belleville, Hutchinson, Manhattan, Kansas, as well as for the pooled analysis for no-till (Manhattan, 2015-16 and 2016-17), and conventional till (Belleville, 2015-16 and 2016-17; and Hutchinson, 2015-16 and 2016-17) site-years.

Treatment		2015-16			2016-17			2015-16 & 2016-17	
Mgmt. Strat.	Exception	Belleville	Hutchinson	Manhattan	Belleville	Hutchinson	Manhattan	No-Till	Conventional Till
						Mg ha^{-1}			
FP	None	11.18	9.33	9.05	19.07	13.07	13.00	11.09	13.1
Standard	+Split Nitrogen	9.70	8.67‡	9.10	18.67	13.87	12.33	10.90	12.7
Standard	+Sulfur	10.66	8.28	8.95	17.73	15.73	13.00	11.03	13.0
Standard	+Chloride	10.63	8.98‡	10.07	17.97	16.10†	14.00	12.1‡	13.3
Standard	+Plant Population	11.59‡	9.16‡	10.7	18.37	11.93	14.67	12.8†‡	12.9
Standard	+Fungicide	13.23‡	10.64‡	9.22	21.30	14.90	14.67	11.77‡	15.0‡
Standard	+Plant Growth Regulator	10.60	7.88	9.52	17.80	14.33	14.00	11.74‡	12.6
Y_w	None	13.47	10.44	10.70	17.40	19.97	15.67	13.08	15.3
Intensive	-Split Nitrogen	13.91	11.76	9.76	15.03	15.93†	13.33	11.68‡	14.5‡
Intensive	-Sulfur	15.02	10.78‡	9.18	18.00	19.23	15.00	11.84‡	15.9
Intensive	-Chloride	14.04	11.08‡	10.55	20.00	18.30	16.00	13.10	15.9
Intensive	- Plant Population	15.45	11.33‡	10.33	20.63	18.73	17.00	13.28	16.6
Intensive	- Fungicide	11.42‡	7.53†‡	9.61	19.53	15.37†‡	13.33	11.58‡	13.4†‡
Intensive	- Plant Growth Regulator	15.92	11.15‡	11.45	23.33	18.20	15.67	13.59	17.1
Significance of single degree of freedom orthogonal contrasts									
Intensive vs Standard		-3.09***	-1.59**	-0.70	-0.42	-3.61***	-1.45	0.94**	2.2***
Split Nitrogen vs. No Split Nitrogen		0.97	0.99	-0.50	-0.98	-2.42*	-0.83	0.61	0.1
Sulfur vs. No Sulfur		1.04	0.70	-0.71	0.97	-1.70	-0.33	0.59	-0.4
Chloride vs. No Chloride		0.57	0.49	-0.60	1.85	-2.35*	-0.33	0.49	-0.2
High Population vs. Low Population		0.79	0.53	-1.05	1.97	-0.05	-0.17	0.76	-0.8
Fungicide vs. No Fungicide		-2.05*	-2.11**	-0.64	-0.05	-3.22**	-2.00	1.09	1.9**
PGR vs. No PGR§		1.52	1.08	0.13	3.6	-1.52	-0.50	0.07	-1.2

*, **, *** indicate significance at the 0.05, 0.01, 0.0001 probability, respectively.

NS-nonsignificant

† Indicates treatment was significantly different from the respective management strategy control at $\alpha<0.05$ (individual treatment additions to the standard control compared to the standard control, and individual treatment removal from the intensive control compared to the intensive control).

‡ Indicates treatment was not significantly different from the alternative management strategy control at $\alpha<0.05$ (individual treatment additions to the standard control compared to the intensive control, and individual treatment removal from the intensive control compared to the standard control).

§ PGR, Plant Growth Regulator

Table 2-15. Harvest index of winter wheat affected by management strategy and by addition or removal of individual treatments from the FP and Y_w controls, respectively for the 2015-16 and 2016-17 growing seasons in Belleville, Hutchinson, Manhattan, Kansas, as well as for the pooled analysis across no-till (Manhattan, 2015-16 and 2016-17), and conventional till (Belleville, 2015-16 and 2016-17; and Hutchinson, 2015-16 and 2016-17) site-years.

Treatment		2015-16			2016-17			2015-16 & 2016-17	
Mgmt. Strat.	Exception	Belleville	Hutchinson	Manhattan	Belleville	Hutchinson	Manhattan	No-Till	Conventional Till
						%			
FP	None	0.33	0.35	0.40	0.35	0.45	0.39	0.40	0.37
Standard	+Split Nitrogen	0.33	0.36	0.38	0.36‡	0.41†‡	0.38	0.38	0.36
Standard	+Sulfur	0.33	0.36	0.37	0.37‡	0.43‡	0.37	0.37	0.37
Standard	+Chloride	0.33	0.37‡	0.39	0.34‡	0.43‡	0.39	0.39	0.37
Standard	+Plant Population	0.31	0.37‡	0.37	0.35‡	0.45	0.39	0.37	0.37
Standard	+Fungicide	0.35	0.41†‡	0.39	0.37‡	0.44‡	0.37	0.39	0.39
Standard	+Plant Growth Regulator	0.31	0.35	0.37	0.37‡	0.45	0.39	0.38	0.37
Y_w	None	0.33	0.39	0.39	0.37	0.43	0.39	0.39	0.38
Intensive	-Split Nitrogen	0.34	0.39	0.37	0.34‡	0.44‡	0.40	0.38	0.38
Intensive	-Sulfur	0.35	0.38	0.39	0.36‡	0.44‡	0.40	0.39	0.39
Intensive	-Chloride	0.33	0.38	0.38	0.36‡	0.42	0.39	0.38	0.37
Intensive	- Plant Population	0.35	0.39	0.38	0.34‡	0.44‡	0.39	0.38	0.38
Intensive	- Fungicide	0.31	0.35†‡	0.38	0.33‡	0.41	0.40	0.39	0.35
Intensive	- Plant Growth Regulator	0.33	0.39	0.36	0.27†	0.43	0.39	0.37	0.36
Significance of single degree of freedom orthogonal contrasts									
Y_w vs FP		0	0.01**	0	-0.02	-0.01	0.01	0	0
Split Nitrogen vs. No Split Nitrogen		-0.01	0	0	0.02	-0.03**	-0.01	-0.01	0
Sulfur vs. No Sulfur		-0.01	0	-0.02	0.01	-0.02*	-0.01	-0.02	0
Chloride vs. No Chloride		0	-0.01	0	0	0.01	0	0	0
High Population vs. Low Population		-0.03	0	-0.01	0.01	-0.01	0	-0.01	0
Fungicide vs. No Fungicide		-0.02	0.05***	0	0.03	0	-0.01	-0.02	0
PGR vs. No PGR§		-0.01	0	0	0.06**	0	0	0	0

*, **, *** indicate significance at the 0.05, 0.01, 0.0001 probability, respectively.

NS-nonsignificant

† Indicates treatment was significantly different from the respective management strategy control at α<0.05 (individual treatment additions to the standard control compared to the standard control, and individual treatment removal from the intensive control compared to the intensive control).

‡ Indicates treatment was not significantly different from the alternative management strategy control at α<0.05 (individual treatment additions to the standard control compared to the intensive control, and individual treatment removal from the intensive control compared to the standard control).

§ PGR, Plant Growth Regulator

Table 2-16. Average winter wheat spikes m^{-2} as affected by management strategy and by addition or removal of individual treatments from the FP and Y_W controls, respectively, for the 2015-16 and 2016-17 growing seasons in Belleville, Hutchinson, Manhattan, Kansas, as well as for the pooled analysis across no-till (Manhattan, 2015-16 and 2016-17) and conventional till (Belleville, 2015-16 and 2016-17; and Hutchinson, 2015-16 and 2016-17) site-years.

Treatment		2015-16			2016-17			2015-16 & 2016-17	
Mgmt. Strat.	Exception	Belleville	Hutchinson	Manhattan	Belleville	Hutchinson	Manhattan	No-Till	Conventional Till
						m^{-2}			
FP	None	954	713	773	970	962	648	731	901
Standard	+Split Nitrogen	954‡	675	752	1016	1115	632	712	935‡
Standard	+Sulfur	823	667	704	874	1004	740	716	839
Standard	+Chloride	977‡	681	784	909	1015	765	778	897
Standard	+Plant Population	923‡	754‡	905†‡	922	829	836	882†‡	864
Standard	+Fungicide	962‡	727‡	771	997	826	763	768	883
Standard	+Plant Growth Regulator	908‡	686	813	948	924	772	799	867
Y_w	None	1064	803	948	945	1433	925	941	1057
Intensive	-Split Nitrogen	983‡	812‡	867‡	734	1026† ‡	784	839	907†‡
Intensive	-Sulfur	1116‡	754‡	869‡	967	1434	852	864	1064
Intensive	-Chloride	1060‡	810‡	892‡	938	1279	913	899	1032‡
Intensive	- Plant Population	1102‡	788‡	852‡	1016	1228†	941	882	1034
Intensive	- Fungicide	1092‡	734‡	849‡	1125	1179†	805	834†‡	1033‡
Intensive	- Plant Growth Regulator	1147	837	932	1083	1392	880	914	1112
Significance of single degree of freedom orthogonal contrasts									
Y_w vs FP		152***	91***	101***	-31	327***	132	110***	148***
Split Nitrogen vs. No Split Nitrogen		-41	24	-31	128	262***	63	41	92
Sulfur vs. No Sulfur		-91	-1	-6	-59	20	83	31	-34
Chloride vs. No Chloride		-14	-20	-34	-50	103	65	44	10
High Population vs. Low Population		-34	28	114*	-60	36	86	105**	-7
Fungicide vs. No Fungicide		9	41	49	-76	59	118	72	3
PGR vs. No PGR§		-64	31	29	-80	1	85	47	-44

*, **, *** indicate significance at the 0.05, 0.01, 0.0001 probability, respectively.

NS-nonsignificant

† Indicates treatment was significantly different from the respective management strategy control at α<0.05 (individual treatment additions to the standard control compared to the standard control, and individual treatment removal from the intensive control compared to the intensive control).

‡ Indicates treatment was not significantly different from the alternative management strategy control at α<0.05 (individual treatment additions to the standard control compared to the intensive control, and individual treatment removal from the intensive control compared to the standard control).

§ PGR, Plant Growth Regulator

Table 2-17. Average winter wheat kernels m^{-2} as affected by management strategy and by addition or removal of each individual treatments from the FP and Y_w controls, respectively, for the 2015-16 and 2016-17 growing seasons in Belleville, Hutchinson, Manhattan, Kansas, and for the pooled analysis across no-till (Manhattan, 2015-16 and 2016-17) and conventional till (Belleville, 2015-16 and 2016-17; and Hutchinson, 2015-16 and 2016-17) site-years.

Treatment		2015-16			2016-17			2015-16 & 2016-17	
Mgmt. Strat.	Exception	Belleville	Hutchinson	Manhattan	Belleville	Hutchinson	Manhattan	No-Till	Conventional Till
					x10^3 m^{-2}				
FP	None	17.0	17.7	17.4	25.6	16.8	19.9	18.9	19.3
Standard	+Split Nitrogen	16.1‡	14.9	15.8	29.4	16.98	18.4	17.2	19.1
Standard	+Sulfur	16.9‡	15.0	15.5	24.7	18.0‡	20.3	17.7	18.6
Standard	+Chloride	16.6‡	16.5	18.7‡	27.7	16.8	24.4	21.3‡	19.3
Standard	+Plant Population	18.5‡	16.2	19.8‡	28.9	14.4	22.2	21.3‡	19.5
Standard	+Fungicide	18.5‡	17.6	17.4	30.6	15.2	21.2	19.3	20.3
Standard	+Plant Growth Regulator	17.1‡	16.1	16.3	26.4	16.6	21.8	18.8	19.0
Y_w	None	18.4	16.6	21.0	22.7	20.5	24.8	22.9	19.7
Intensive	-Split Nitrogen	18.4‡	18.0	18.8‡	18.6	17.2†‡	20.9	20.1‡	18.5
Intensive	-Sulfur	20.4‡	16.6	18.6‡	24.6	22.6	23.3	20.8‡	21.1
Intensive	-Chloride	19.1‡	17.8	20.1	30.7	21.5	25.1	22.4	22.1
Intensive	- Plant Population	22.5†	18.1	19.9‡	25.3	20.6	29.2	23.6	21.9
Intensive	- Fungicide	18.9‡	14.3	17.9†‡	28.4	18.6‡	20.8	19.5†‡	20.1
Intensive	- Plant Growth Regulator	21.5	17.5	20.3	23.7	19.5‡	27.5	23.3	20.9
Significance of single degree of freedom orthogonal contrasts									
Y_w vs FP		2.6**	0.7	2.2***	-2.7	3.6***	3.3	2.5***	1.2
Split Nitrogen vs. No Split Nitrogen		-0.4	-2.0	0.3	4.0	1.6	1.2	0.6	0.5
Sulfur vs. No Sulfur		-1.0	-1.3	0.2	-1.4	-0.5	0.9	0.5	-1.1
Chloride vs. No Chloride		-0.5	-1.2	1.1	-2.9	-5.8	2.1	1.4	-1.2
High Population vs. Low Population		-1.3	-1.5	1.8	0.3	-1.3	-1.1	0.8	-1.0
Fungicide vs. No Fungicide		0.5	1.0	1.5	-0.4	0.1	2.6	1.9	0.3
PGR vs. No PGR§		-1.5	-1.2	-0.2	-0.1	-0.4	-0.4	-0.3	-0.7

*, **, *** indicate significance at the 0.05, 0.01, 0.0001 probability, respectively.

NS-nonsignificant

† Indicates treatment was significantly different from the respective management strategy control at α<0.05 (individual treatment additions to the standard control compared to the standard control, and individual treatment removal from the intensive control compared to the intensive control).

‡ Indicates treatment was not significantly different from the alternative management strategy control at α<0.05 (individual treatment additions to the standard control compared to the intensive control, and individual treatment removal from the intensive control compared to the standard control).

§ PGR, Plant Growth Regulator

Table 2-18. Average winter wheat 1000-kernel weight as affected by management strategy and by addition or removal of individual treatments from the FP and Y_w controls, respectively, for the 2015-16 and 2016-17 growing seasons in Belleville, Hutchinson, Manhattan, Kansas, as well as for the pooled analysis for no-till (Manhattan, 2015-16 and 2016-17), and conventional till (Belleville, 2015-16 and 2016-17; and Hutchinson, 2015-16 and 2016-17) site-years.

Treatment		2015-16			2016-17			2015-16 & 2016-17	
Mgmt. Strat.	Exception	Belleville	Hutchinson	Manhattan	Belleville	Hutchinson	Manhattan	No-Till	Conventional Till
						g			
FP	None	21.6	18.7	20.7	27.1	30.6	25.9	23.2	24.4
Standard	+Split Nitrogen	19.5	20.6†	21.3	23.1	25.2†	26.3	23.7	22.1
Standard	+Sulfur	20.5	19.6	21.1‡	26.9	28.3‡	24.5	22.9	23.8‡
Standard	+Chloride	20.9	20.1	20.3‡	22.5	31.1‡	23.3	22.0	23.6‡
Standard	+Plant Population	18.8†	21.0†	19.8‡	22.1	28.3‡	25.8	22.7	22.5
Standard	+Fungicide	25.5†‡	24.7†‡	20.9‡	26.0	32.5‡	26.1	23.4	27.2‡
Standard	+Plant Growth Regulator	19.3†	17.4	21.6	24.8	29.0‡	24.8	23.3	22.4
Y_w	None	23.4	24.4	19.6	28.3	31.3	24.7	22.1	26.8
Intensive	-Split Nitrogen	26.3†	25.7	19.3‡	27.8	31.0‡	26.0	22.4	27.8‡
Intensive	-Sulfur	25.7†	25.0	18.9	26.7	28.9‡	25.6	22.0	26.7‡
Intensive	-Chloride	24.4	23.9	19.9‡	24.0	27.0†‡	25.0	22.4	25.0‡
Intensive	- Plant Population	24.1	24.5	19.6‡	27.5	29.9‡	22.7	21.3	26.5‡
Intensive	- Fungicide	18.7†	18.3†‡	20.5‡	23.5	25.5†	25.5	22.9	21.5†‡
Intensive	- Plant Growth Regulator	24.5	25.0	20.1‡	27.1	29.8‡	21.9	21.3	26.7‡
Significance of single degree of freedom orthogonal contrasts									
Y_w vs FP		3.0***	3.6***	-1.1**	1.7	0.2	-0.9	-1.0	2.1**
Split Nitrogen vs. No Split Nitrogen		-2.5**	0.3	0.4	-1.8	-2.5	0.5	0.1	-1.6
Sulfur vs. No Sulfur		-1.7*	0.2	0.6	0.7	0.1	1.2	-0.1	-0.3
Chloride vs. No Chloride		-0.9	1.0	-0.4	-0.2	2.4	1.4	-0.8	0.5
High Population vs. Low Population		-1.7*	1.1	-0.5	-2.2	-0.5	1.0	0.1	-0.8
Fungicide vs. No Fungicide		4.3***	6.1***	0.4	1.8	3.9*	0.3	-0.3	4.1**
PGR vs. No PGR§		-1.7*	-1.1	0.20	-0.6	0	0.9	0.5	-0.9

*, **, *** indicate significance at the 0.05, 0.01, 0.0001 probability, respectively.

NS-nonsignificant

† Indicates treatment was significantly different from the respective management strategy control at α<0.05 (individual treatment additions to the standard control compared to the standard control, and individual treatment removal from the intensive control compared to the intensive control).

‡ Indicates treatment was not significantly different from the alternative management strategy control at α<0.05 (individual treatment additions to the standard control compared to the intensive control, and individual treatment removal from the intensive control compared to the standard control).

§ PGR, Plant Growth Regulator

Table 2-19. Description of seed, nitrogen (N), sulfur (S), chloride (Cl), foliar fungicide, plant growth regulator (PGR), dry fertilizer and liquid application costs, which are referred as variable input costs used in the economic analysis. Price were determined through MKC cooperative which is an agricultural retail location located in Manhattan, KS.

Input	Cost
Seed	0.49 \$ kg^{-1} seed
Nitrogen (Urea)	0.77 \$ kg^{-1} N
Sulfur (Gypsum)	0.29 \$ kg^{-1} S
Chloride (Potash)	0.86 \$ kg^{-1} Cl
Fungicide (Aproach and Aproach Prima)	0.08 \$ mL^{-1}
Plant Growth Regulator (Palisade)	0.04 \$ mL^{-1}
Dry Fertilizer application	15.44 \$ ha^{-1}
Liquid Chemical Application	19.14 \$ ha^{-1}

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Appendix A - Supporting Figures and Graphs

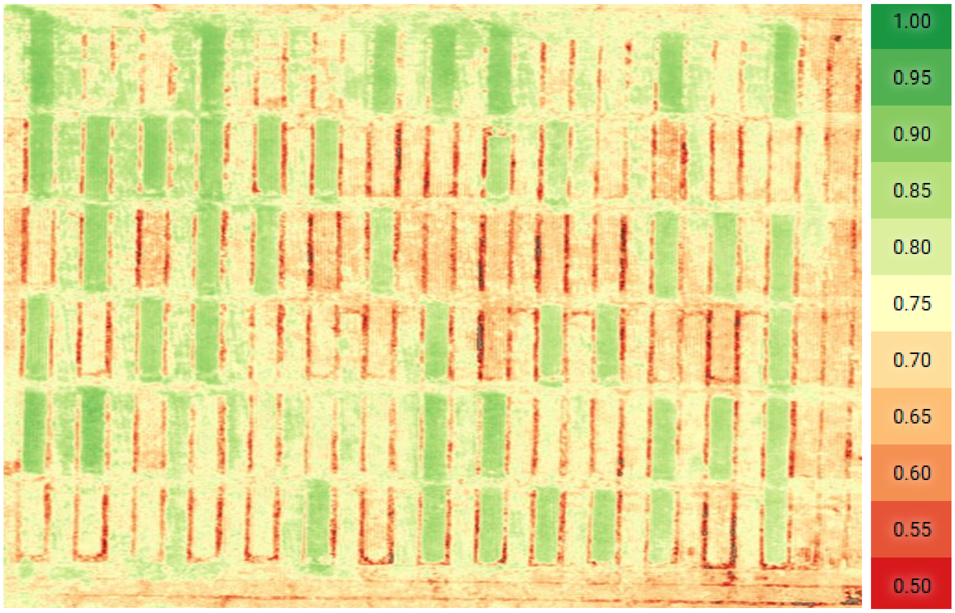

Figure A-1. Aerial photo taken by a MicaSense RedEdge camera mounted on a UAV drone to measure normalized difference vegetation index. Higher NDVI values in experimental units that received foliar fungicide (green rectangles and Treatment 6&8), and no foliar fungicide resulted in lower NDVI values (Treatment 1&13) at Hutchinson on May 17, 2016.

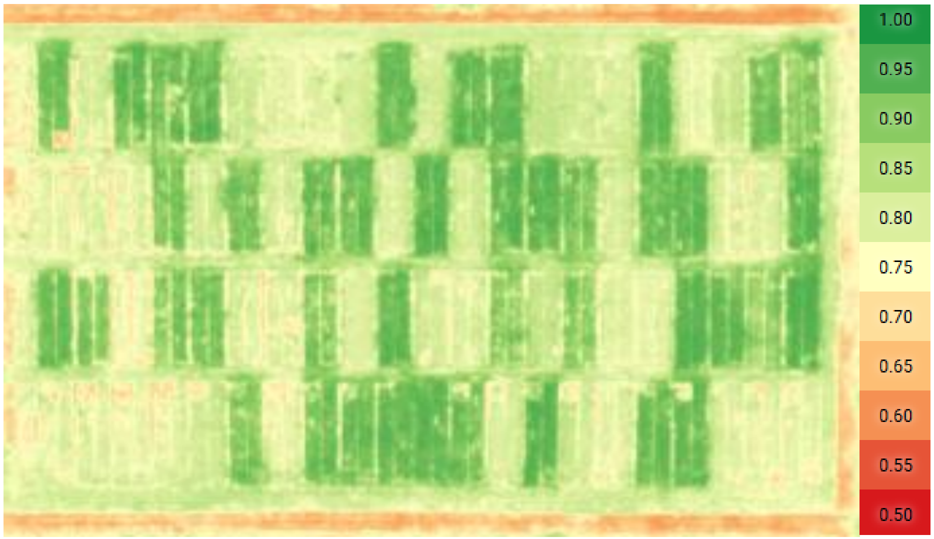

Figure A-2. Aerial photo taken by a MicaSense RedEdge camera mounted on a UAV drone to measure normalized difference vegetation index. Higher NDVI values in experimental units that received foliar fungicide (green rectangles and Treatment 6&8), and no foliar fungicide resulted in lower NDVI values (Treatment 1&13) at Belleville 2016-17 on June 7, 2017.

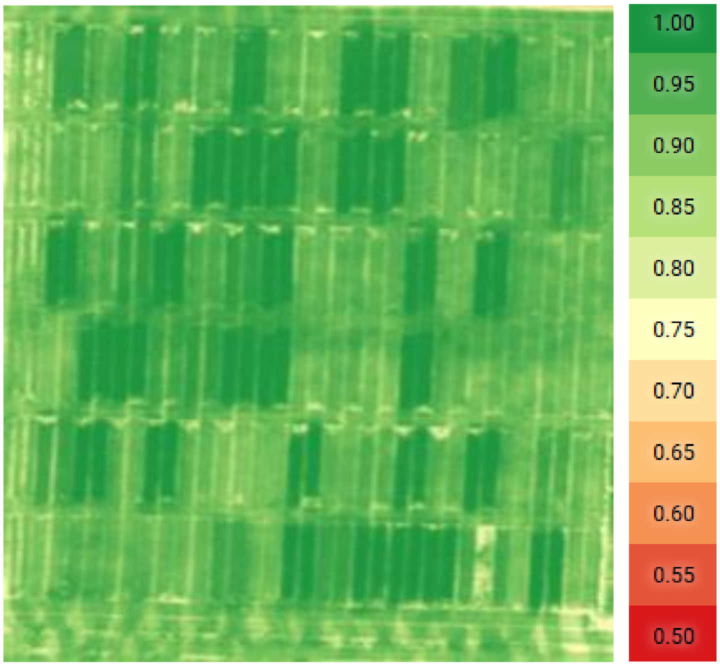

Figure A-3. Aerial photo taken by a MicaSense RedEdge camera mounted on a UAV drone to measure normalized difference vegetation index. Higher NDVI values in experimental units that received foliar fungicide (green rectangles and Treatment 6&8), and no foliar fungicide resulted in lower NDVI values (Treatment 1&13) at Hutchinson 2016-17 on May 18, 2017.

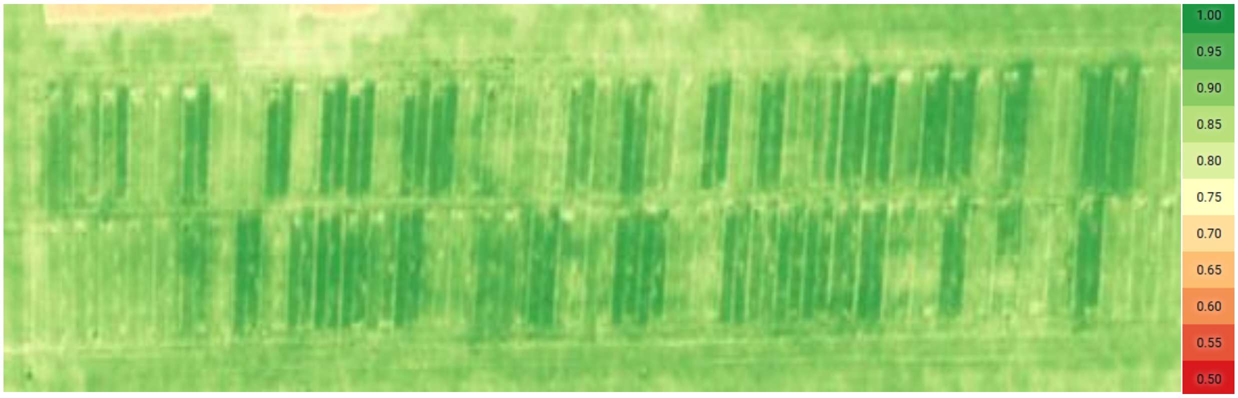

Figure A-4. Aerial photo taken by a MicaSense RedEdge camera mounted on a UAV drone to measure normalized difference vegetation index. Higher NDVI values in experimental units that received foliar fungicide (green rectangles and Treatment 6&8), and no foliar fungicide resulted in lower NDVI values (Treatment 1&13) at Manhattan 2016-17 on June 2, 2017.

Appendix B - SAS Code

Table B-120. SAS code for yield in Belleville and Hutchinson during the growing seasons of 2015-16 and 2016-17.

```
PROC mixed DATA=_Bell_Hutch_bothseasons covtest;
CLASS Year Site BLK TRT;
MODEL YIELD=TRT/DDFM=KR;
RANDOM YEAR SITE BLK(YEAR SITE) YEAR*TRT SITE*TRT YEAR*SITE
YEAR*SITE*TRT;
LSMEANS TRT;
Title '_Bell_Hutch_bothseasons_yield';
estimate 'standard vs + splitnitrogen' trt 1 -1 0 0 0 0 0 0 0 0 0 0 0 0;
estimate 'standard vs + sulfur' trt 1 0 -1 0 0 0 0 0 0 0 0 0 0 0;
estimate 'standard vs + chloride' trt 1 0 0 -1 0 0 0 0 0 0 0 0 0 0;
estimate 'standard vs + pop' trt 1 0 0 0 -1 0 0 0 0 0 0 0 0 0;
estimate 'standard vs + fungi' trt 1 0 0 0 0 -1 0 0 0 0 0 0 0 0;
estimate 'standard vs + PGR' trt 1 0 0 0 0 0 -1 0 0 0 0 0 0 0;
estimate 'standard vs int - splitnitrogen' trt 1 0 0 0 0 0 0 0 -1 0 0 0 0 0;
estimate 'standard vs int - sulfur' trt 1 0 0 0 0 0 0 0 0 -1 0 0 0 0;
estimate 'standard vs int - chloride' trt 1 0 0 0 0 0 0 0 0 0 -1 0 0 0;
estimate 'standard vs int - pop' trt 1 0 0 0 0 0 0 0 0 0 0 -1 0 0;
estimate 'standard vs int - fungi' trt 1 0 0 0 0 0 0 0 0 0 0 0 -1 0;
estimate 'standard vs int - PGR' trt 1 0 0 0 0 0 0 0 0 0 0 0 0 -1;
estimate 'intensive vs - splitnitrogen' trt 0 0 0 0 0 0 0 -1 1 0 0 0 0 0;
estimate 'intensive vs - sulfur' trt 0 0 0 0 0 0 0 -1 0 1 0 0 0 0;
estimate 'intensive vs - chloride' trt 0 0 0 0 0 0 0 -1 0 0 1 0 0 0;
estimate 'intensive vs - pop' trt 0 0 0 0 0 0 0 -1 0 0 0 1 0 0;
estimate 'intensive vs - fungi' trt 0 0 0 0 0 0 0 -1 0 0 0 0 1 0;
estimate 'intensive vs - PGR' trt 0 0 0 0 0 0 0 -1 0 0 0 0 0 1;
estimate 'intensive vs std + splitnitrogen' trt 0 1 0 0 0 0 0 -1 0 0 0 0 0 0;
estimate 'intensive vs std + sulfur' trt 0 0 1 0 0 0 0 -1 0 0 0 0 0 0;
estimate 'intensive vs std + chloride' trt 0 0 0 1 0 0 0 -1 0 0 0 0 0 0;
estimate 'intensive vs std + pop' trt 0 0 0 0 1 0 0 -1 0 0 0 0 0 0;
estimate 'intensive vs std + fungi' trt 0 0 0 0 0 1 0 -1 0 0 0 0 0 0;
estimate 'intensive vs std + PGR' trt 0 0 0 0 0 0 1 -1 0 0 0 0 0 0;
estimate 'standard vs intensive' trt .14 .14 .14 .14 .14 .14 .14 -.14 -.14 -.14 -.14 -.14 -.14 -.14;
estimate 'nitrogen vs splitnitrogen' trt .5 -.5 0 0 0 0 0 -.5 .5 0 0 0 0 0;
estimate 'nonsulfur vs sulfur' trt .5 0 -.5 0 0 0 0 -.5 0 .5 0 0 0 0;
estimate 'nonchloride vs chloride' trt .5 0 0 -.5 0 0 0 -.5 0 0 .5 0 0 0;
estimate 'lowpop vs highpop' trt .5 0 0 0 -.5 0 0 -.5 0 0 0 .5 0 0;
estimate 'nonfungicide vs fungicide' trt .5 0 0 0 0 -.5 0 -.5 0 0 0 0 .5 0;
estimate 'nonPGR vs PGR' trt .5 0 0 0 0 0 -.5 -.5 0 0 0 0 0 .5;
Run;
```