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Determination of Optimum Fall and Spring Nitrogen Fertilizer Rate for Maximizing Grain Yield of Soft Red Winter Wheat Sown at Variable Planting Dates

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Determination of Optimum Fall and Spring Nitrogen Fertilizer Rate for Maximizing Grain Yield of Soft Red Winter Wheat Sown at Variable Planting Dates

A thesis submitted in partial fulfillment
of the requirements for the degree of
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by

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Abstract

An optimum planting date is important for winter wheat nitrogen (N) management as it dramatically changes the growing environment including temperature and moisture, ultimately affecting fertilizer efficiency and grain yield (GY). In Arkansas, high precipitation in the fall often forces farmers to delay planting and current Arkansas recommendations include the application of fall N when soft red winter wheat (SRWW) is sown later than optimum, despite the lack of data supporting this practice. This study evaluated the effect of rate and timing of N application on GY of SRWW sown at variable planting dates in Arkansas. Granular urea was split applied between the fall (F), late winter (LW) and/or early spring (ES) and compared to N only applied in the spring (LW, or LW + ES). Experiments were conducted at the Newport Research Station (NPRS), Pine Tree Research Station (PTRS), and Rohwer Research Station (RWRS), representing the diverse wheat growing regions in Arkansas. Wheat was sown at three planting dates and supplied with total N rates of 67, 101, 135, 169, and 202 kg N ha^{-1}. Fall-N rates equal to 0, 34, 67 kg N ha^{-1} were applied after planting at Feekes 3 and spring-N rates equal to 67, 101, 135 and 169 kg N ha^{-1} were applied at Feekes stage 4 or 5. There was no statistical difference between spring (LW and ES) and split N applications at NPRS where there was low precipitation and the highest residual soil-N and thus decreased potential for volatilization and denitrification. A split fall and spring application was important for maximizing GY on the latest planting date at both PTRS and RWRS and increased mean GY by 1122 and 544 kg ha^{-1} compared to spring only application, respectively. Overall, results suggest that splitting fertilizer-N between fall and spring has the potential for increasing GY in late-planted wheat in fine-textured soils when there is high precipitation, which favors N loss.

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Dedication

In memory of Dr. João Ambrósio Araújo Filho for teaching me the importance of scientific developments leading to the progress in our society. I dedicate this work to my loving parents, Luiz and Fátima, and my caring sisters, Luise and Laise, for their unconditional support. I am very thankful to my undergraduate advisor, Dr. Henrique Antunes de Souza who always encouraged me to pursue my professional goals. A special thanks to my dearest friends, Vidit Agrawal, Sanghamitra Mandal, Miranti Rahmaningsih, Anaclaudia Primo, Angelo Matos, Mariana Lira, Walter Nogueira, and Henrique Ziegler for teaching me the true values of hard work and success.

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CHAPTER 1: LITERATURE REVIEW

Introduction

Fertilizer-N is one of the most important agronomic inputs for bread wheat (*Triticum aestivum* L.) and represents a large portion of production cost. Nitrogen must be applied using the most economical practices in order to maximize profitability for producers. Yield gains due to fertilizer-N are attributed to better seedling establishment, vigorous vegetative growth, larger leaves with prolonged photosynthetic activity, and a larger number of tillers surviving to maturity (Borghi, 2000). Determining optimum-N rates and application times is crucial to obtain greater economic returns from applied fertilizer-N (Stewart et al., 2005). In winter wheat production systems, split applications of fertilizer-N between fall and spring have been shown to be more beneficial than a single application as there is greater N demand in the spring during rapid stem elongation (Sowers et al., 1994; Welch et al., 1966). Fall-applied N promotes adequate root and tiller growth but may result in lower fertilizer-N recovery efficiency due to N loss during the winter when wheat is dormant and has a low demand for N.

Planting date is also a critical management component for successful wheat cultivation (Barnett and Chapman, 1975; Tapley et al., 2013). An early planting date increases uptake of N by providing a longer vegetative growth period prior to dormancy. Conversely, a later-than-optimum planting date results in decreased uptake of N due to a truncated vegetative period prior to dormancy and inadequate root and tiller development (Winter and Musick, 1993). Understanding the ability of application of fertilizer-N to help overcome yield losses from non-optimal planting dates can ensure better economic return of the applied N by avoiding deficient or excessive supply.

Importance of Nitrogen for Cereal Growth and Development

Nitrogen is the fourth most abundant element in plants and frequently limits crop production in many of the arable soils worldwide (Havlin, 2013; Yahdjian et al., 2014). Nitrogen is part of several important metabolic processes and is essential for maintaining energy and structural functions in crops. Nitrogen is a precursor in the synthesis of adenosine triphosphate, deoxyribonucleic acid, amino acids and chlorophyll which are all essential for biosynthesis of proteins and enzymes regulating metabolic pathways (Taiz and Zeiger, 2010). As such, cereals grown with low N availability become stunted and develop fewer tillers and chlorotic leaves which ultimately leads to yield losses (Borghi, 2000).

Dinitrogen (N_2) is a major reservoir of N in the biosphere, making up 78% of the atmosphere. Dinitrogen holds a triple atomic bond, making it relatively inert with limited availability for biological use (Harper et al., 1987). Plant-available N is further limited in agricultural systems due to competition between plants and soil microorganisms inorganic-N. High demand and low availability has made N management one of the most important factors leading to yield improvement of cereals. Unlike legumes, cereals are not capable of establishing a symbiotic relationship with N-fixing microorganisms, instead relying almost exclusively on available soil-N. Therefore, to ensure proper growth and development, management of N is critical. This literature review highlights the important considerations regarding N utilization by plants, N forms and transformations in the soil, fertilizer-N management practices including rate and timing of fertilizer-N applications and considerations of other management practices on winter wheat in Arkansas.

Wheat production

Cereal crop production has increased throughout history as a result of the incorporation of scientific and technological innovations into the agriculture industry. This was particularly evident during the second half of the 20th century with the green revolution leading to advances in crop management and the development of high-yielding varieties highly responsive to N (Hedden, 2003). Bread wheat is a staple for almost half of the population in North America, Europe and Asia (Peng et al., 2011). Wheat ranks third in worldwide grain production behind maize (*Zea mays* L.) and rice (*Oryza sativa* L.). In 2012, 60 million tons of wheat were harvested from 1.9 x 10^7 ha^2 of planted area in the U.S. (USDA Census of Agriculture, 2014), making the U.S. the third largest global wheat producer. In comparison, in the same year China, the largest global producer of wheat, harvested more than 125 million tons. Arkansas produced 680,000 tons of winter wheat, planted over 73,200 ha^2, ranking as the 19th largest wheat producer in the U.S. in 2012. With this high level of production, there is an increased reliance on properly managed N fertilization programs to maximize yield and profitability due in part to continuous genotype selection favoring increased grain-to-stem ratio traits in semi-dwarf wheat cultivars (Law et al., 1978). Semi-dwarf varieties partition carbon accumulation during photosynthesis increasingly towards grains as opposed to biomass that increases harvest index and reduce susceptibility to lodging (Austin et al., 1980; Law et al., 1978). Furthermore, the importance of wheat as a staple food and its self-pollination has led to the development of identifiable cultivars. As a result, wheat has become an important cash crop worldwide with development of high-yielding and disease-resistant cultivars in both the public and private sectors.

Important anatomical characteristics in wheat

Wheat production is geographically distributed over diverse climates, ranging from tropical to temperate areas, from warm to cold, and humid to dry environments (Gustafson et al., 2009). Bread wheat is an allohexaploid (AABBCC, 2n=6x=42) with seven groups of chromosomes (Dubcovsky and Dvorak, 2007) that originated 8,000 to 10,000 years ago through the hybridization of three diploid species in regions corresponding to modern-day Iraq, Kuwait and Turkey (Gill and Friebe, 2002). Old wheat cultivars supported the emergence of the first city-based societies as it was one of the first crops cultivated in large scale (Gustafson et al., 2009). A fully grown wheat plant consists of a grain-bearing spike (also known as an ear), leaves and stalks (Slafer and Satorre, 2000). Wild wheat varieties are characterized by the presence of a tighter hull covering their seeds and a semi-brittle rachis which separates easily on threshing, causing the wheat spike to break into spikelets instead of seeds (Peng et al., 2011). Domesticated varieties are free-threshing and favored due to their adaptability for mechanical harvest (Gustafson et al., 2009).

End-use qualities of wheat

The diverse food products developed from wheat grains are a staple for almost half of the human population, including Europe, North America and Asia (Peng et al., 2011; Shewry, 2009). Wheat flour is the main ingredient for making bread, pasta, crackers, cookies, noodles, cakes and many others products consumed worldwide. The multiple uses for wheat are attributed to the gliadin and glutenin proteins inside the wheat grain, which combine to make a storage protein called gluten, characterized by its plasticity, strength and elasticity (Wall, 1979). Gluten protein content gives wheat flour different levels of elastic toughness and as such wheat classes are categorized based on amount of protein, with soft wheat having lower protein content compared to hard. The amount of protein in the grain is strongly influenced by the N availability as N is required by plants to metabolize amino acids and proteins (Mallory and Darby, 2013; Subedi et al., 2007). In addition to protein content, wheat is categorized according to the vernalization or chilling requirement. Winter wheat requires an extended period of cold to initiate the reproductive phase so is planted in the fall and harvested in the summer. Spring wheat is sown in the spring and harvested in the late summer. In total, there are six principal classes of wheat in the U.S., including: soft red winter wheat (SRWW) and soft white winter wheat (SWWW) used to make products requiring low-protein flour; hard red winter wheat (HRWW), hard red spring wheat (HRSW) and hard white (HW) used for making bread; and durum wheat used for making pasta (Shewry, 2009).

Wheat growth and development

An understanding of the growth cycle of winter wheat is necessary to optimize management of inputs including fertilizer, herbicides and fungicides. The sequence and duration of phenological events driving crop development are controlled by genetic and environmental factors. Wheat growth is comprised of germination, emergence, tillering, stem elongation, flowering, anthesis and grain-filling stages (Miralles and Slafer, 2000). Scales describing the wheat growth cycle include Zadoks (Zadoks et al., 1975) and Feekes (Large, 1954), with the latter being most widely used in the U.S. Feekes stages include establishment and tillering from 1 to 5, stem extension from 6 to 10, heading from 10.1 to 10.5; and grain ripening at 11. Wheat seeds normally germinate at temperatures between 12 and 25°C. Following germination, a seminal root begins to grow followed by coleoptile emergence and the unfolding of the first leaf, allowing for energy production through photosynthesis. In addition to the main-stem, secondary stems known as tillers are formed and nutritionally dependent on the main shoot until the development of their own nodal root system. Wheat sown in the fall will continue to grow until temperatures begin to drop, signaling the onset of vernalization, a chilling treatment required for winter wheat to flower in the spring (PrÁŠIl et al., 2004). Tillers are segmented and each segment is separated by nodes, which elongate after dormancy promoting faster biomass growth and thus increased nutrient uptake. Grain yield is dependent on the growth and development of tillers; however not all tillers will be fertile, especially if the density is high or if they are produced after the winter (Slafer and Rawson, 1995). Stem elongation starts when the first node is visible (feekes growth stage 6) on the stem and is completed when the flag leaf is detectable (feekes growth stage 9). Carbon portioning before and after flowering influences the development of the growing spike and impacts the number and weight of individual grains (Schnyder, 1993). During grain-filling, assimilates such as amino acids are translocated to grains and their individual weights are determined. The number of grains harvested is the most important component for total GY production (Fischer, 2008). Pre and post-anthesis photosynthesis carried out in the leaves, stems and spike contributes to the production of assimilates translocated to grains (Ehdaie and Waines, 2001). A tradeoff between the number and the weight of individual grains has been shown, with grain number per spike more correlated to gains in yield (García et al., 2014). The critical period for determining grain number occurs when the spikelets are actively growing during the stem elongation phase from a few weeks before to immediately after anthesis. If spikelet primordia development is negatively impacted by external factors, the number of grains will be reduced. Thus, an adequate supply of N during spikelet development is critical for grain number determination. Nitrogen fertilizers are utilized more efficiently by winter wheat when applied just prior to the period of rapid vegetative growth.

Nitrogen Uptake and Assimilation by Plants

Plant available N (PAN) such as NO_3^- and NH_4^+ is taking up by plant through the root system (Liu et al., 2015). For winter crops, the demand for N generally increases slowly during the stages preceding dormancy (Feekes stage 1, 2 and 3) followed by rapid vegetative growth and nutrient assimilation (Feekes stage 4 to 10.1) and a decline as the plant approaches physiological maturity (Feekes stage 10.5 and 11) (Baethgen and Alley, 1989). Most N uptake in cereals occurs during stem elongation before heading. After flowering, N flux is oriented mainly towards accumulation in grain and this process is largely sustained by remobilization from vegetative to reproductive organs (Suprayogi et al., 2011). Only a relatively small portion of final grain-N content is derived from the soil during grain development. Nitrate allocated to the leaves may be stored in vacuoles and then remobilized when N supply from the soil is insufficient to meet demand (Xu and Ni, 1990). Conversely, NH_4^+ is toxic in high concentrations and must be assimilated in roots prior to translocation to leaves. Absorption of NO_3^- by roots transports bicarbonate (HCO_3^-) and hydroxide (OH^-) out of the cells, which increases soil alkalinity. For NH_4^+ absorption by root cells, hydrogen is exuded to maintain charge balance inside the roots, which increases soil acidity (Havlin, 2013). Therefore, plants usually require a balanced ratio of NO_3^- to NH_4^+ in the soil so basicity generated from absorption of one is counterbalanced by H^+ production from absorption of the other, resulting in an optimum soil pH around 7.0 (Riley and Barber, 1969).

After N absorption from the soil solution by the roots, N undergoes a complex system of assimilation, transformation and mobilization within the plant (Gurpreet et al., 2015). Nitrogen assimilation into carbon skeletons is an important plant metabolism process (Robinson et al., 1991). In plants, inorganic-N including NO_3^- must be reduced to NH_4, as it is the only reduced N form available for plant assimilation into amino acids (O'Leary and Plaxton, 2015). Nitrate reductase catalyzes the reduction of nitrate to nitrite ($NO_3^- \rightarrow NO_2^-$)

(Balotf et al., 2016). Nitrite is then immediately reduced to ammonia by nitrite reductase ($NO_2^- \rightarrow NH_3$), due to nitrate toxicity to plant tissue. Ammonia is then assimilated via glutamine and glutamate synthase into amino acids including glutamate, glutamine and asparagine, which are precursors of many structural compounds in plants (Joy, 1988).

Nitrogen in the Soil

The N cycle in agricultural systems involves many transformations between organic and inorganic forms. Organic-N is necessary for inorganic-N forms to become available in the soil during the growing season to support growth and development of plants. Ammonium and NO_3^- move in the soil via diffusion and mass flow, respectively. Nitrate has greater mobility than NH_4^+ as it is negatively charged and not chemically attracted to soil particles. This leads to a greater susceptibility for leaching and potential contamination of groundwater supplies. Conversely, NH_4^+ is positively charged and holds onto negatively charged clay-sized soil particles and is supplied by plants via the soil solution driven by the electrical gradient. A constant interchange between organic- and inorganic-N is carried out by organisms, prevailing climatic conditions and soil characteristics including pH and texture (Havlin, 2013). Therefore, a thorough understanding of the pathways N is subjected to in the soil can assist growers to synchronize fertilizer-N application with favorable environmental conditions to minimize loss from the field and maximize return of applied N.

Nitrogen Forms and Transformations in the Soil

Mineralization is a two-step process converting organic-N into inorganic NH_4^+ as microorganisms decompose soil organic matter (SOM) (Havlin, 2013). The first step of mineralization is called aminization, in which complex proteins are break down to simpler molecules such as amino acids. Further conversion to ammonium is called ammonification. Soil moisture, temperature and oxygen (O_2) availability all impact the rate of mineralization, with increased temperature and moisture favoring microbiological activity. Cold temperatures decrease microbial activity and as such, N uptake of winter wheat does not coincide with the peak of N release from mineralization.

Recently, methods have been developed to better understand the ability of soils to provide N to annual crops. For example, N-STaR, the Nitrogen Soil Test for Rice developed by the University of Arkansas, estimates site-specific availability of PAN resulting from mineralization (Roberts et al., 2011). Alkaline-hydrolysable N is an important pool of N during the growing season as it is more susceptible to undergo mineralization. Amino acids and amino sugars, comprising 20 to 40% and 5 to 10% of total organic-N, respectively, are responsible for a large amount of PAN released during the growing season and can therefore be used to predict contributions of N from mineralization of SOM (Barker et al., 2006; Kwon et al., 2009).

Ammonia Volatilization

Nitrogen loss through ammonia volatilization is a major concern for many commonly used N-fertilizer worldwide including urea [$CO(NH_2)_2$]. Conversion of NH_4^+, a product of urea hydrolysis in the soil and NH_3 is primarily governed by soil pH (Ni et al., 2014). During the hydrolysis of urea, there is an initial increase in pH surrounding the granule at which point ammonia volatilization is most likely to occur. Soil pH greater than 7.0 increases the risk of NH_3 volatilization. Incorporation of the fertilizer and prompt irrigation prevent immediate gas loss after hydrolysis by allocating more time for NH_4^+ to be absorbed by the roots or trapped onto active sites of clay particles. Many other factors also influence the rate of N loss via NH_3

volatilization including fertilizer type and placement, cation exchange capacity and temperature.

Immobilization

Micro and macro activity of other organisms in the soil play a key role on actual N supply to plants as they compete with plants for inorganic-N to support their growth. Incorporation of N into biological organisms is called immobilization, which leads to temporary unavailability of N to crops until further decomposition and mineralization. In soils where residues from the previous crop are present, N immobilization becomes a major concern for the subsequent crop as the amount of inorganic-N converted to organic forms is governed by the ratio of C to N (Partey et al., 2014). Residues are primarily composed of C and microbes require N in a C:N ratio of 8:1, therefore high C:N ratio residues (>30:1) promote microbial growth with immobilization of inorganic N from the soil solution. Conversely, residues containing low C:N ratios (<20:1) will be decomposed rapidly and organic-N will be mineralized, supporting both crops and microbial growth without negatively impacting crop demand for N (Havlin, 2013). Therefore, application of fertilizer-N must consider these ratios to provide sufficient N for crops to compensate for any possible immobilization occurring during the growing season.

Nitrification and Denitrification

Nitrification is a microbial oxidation process where NH_4^+ is first converted to NO_2^- and then to NO_3^- by the chemotrophic organisms *nitrosomonas* and *nitrobacter*, respectively (Huang et al., 2014). Nitrification is undesirable in certain soil textures as NO_3^- is more susceptible to being lost. Nitrification occurs over a wide range of pH (5 to 9) with an optimum at 8 and stops at temperatures below 0°C and in anaerobic conditions (Havlin, 2013). In waterlogged or flooded conditions, soil microorganisms which utilize N in the NO_3^- form as an electron acceptor instead of O_2 are favored. Denitrification occurs when there is microbial reduction of NO_3^- and NO_2^- to produce gaseous N oxides like nitrous oxide (N_2O) and nitrogen oxide (NO). These gaseous N oxides are released into the atmosphere and decrease the availability of N for crops and are a potential greenhouse gas, which may damage earth's ozone layer (Cui et al., 2012; Su et al., 1995).

Additional N loss mechanisms not influenced by soil microorganisms include leaching, surface run-off and temporary fixation. Leaching occurs when soluble NO_3^- is percolated through the soil profile below the root zone and is commonly seen in coarse-textured soils with low water holding capacity. Surface run-off commonly occurs from fields with increased slope. Both leaching and surface run-off intensify with heavy precipitation and water overflow (He et al., 2014). Illite and vermiculite, 2:1 clay minerals, are capable of temporarily fixing NH_4^+ by replacement of large-sized cations in their expanded lattices e.g.- Ca^{+2}, Mg^{+2}, Na^+ and H^+.

Nitrogen Fixation

Biological Nitrogen fixation

Biological N fixation (BNF) is carried out by microorganisms from the diazotrophs group able to grow without external sources of fixed N (Araújo et al., 2014). In this process, the enzyme nitrogenase converts atmospheric N to ammonia. Some species in the genera of *bradyrhizobium* and *azorhizobium* are capable of establishing symbiotic relationships with plant roots from the botanical family *Fabaceae*, including soybean and other crop species (Zimmer et al., 2016). These microorganisms fix N_2 in exchange for carbohydrates and proteins produced by the chlorophyll containing organism and in return plant-available-N becomes strategically available for uptake (Nelson and Sadowsky, 2015). Nitrogen fixed by legumes in rotation with other crops have been shown to partially substitute for fertilizer-N requirements. In developing countries the use of legumes in rotation plays a key role where industrial N fertilizer is scarcely available or of high cost. For example, in northeastern Brazil, intercropping of legumes, including leucaena (*Leucaena leucocephala*), with other crops is the primary strategy to maintain long-term N fertility (Carvalho et al., 1999).

Industrial Nitrogen Fixation

Another critical and rapid solution to meet crop N demand and low soil availability is the application of industrial N fertilizer (NF). Industrial fixation of N is most commonly carried out through the Haber-Bosch process, where reaction of N_2 with hydrogen gas (H_2) occurs under controlled temperature and pressures to obtain ammonia (NH_3) (Vojvodic et al., 2014). Ammonia is used to make several other fertilizer materials varying in N content. Anhydrous ammonia has a standard N-P_2O_5-K_2O rating of 820 g N kg^{-1}, is stored under pressure as a liquid and applied to the soil through high-pressure tanks. Aqueous NH_3 has an N content ranging from 20 to 25% and is produced by dissolving anhydrous ammonia in water. Aqueous NH_3 has lower vapor pressure coupled with high water content allowing soil application regardless of soil moisture and texture. Ammonium nitrate (NH_4NO_3) has an N content ranging from 33 to 34% and is one part NH_4^+ and one part NO_3^-. Fertilizer salts including NH_4NO_3 and ($CO (NH_2)_2$) have high hygroscopicity and should not be stored in humid conditions. Urea ($CO (NH_2)_2$) is the commercially available granular form of urea fertilizer and has a standard N analysis of 460 g N kg^{-1}. In addition to having one of the lowest transportation costs per unit of N, urea also has the advantage of favorable handling and storage compared to more chemically unstable forms including NH_4NO_3 (Angus et al., 2014). Anhydrous ammonia, urea and aqua NH_3 represent about half of total N used in crop production.

Nitrogen fertilizers account for a considerable portion of yield performance of crops, including an estimated 40 to 60% of crop production in the U.S. The average US corn, rice and wheat yields would potentially be reduced by 41, 37 and 16%, respectively, if N fertilizers were to be removed from agricultural production practices (Stewart et al., 2005). Nitrogen fertilizers represent a major cost in wheat production systems, which increased 120% between 2000 and 2007 in the U.S. (USDA, 2009). Despite the high cost, only 33% of the total N applied to cereal crops is estimated to be recovered in the harvested grain (Raun and Johnson, 1999).

Nitrogen Fertilizer Management: Urea

Urea, one of the most commonly used N sources in the world, is the product of a chemical reaction of NH_3 with carbon dioxide (CO_2) (Galloway et al., 2008). Urea is an uncharged molecule that is highly soluble in water (1,080 g L^{-1} at 20°C). The movement of urea through the soil profile is facilitated if the molecule remains unchanged. Plants can also actively take up urea from the soil solution. Unlike organic-N sources, which require mineralization to release plant available N, urea-based fertilizers require only a fast enzyme-substrate reaction between urease and the urea molecule to release NH_4^+. The enzyme urease catalyzes the hydrolysis of urea and occurs naturally in soils and thus NH_4^+ becomes rapidly available following urea application. Ammonium$^-$forming fertilizers including urea must be managed carefully when applied to crops due to high susceptibility to N loss via NH_3 volatilization. Several factors affect the rate of urea hydrolysis in the soil including urease activity, soil temperature, soil water content and method of urea application. These factors must be carefully taken into account when applying urea to agricultural systems. The rate of urea hydrolysis is greatest immediately following application and proceeds more rapidly in warm and moist conditions as it favors the enzymatic activity of urease (equation 1) (Havlin, 2013).

Once NH_4^+ is formed, soil pH will also influence the fate of applied fertilizer. When granular urea is added to the soil, solution pH around the granule increases due to the formation of ammonium carbonate favoring NH_3 volatilization (equation 2). Hydrolysis of urea takes only a few days to exceed the ability of the soil to protonate NH_3 back to NH_4^+ (equation 3). In acidic soils, NH_3 buffer capacity increases due to the presence of H^+, thus decreasing volatilization of NH_4^+. Therefore, urea application to moist, warm and high pH soils is highly conducive to urea hydrolysis and NH_3 volatilization. Optimal conditions to reduce N losses include application of urea in cool and dry soils and incorporation by machinery or rain.

Equations 1: $CO\ (NH_2)_2 + H^+ + 2H_2O + \textit{Urease} \rightleftharpoons 2NH_4^+ + HCO_3^-$

Equations 2: $NH_4^+ + HCO_3^- \rightarrow NH_3 + CO_2 + H_2O$

Equations 3: $NH_4^+ \rightleftharpoons NH_3 + H^+$

Several strategies have been developed to alleviate the potential for N loss following urea application. Urea amended with urease inhibitors helps to prevent N loss through their interaction with urease by blocking its affinity towards urea, thus minimizing time between NH_4^+ release and crop N demand. Inhibition of urease activity allocates time for better percolation and distribution of urea in the soil profile and prevents NH_3 volatilization by covering a larger region in the soil favoring crop uptake and/or adsorption of NH_4^+ by clay-sized particles and organic matter (Dai et al., 2013; Dawar et al., 2011; Qu et al., 2015). By maintaining applied N as part of either the plant tissue or onto clay particles, potential environmental impacts may be mitigated. Temporary inhibition of the breakdown of urea also allows farmers to more precisely match the application of N with plant requirements (Norman et al., 2009). The urease inhibitor NBPT (n-butyl-thiophosphoric triamide) is often used with granular urea when surface applied. Norman et al. (2009) evaluated the amount of NH_3

volatilized from four fertilizer-N sources (urea, urea + NBPT, $(NH_4)_2SO_4$ and urea-ammonium sulfate) with rates ranging from 0 to 134 kg N ha^{-1} over a 20 day period on a Calloway silt loam (Fine-silty, mixed, active, thermic Aquic Fraglossudalfs) soil under flooded-rice cultivation. The authors reported similar N uptake and grain yield among the four N sources when a flood was applied 1 days after application. However, as flooding was delayed in relation to fertilizer application, NH_3 volatilization from urea increased substantially between 2 and 5 days after fertilizer application. Urea + NBPT treatment reduced N loss in 60 % with volatilization peak delayed until 10 days after application. The authors concluded the Calloway silt loam soils are conducive to NH_3 volatilization and thus urea + NBPT or $(NH_4)_2SO_4$ should be the fertilizer choice when flooding must be delayed for rice cultivation.

Additionally, urea is applied to agricultural systems through various methods including direct application to soils or as a solution onto crop leaves (Shetty et al., 2015). Urea is frequently broadcasted at pre or post-planting, top-dressed on the standing crop, or sub-surface applied. Topdressing application of granular urea has been shown to have the greatest potential for NH_3 volatilization when it is applied without incorporation into the soil (Espindula et al., 2014). Incorporating urea after soil application provides better distribution in the root zone and can prevent losses by both surface run-off and volatilization, but may increase the cost of application (Havlin, 2013).

Timing and Rate of Nitrogen Fertilizer Application on Winter Wheat

Allocating less time between application and plant uptake is important particularly for winter crops as they undergo dormancy when exposed to cooler growing conditions. As such, application of N on winter wheat is often recommended after the dormancy period to shorten the time between application and plant uptake, including in Arkansas (Sabbe, 1978). While fall N application is a much less common practice, an adequate supply of fall-N is necessary for winter wheat to ensure optimum tillering and root establishment prior to dormancy.

The efficiency of N application timing is dependent on weather conditions, soil texture and residual soil NO_3^- levels, and thus they are not consistent year after year (Gravelle et al., 1988). Studies from humid conditions showed split-N applications can be sometimes more beneficial than spring application (Hargrove et al., 1983; Sabbe, 1978; Welch et al., 1966). Applying all fertilizer-N at once during the fall in environments where N is likely to be lost from the field through processes such as leaching and volatilization can negatively affect fertilizer-N recovery efficiency.

In dry conditions, Vaughan et al. (1990) showed that spring N applications are more profitable over split application between fall and spring where N losses from the field are expected to be lower. Wheat receiving spring-applied N required 20% less fertilizer-N to achieve the same grain yield as wheat fertilized with fall-applied N. Allocating all N to be applied at late winter in soils where split and spring-N have similar GY potential is more advantageous than splits considering only one pass over the field will be needed. Gravelle et al. (1988) found spring-applied fertilizer-N should be prioritized on winter wheat grown in sandy soils where there is a greater probability of leaching compared to silt and clayey soils. However, these studies did not evaluate the effects of planting date on grain yield response to timing and rate of fertilizer-N.

Split applications between fall and spring have the advantages of both times of application. Spring-applied N allows time to evaluate crop status and determine likely return from additional fertilizer-N before application. Split N application not only avoids the risk of one-time application of all required N, but also supplies fractional amounts to times of greater demand (Welch et al., 1966). Splitting the fertilization into two or more application times avoids exceeding the capacity of N absorption by plants balancing N uptake both in time and amount (Olson et al., 1979). Nevertheless, allocating fractional amounts distributed over the main N uptake stages of winter wheat is not always the most economical strategy considering the application costs. Multiple fertilizer-N applications also offer farmers flexibility to deal with changing of weather or other growth conditions because application of a small amount of fertilizer-N at key stages of crop development minimizes N losses and adequate application rate to crop demand at a given point in time. Gravelle et al. (1988) evaluated two N rates (90 and 135 kg N ha^{-1}) split applied in different rate and time combinations in Virginia. They showed that split N application at Feekes growth stages 3-5, 10 and/or 10.5 increased grain yields by 267 to kg ha^{-1} in relation to single application of 90 and 135 kg N ha^{-1} at Feekes 3-5. The authors also reported increased spike density and lodging with single applications of 135 kg N ha^{-1} at Feekes growth stage 3-5. While Roth and Marshall (1987) reported decreased levels of powdery mildew in SRWW supplied with split N applications.

For Arkansas, Sabbe (1978) suggested a N rate of 80 to 101 kg N ha^{-1} applied only in the late-winter for wheat to achieve 90 to 95% of relative GY. Nevertheless, wheat often requires application of a starter-N fertilizer to compensate for low soil-N levels early in the season. Kelley (1995) showed that yields of winter wheat decreased 1401 kg ha^{-1} when following grain sorghum (*Sorghum bicolor*) in crop rotation compared to soybean (*Glycine max*) where no N fertilizer was applied. The experiment was conducted in Kansas to evaluate the effect of previous crop in rotation and N time and rate treatment combinations. Broadcast urea was applied at total N rates of 45, 90 and 135 kg N ha^{-1} during fall, late winter, or splits among fall, late-winter and early-spring on winter wheat. Grain yield decreased due to the main effect of previous crop, with grain yield of wheat following grain sorghum having the lowest yield. Residual soil NO_3^- was frequently the lowest in wheat following sorghum compared to oat (*Avena sativa*) and soybeans due to the high C:N ratio in sorghum residue. Regression analysis showed increased slopes for wheat following grain sorghum in crop rotation with soil with low-N levels tended to be more responsive to N fertilization. However, more recently Slaton et al. (2004) showed late-winter or early-spring N application to be more efficient than a split application between fall and spring unless following flooded rice in crop rotation. Maximum yields were obtained with total N application ranging from 90 to 135 kg N ha^{-2}, 90 to 179 kg N ha^{-2} and 179 to 269 kg N ha^{-2} following corn, grain sorghum and rice, respectively.

Roth and Marshall (1987) studied the effects of the time of fertilizer-N application on SRWW applied at the rate of 100 kg N ha^{-1} (NH_4NO_3) up to three times as either splits or single, spring-applied N. The study was conducted in silt loam soils of Pennsylvania where single, spring N applications frequently leads to excessive growth and incidence of powdery mildew. The authors proposed that by reducing excessive growth with split or delayed fertilizer-N application the levels of powdery mildew would also decrease. They compared grain yield response of split-N applications (Feekes 3, 5 and/or 8) to spring-N applications made at Feekes 5 and 8. Application of a single, spring N rate of 100 kg N ha^{-1} at Feekes 8 yielded statistically different in three out of six site-year trials compared to a single application at Feekes 3. Overall, there were no statistical yield differences among single, spring-N and split-N applications. Only one out of 6 site-years benefited from the split application of 100 kg N ha^{-1}. In the same study, a single, spring-N application at Feekes 8, or split with part of the N allocated to be applied at Feekes growth stage 3 resulted in decreased lodging compared to the other treatment combinations. Lastly, the authors found grain yield response to split-N applications would occur where there is a high N requirement, substantial risk of N loss due to leaching and denitrification and/or low levels of foliar diseases.

Knowles et al. (1994) evaluated the effects of rate and time of N application using three N rates (0, 45 and 90 kg N ha^{-1}) as NH_4NO_3 applied at planting, jointing (Feekes 6), booting (Feekes 10) and/or heading (Feekes 10.5) in Texas in a silty clay soil. The authors reported lower grain yield from a single application of 45 kg N ha^{-1} applied at planting compared to application of 90 kg N ha^{-1} applied at the same time. A single application of 45 kg N ha^{-1} at Feekes growth stage 6 produced yields equivalent to those produced by split application of 90 kg N ha^{-1} at planting and at Feekes 6, and to single application of 90 kg N ha^{-1} at planting and at Feekes growth stage 6. These results suggest overwinter losses from the applied fertilizer-N at planting. The authors concluded that a split N application did not improve grain yield as long as N availability is adequate prior to booting.

Sowers et al. (1994) conducted a two-year experiment with winter wheat evaluating three application regimes (all-fall, split and all-spring) with five N rates (0, 56, 84, 112 and 140 kg ha^{-1}). The authors reported increased NUE (grain yield produced per unit of N supplied) in split and all-spring treatments compared to all-fall in three of the four site-years, with no benefit of fall-applied N. The study found a decline in NUE as the rate of fall-N increased, possibly due to high levels of pre-plant residual N. The authors concluded the lack of N uptake was a result of N loss during the fall than the inability of the plant to absorb the nutrient.

Overall, based on these studies grain yield response from fall and/or spring-N applications have shown to differ depending upon soil texture and moisture, previous crop and weather conditions. All these factors directly influence the fate of the applied fertilizer-N and therefore should be taken into account prior to deciding when split N applications are necessary.

Effect of Planting Date on Grain Yield

Sabbe (1978) found that soil moisture can have a profound influence on when farmers decide on a planting date for wheat. While low availability of water in soils is detrimental for seeds to germinate and grow, high soil moisture prevents machinery from entering the field. In some years, precipitation in the fall delays planting which affects time allocated for crop growth prior to freezing temperatures. Cao and Moss (1991) reported that planting date is a critical management component for successful wheat cultivation and can significantly impact growth and development of SRWW. Wheat yield may be negatively affected when planted at non-optimum dates due to growth not coinciding with optimal environmental conditions. An early planting date increases uptake of N by providing a longer vegetative growth period prior to dormancy but increases the risk of injury from frost and damage from diseases (Tapley et al., 2013). A later than optimum planting date may result in decreased uptake of N due to a truncated vegetative period, decreased tillering prior to vernalization, and increased risk of heat damage (Barnett and Chapman, 1975).

Bassu et al. (2010) investigated the effect of three planting dates (October, December and March) on durum wheat grown in Italy over two seasons. Grain yield increased from 5260 kg ha^{-1} in the first planting date to 6320 kg ha^{-1} in the second and decreased to 3000 kg ha^{-1} in the third. Kernels m^{-2} increased by 23% from the first to the second planting date and decreased by 36% from the second to the third. Planting date had a significant effect on spike density (SD) which increased by 20% and 18% from the first to the third planting dates in both years, respectively. Results also showed delaying planting from Oct to March decreased the length of phenological phases with the time required to reach terminal spikelet, appearance of the flag leaf and anthesis decreasing by 56, 60 and 56%, respectively.

Earlier than optimum planting dates may negatively impact GY by depleting essential resources including water and nutrients in limiting environments. Winter and Musick (1993) conducted a field experiment in Texas over two growing seasons to evaluate the effect of planting date (August, Oct and Nov) on winter wheat production. Mean grain yield across the two years increased from 850 to 2800 kg ha^{-1} from the first to the second planting dates and decreased to 1710 kg ha^{-1} when further delays. The second planting date had the highest mean total biomass, spike m^{-2} and seed m^{-2}. The authors attributed the lower GY from early planting date to depletion of summer soil moisture due to excessive growth.

In Arkansas, the optimum planting date for wheat depends on both the photoperiod requirement of the cultivar and temperature and varies based on latitude. Optimum planting dates for Arkansas are suggested to be Oct. 1 to Nov. 1, Oct. 10 to Nov. 10, Oct. 15 to Nov. 20, for the North, Central and South regions, respectively (Roberts and Slaton, 2014). The University of Arkansas System Division of Agriculture's fertilizer-N rate recommendations are based on soil texture and previous crop in rotation. Regardless of soil texture, a fall application of 50 kg N ha^{-1} is recommended when wheat follows flooded-rice. In silt and sandy loam soils, late-winter application of 100 kg N ha^{-1} after fallow and 134 kg N ha^{-1} when following rice or other crops is recommended. In clay and clay loams soils, late-winter application of 157 kg N ha^{-1} is recommended when wheat follows other crops. Fine-textured soils have the potential for N losses due to denitrification and a split application decreases the likelihood of N loss. Although fall N is only recommended when winter wheat follows flooded-rice, fall application of 34 kg N ha^{-1} in late-planted wheat is advised in these soils regardless of the previous crop in rotation (Roberts and Slaton, 2014).

Conclusion

If managed efficiently, fertilizer-N has the greatest potential of all wheat inputs for increasing profitability. The most efficient fertilizer-N programs minimize the time between application and crop demand to minimize N loss and maximize potential economic return. However, non-optimum planting dates can affect the use efficiency of the applied N. Understanding the ability of the applied N to help overcome yield losses from non-optimal planting dates can ensure better economic return by matching the timing and rate of N application to the period of greater N demand.

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CHAPTER 2 - SPLIT VERSUS SPRING NITROGEN FERTILIZER APPLICATION ON SOFT RED WINTER WHEAT SOWN AT VARIABLE PLANTING DATES

Abstract

For soft red winter wheat (SRWW) production in the southeastern United States, fertilizer-N is applied during the late-winter or early spring prior to the onset of rapid growth. In addition to late-winter N, current Arkansas recommendations include the application of fall N when SRWW is planted later than optimum, despite a lack of data supporting this practice. Therefore, the objectives of this study were to evaluate grain yield (GY) and GY component responses of two SRWW cultivars to fertilizer-N timing and rate to SRWW sown at three planting dates. Experiments were conducted during the 2014-2015 growing season at the University of Arkansas System Division of Agriculture's Newport Research Station (NPRS), Pine Tree Research Station (PTRS) and Rohwer Research Station (RWRS). Total-N rates ranging from 67 to 202 kg N ha^{-1} were assigned in a randomized complete block design to two cultivars. Granular urea was applied in the fall (F), late-winter (LW) and/or early-spring (ES). At NPRS, there was no GY difference between rate and time of N application. At both PTRS and RWRS, fall-applied N was important to maximize yield at the latest planting date with a mean GY increases of 1122 and 544 kg ha^{-1}, respectively, compared to spring only applications. At PTRS, GY differences were observed when averaged across spring-N rates. At RWRS, GY response to application times and N rates varied within and between planting date and resulted in a significant 4-way interaction. Overall, both spike density and kernel weight per spike explained a significant amount of total GY variation across all locations.

Introduction

Application of fertilizer nitrogen (N) is arguably the most important agronomic input for SRWW (*Triticum aestivum* L.) and represents a large portion of production cost. In order to maximize profitability for producers, N must be applied using the most economical practices. For soft red winter wheat (SRWW) production in the southeastern United States, fertilizer-N is applied during the late-winter prior to the onset of rapid growth and optimum application time (Sabbe, 1978). While fall application is much less common than late winter in eastern Arkansas, an adequate supply of N is necessary to ensure optimum tillering and root establishment prior to dormancy (Sabbe, 1978; Slaton et al., 2004). In addition, more efficient N fertilizer use in agriculture is needed to reduce environmental contamination from excessive N application which can lead to eutrophication and other environmental problems (Follett and Hatfield, 2001; Galloway and Cowling, 2002).

The efficiency of N application timing is dependent on weather conditions, soil texture and residual soil NO_3^- levels, and thus is not always consistent from year to year (Gravelle et al., 1988). Application of N in the late-winter allows time to evaluate crop status and determine likely return from additional fertilizer-N before application, spring-N application also coincides with the period of increased N uptake and thus likely greater net return from applied N (Welch et al., 1966). Nevertheless, wheat may require application of a starter N fertilizer to compensate for low soil-N availability early in the season.

Studies from humid environments show split N applications to have benefits over single applications (Hargrove et al., 1983; Sabbe, 1978; Welch et al., 1966). Kelley (1995) showed that yields of winter wheat decreased 1401 kg ha^{-1} when following grain sorghum in crop rotation compared to soybean (*Glycine max*) when no fall-N fertilizer was applied. Gravelle et al. (1988) showed that split N application at Feekes growth stages 3-5, 10 and

10.5 increased grain yields by 267 to kg ha^{-1} in relation to a single application of 90 or 135 kg N ha^{-1} at Feekes 3. The authors also reported increased lodging with single applications of 135 kg N ha^{-1} at Feekes growth stage 2-3. Roth and Marshall (1987) reported decreased levels of powdery mildew in SRWW supplied with split N as opposed to a single application.

Sabbe (1978) suggested 80 to 101 kg N ha^{-1} applied only in the late-winter for wheat grown in Arkansas to achieve 90 to 95% of relative GY. More recently Slaton et al. (2004) showed late-winter or early-spring N application to be more efficient than a split application between fall and spring unless following flooded rice in crop rotation. Maximum yields were obtained with total-N rates ranging from 90 to 135 kg N ha^{-2}, 90 to 179 kg N ha^{-2} and 179 to 269 kg N ha^{-2} following corn (*Zea mays*), grain sorghum (*Sorghum bicolor*) and rice (*Oryza sativa*), respectively. Vaughan et al. (1990) showed that in dry conditions when N losses are expected to be low, spring N applications are more profitable over split application between fall and spring. In this study, spring applied N required 20% less total N input to achieve the same GY as fall-applied N. Allocating all N to be applied at late winter in soils where split and spring-N have similar GY potential is more advantageous than splits considering only one pass over the field is needed, which reduces the cost of fertilizer application. Additionally, Gravelle et al. (1988) found that spring-N fertilizer should be prioritized over splits between fall and spring on winter wheat grown in sandy soils where there is a greater probability of leaching compared to silt and clayey soils.

Sabbe (1978) pointed out that soil moisture can have a profound influence on planting date of wheat with excessive fall precipitation delaying planting beyond the optimal range. Later-than-optimum planting dates can negatively impact wheat yield due to growth not coinciding with optimal environmental conditions. It may result in low fall-N use efficiency and shortened life cycle due to a truncated vegetative period prior to winter vernalization and a reduction in the number of fertile tillers and grain weight, ultimately leading to yield losses

(Ehdaie and Waines, 2001; Hussain et al., 2012). On the contrary, early-than-optimum planting date provides a longer vegetative growth period prior to dormancy which may increase the risk of injury from frost and increase competition for resources (Winter and Musick, 1993). Researchers have reported increased number of fertile tillers with fall-applied N to promote early-vegetative growth (Gravelle et al., 1988; Slaton et al., 2004).

In Arkansas, the optimum planting date for wheat varies based on latitude. Recommended planting dates are Oct 1st to Nov 1st, Oct 10th to Nov 10th, Oct 15th to Nov 20th, for the Northern, Central and Southern regions of the state, respectively (Roberts and Slaton, 2014). We hypothesize that GY decreases as planting date is delayed and that the application of fall-N in a split with late winter and early spring applications will overcome these GY reductions. We further hypothesize that the number of fertile tillers will have the greatest influence on GY. Current data supporting these hypotheses is lacking which makes producer recommendations difficult. Therefore, the objectives of this study are:

Objective 1. Determine the effect of planting date on grain yield of SRWW grown in southern, central and northern locations in Arkansas.

Objective 2. Determine the grain yield response and optimum fertilizer-N timing and rate for SRWW sown at different planting dates in Arkansas.

Objective 3. Determine how yield components of SRWW are influenced by planting date and N fertilization strategy (e.g., rate and timing).

Materials and Methods

Study locations and plot establishment

Field experiments were conducted during the 2014-2015 growing season at the University of Arkansas Division of Agriculture’s Newport Extension Center (NPRS) on a Beulah fine sandy loam (coarse-loamy, mixed, active, thermic typic dystrudepts), Pine Tree Research Station (PTRS) on a Calloway silt loam (fine-silty, mixed, active, thermic aquic fraglossudalfs) and Rohwer Research Station (RWRS) on a Herbert silt loam (fine-silty, mixed, active, thermic aeric epiaqualfs). Primary nutrients P, K, S were applied according to soil-test results taken prior to planting in all locations. Weeds, insects and diseases were controlled using best management practices according to University of Arkansas wheat production recommendations (Roberts and Slaton, 2014). Two SRWW cultivars including Armor Vandal (medium maturity) and Armor Havoc (full season) were used for this study. Wheat seeds were pre-treated with commercial fungicides (Imidacloprid, Tebuconazole and Metalaxyl) by Armor Seeds prior to shipping. Both cultivars were planted at three planting dates: Oct 16, Nov 4 and Nov 18 at NPRS; Oct 17, Nov 2 and Nov 13 at PTRS; and Oct 21, Nov 3 and Nov 14 at RWRS. Plots in all locations were drill seeded at a density of 350 plants m^{-2}. At Newport, split-split plots dimensions were 1.42 m wide by 4.5 m long consisting of 7 rows with 17.8 cm between each row. At PTRS and RWRS, split-split-plot dimensions were 1.3 m wide x 6 m long consisting of 7 rows spaced 19 cm apart. According to the Koppen Climate Classification system, these research stations have a humid subtropical climate. Monthly temperatures during the experiment were similar at NPRS and PTRS, but were higher at RWRS, the southernmost location (Fig. 1). Monthly precipitation at NPRS did not exceed 2 mm $month^{-1}$. Whereas at PTRS and RWRS the wettest months were October, March, April and May (Fig. 2). Soil fertility for the three locations in our study is presented in Table 1. Wheat followed fallow at NPRS and soybeans at PTRS and RWRS.

Experimental design and nitrogen treatments

For all trials and locations, the experimental design was a four-factor factorial design in a randomized complete block in a split-split plot arragement where whole plots were planting dates and split plots were cultivars. Split-split plots consisted of application of 67, 101, 135, 168 and 202 kg N ha^{-1} split over one to three application times: fall (F) and spring consisting of late winter (LW) and/or early-spring (ES) (Table 2). Spring-N rates greater than 67 kg ha^{-1} were split applied with 50% applied at late-winter and 50% at early-spring. For simplicity, application timing will be referred to herein as either fall or spring or split between fall and spring. Specificity will be provided in cases where the spring rate was applied in two doses. An additional treatment receiving no fall-N plus 169 kg N ha^{-1} as a split-spring was included within each planting date-cultivar trial. That rate represents a fertilizer-N rate commonly applied by farmers in the Arkansas Delta region and close to that recommended by the University of Arkansas Each treatment combination was replicated 4 times. For fall-N applications, granular urea + NBPT (at 3.4 kg ton^{-1} urea) (N-n-butyl thiophosphoric triamide), trade name Agrotain Ultra, was uniformly broadcasted by hand following seedling emergence. For late winter and early-spring N applications, urea+NBPT was uniformly broadcast by hand prior to stem elongation and during stem elongation close to Feekes 4 and 5, respectively.

Trait measurement

Grain yield (kg ha^{-1}) was determined for each plot by combine harvesting with final GY adjusted to 13% moisture. Yield components including spike density (SD), kernel number per spike (KNS) and kernel weight per spike (KWS) were determined by harvesting 50 spikes at maturity. The weight of 1000 kernels was determined using a seed counter. Yield components were determined using the following formulas: KWS (g) = 50 SGW/50; KNS = KWS/[1000-(KWS/1000)]; SD (spikes m^{-2}) = GY/KWS.

Statistical analysis

The experiment was analyzed as an incomplete factorial arrangement of 3 fall-N rates (0, 34, 67 kg ha^{-1}) and 4 spring-N rates (67, 101, 135 and 169 kg ha^{-1}) in a randomized complete block in a split-split-plot design. The incomplete factorial was due to the fact that not all possible treatment combinations were included in the experiment. Therefore, a total of 240 plots consisting of 10 N treatment replicated four times at each location. All statistical procedures were performed using SAS 9.4 (SAS Institute Inc. 2016). Analysis of variance (ANOVA) was performed using PROC MIXED. For the ANOVA, cultivars, planting dates, fall-N and spring-N and their interactions were considered as fixed effects while replication and its interaction with planting date and cultivars were considered as random effects (error A and B). When appropriate, least square means were compared using a Fisher's least significance difference (LSD) tested at 5% probability level. Data were analyzed using the following model:

$$Y_{ijklm} = \mu + A_i + B_j + C_k + D_l + \eta_{iklm} + \beta_{jklm} + AB_{ij} + AC_{ik} + AD_{il} + BC_{jk} + BD_{il} + CD_{kl} + ABC_{ijk} + ABD_{ijl} + ACD_{ikl} + BCD_{jkl} + ABCD_{ijkl} + \varepsilon_{ijklm}$$

Y_{ijklm} = yield response on the mth experimental unit of the ith cultivar (A) planted on the jth date (B) with the kth level of fall N (C) and lth level of spring-N (D),

where i= 1, 2; j = 1, 2, 3; k = 1, 2, 3; l = 1, 2, 3, 4; m = 1, 2, 3, 4; Error A= $\eta_{iklm;}$ Error B= $\beta_{jklm.}$

Stepwise regression analysis was performed using PROC GLM to develop polynomial equations to describe GY response to total N with predictors removed based on the t-statistic of their estimated coefficients. Separated linear equations for each fall-N level were developed to compare the rate of yield increase with increasing spring applied N at each planting date-cultivar-Fall-N trial. The significance of all predictors were tested at 0.10 probability level.

Quadratic response surface models were also fit to each cultivar-planting date trial using PROC RSREG at locations where the 3-way interaction cultivar x planting date x fall N was significant ($P < 0.05$). To minimize the effect of fluctuations in yield across planting dates, GY was expressed as a percentage of the relative maximum yield, using the highest mean yield for each planting date by cultivar trial as 100%. The model included linear, quadratic and linear interaction terms for fall-N and spring-N rates. Models that did not fit either linear, quadratic or interactive function were not discussed. Significance of the slope coefficients for each term was tested at a 0.10 probability level. Lower and upper boundaries for fall-N and spring-N rates were 0 to 67 kg N ha^{-1} and 67 to 134 kg N ha^{-1}, respectively (check treatments were excluded from the analysis). Absolute maxima were used to determine optimum fall and spring N rates. The absolute maximum of the model for Vandal planted on Nov 14 at RWRS was found to be above the spring N rates used in the experiment and thus the partial maximum of the GY function was set equal to zero and solved at the highest used N rate of 135 kg N ha^{-1}. Analysis of covariance (ANCOVA) was performed to determine which yield components explained the greatest variation in GY with the coefficient decomposition being tested at 10% probability level.

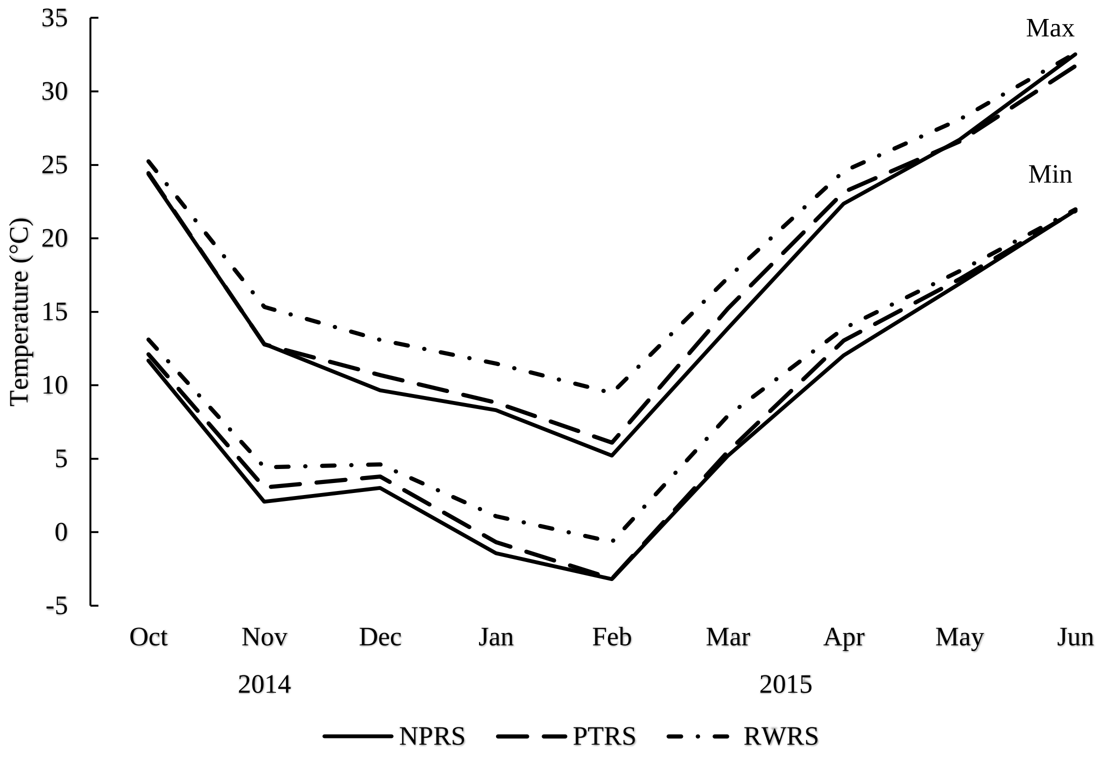


Figure 1. Minimum and maximum monthly temperature during the experiment of 2014/2015 growing season at Newport (NWRS), Pine Tree (PTRS) and Rohwer (RWRS).

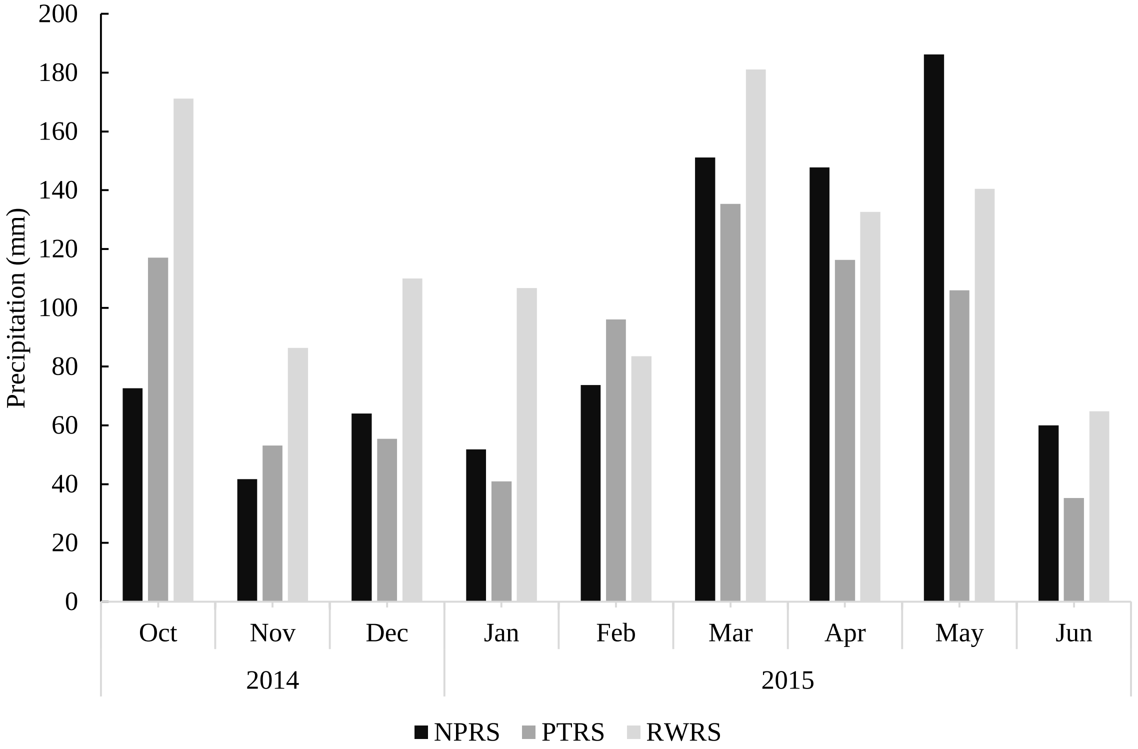


Figure 2. Monthly precipitation at Newport (NPRS), Pine Tree (PTRS) and Rohwer (RWRS) during 2014-2015 growing season.

Table 1. Selected soil chemical attributes at Newport (NPRS), Pine Tree (PTRS), and Rohwer (RWRS).

Location	pH	P	K	Ca	Mg	S	Na	Fe	Mn	Zn	Cu	B	Total N	SOM
		---						mg kg^{-1}				---		g kg^{-1}
NPRS	5.90	63	113	1043	146	7	6	145	107	13.4	0.6	0.3	1241	18.3
PTRS	7.62	35	125	1325	312	9	29	197	331	1.8	1.1	0.3	1023	18.8
RWRS	5.93	95	254	1045	110	33	24	466	141	11.5	1.1	1.5	996	18.6

SOM – organic matter through loss of ignition method

Table 2. Fall, late winter and early-spring N combination rates applied as granular urea amended with NBPT.

N Treatment	Fall N rate	Late-winter N	Early-spring	Total N
	------------------------------	kg ha^{-1}	------------------------------	
1	0	84	84	169
2	0	67	-	67
3	0	51	51	101
4	0	67	67	135
5	34	67	-	101
6	34	51	51	135
7	34	67	67	169
8	67	67	-	135
9	67	51	51	169
10	67	67	67	202

Results for Grain Yield

Newport Research Station (NPRS)

Effect of planting date and cultivar on grain yield

At NPRS, the main effect of planting date and the interaction planting date x cultivar significantly affected GY ($P < 0.05$) (Table 3). Grain yield decreased from the first to the third planting dates by 541 kg ha^{-1} for Havoc and 1149 kg ha^{-1} for Vandal (Table 4, Fig 2b). For Vandal, GY for the Oct 16 planting date was greater than all other planting dates (Fig. 2b). Grain yields on Nov 4 and 18 did not differ statistically at any rate of total N.

Effect of N timing and rate on grain yield

The main effect of fall and spring-N and the interaction planting date x spring-N ($P < 0.05$) significantly impacted GY at NPRS (Table 3). When averaged across planting date, cultivar and spring-N rate, 34 and 67 kg N ha^{-1} of fall N increased GY by 257 and 268 kg ha^{-1}, respectively (Table 4). When averaged across cultivar and fall-N rate, spring applications of 101 and 135 kg N ha^{-1} significantly increased GY over the lowest spring-N-rate for both the Nov 4 and Nov 18 planting dates, with increases ranging from 496 to 1197 kg ha^{-1} (Table 6)

Table 3. ANOVA for grain yield as influenced by planting date, cultivar, fall-N and spring-N at Newport (NPRS), Pine Tree (PTRS) and Rohwer (RWRS).

		NPRS	PTRS	RWRS
Source of Variation	df	--------------- p-value ---------------		
Planting Date	2	0.0037	0.0099	0.0001
Cultivar	1	0.8312	0.0018	0.0010
Fall-N	2	0.0085	0.0637	0.0035
Spring-N	2	<0.0001	0.6917	<0.0001
Cultivar x Planting Date	2	<0.0001	<0.0001	<0.0001
Planting Date x Fall-N	4	0.9235	0.0050	0.2410
Planting Date x Spring-N	4	0.0012	0.8709	0.0622
Cultivar x Fall-N	2	0.4391	<0.0001	0.0309
Cultivar x Spring-N	2	0.6472	0.6800	0.5723
Fall-N x Spring-N	4	0.0637	0.0016	0.0026
Planting Date x Fall-N x Spring-N	8	0.6973	0.6779	0.003
Planting Date x Cultivar x Fall-N	4	0.7478	<0.0001	0.6823
Planting Date x Cultivar x Spring-N	4	0.2105	0.3730	0.0288
Cultivar x Fall-N x Spring-N	4	0.3104	0.7024	0.2541
Planting Date x Cultivar x Fall-N x Spring-N	8	0.3301	0.3068	0.0291

Table 4. Grain yield as affected by fall-N rate at NPRS.

Fall-N treatment	Grain Yield (kg ha^{-1})
Fall$_{0N}$	4050
Fall$_{34N}$	4307
Fall$_{67N}$	4318

LSD = 193 kg ha^{-1}

Table 5. Grain yield as affected by planting date and cultivar at NPRS.

Planting date	Havoc	Vandal
	------------------------- kg ha^{-1}	-------------------------
Oct 16	4485	4974
Nov 4	4271	3851
Nov 18	3944	3825

LSD to compare means in different cultivars and the same planting date = 272 kg ha^{-1}
LSD to compare means in the same cultivar and different planting dates = 397 kg ha^{-1}
LSD to compare means in different cultivars and different planting dates = 398 kg ha^{-1}

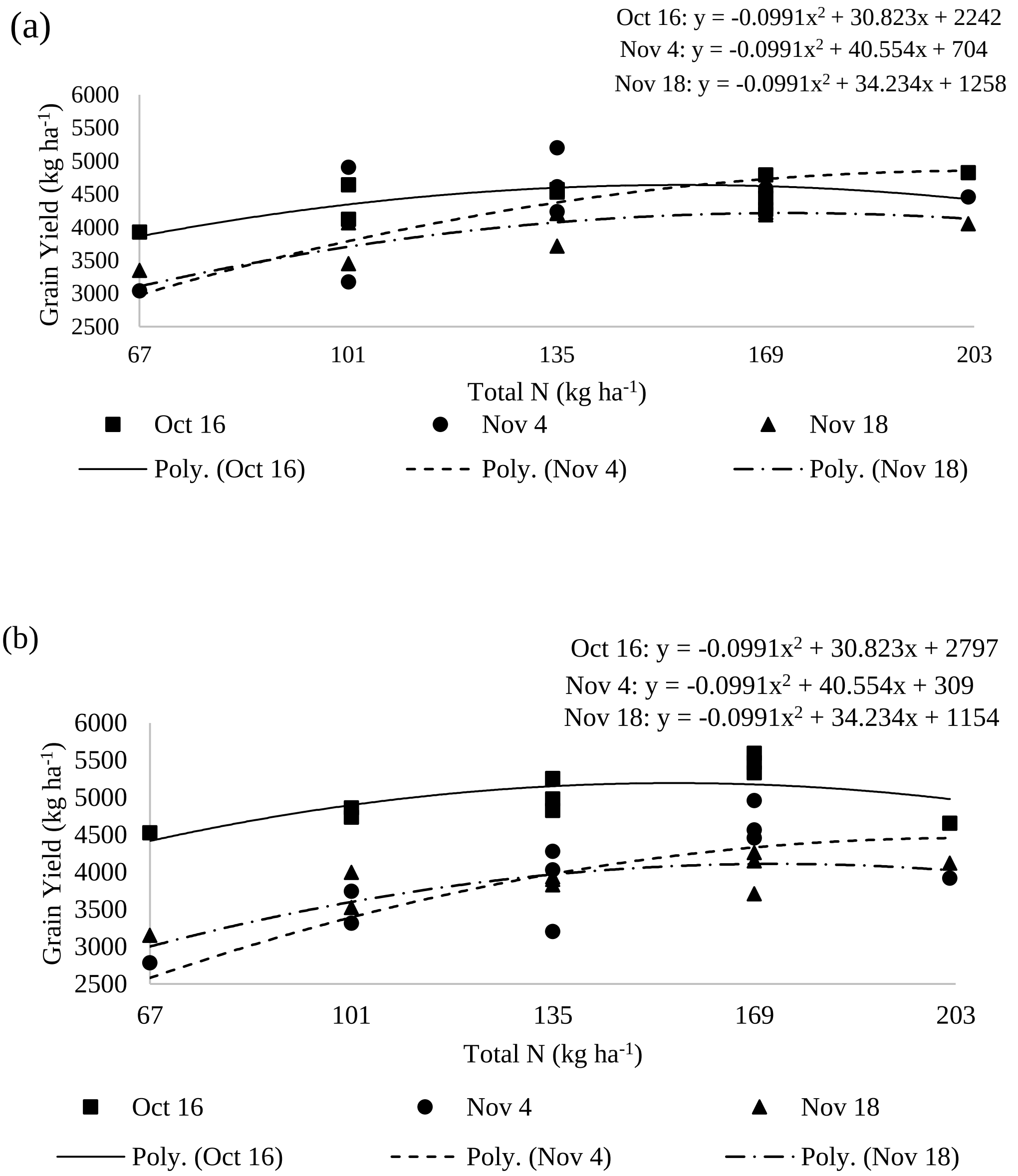


Figure 3. Grain yield of Havoc (a) and Vandal (b) as a function of total N rates and affected by planting date at NPRS.

Table 6. Grain yield as affected by planting date and spring-N rate at NPRS.

Spring-N rate	Planting date by grain yield		
	Oct 16	Nov 4	Nov 18
	--------------------------------- kg ha^{-1} ----------------------------------		
$Spring_{67N}$	4536	3292	3521
$Spring_{101N}$	4864	4489	4017
$Spring_{135N}$	4787	4403	4116
$Check_{169N}$	4866	4574	4169

LSD to compare means in the same planting date (no check) = 337 kg ha^{-1}
LSD to compare means in different planting dates (no check) = 419 kg ha^{-1}

Regression Analysis

To determine the rate of change in GY at each cultivar-planting date trial, linear regression equations using total N as independent and fall-N rates as categorical variables were developed using a stepwise method. Both planting date ($P < 0.05$) and fall-N ($P < 0.10$) significantly affected the regression coefficients (β slopes) and thus influenced the prediction of GY ($R^2 = 0.52$, $P < 0.0001$) (Tables 8 and 9). Slopes for planting date Nov 4 were greater than Oct 16 and Nov 18, while slopes for spring and split applications with 34 kg N ha^{-1} applied in the fall did not differ statistically. For the Nov 4 and 18 planting dates, GY was predicted to increase by 14 and 8 kg ha^{-1} per kg spring-N ha^{-1}, respectively. The GY increase was greater from split applications receiving 34 kg N ha^{-1} in the fall but it did not statistically differ from spring-N only applications (Table 10). Both rates of fall N increased GY by an average of 10.5 kg grain kg^{-1} N applied in the spring.

Overall, statistical differences in GY at NPRS were mainly due to the influence of the interaction of N-rate and timing by planting date on GY. No statistical differences in GY among fall-N levels within any cultivar-planting date trials at any total N rate were observed with the exception of Vandal planted on Nov 4. At this planting date-cultivar trial, GY response to N treatments receiving only spring-N rates greater than 125 kg N ha^{-1} as well as split applications with 34 kg N ha^{-1} in the fall and rates greater than 96 kg N ha^{-1} in the spring were predicted to produce better GY compared to N treatments receiving fall-N rates of 67 kg N ha^{-1} with rates greater than 58 and 67 kg N ha^{-1} in the spring, respectively (Fig. 4b).

Table 7. Stepwise regression analysis for grain yield (GY) of winter wheat as affected by cultivar, planting date, fall-N and spring-N rate at NPRS.

Source of Variation	df	f-value	p-value
Intercept decomposition			
Planting date	2	10.94	<.0001
Cultivar	1	0.06	0.8122
Fall-N	2	1.42	0.2451
Planting Date x Cultivar	2	12.24	<.0001
Planting Date x Fall-N	4	1.66	0.1615
Cultivar x Fall-N	2	0.75	0.4739
Planting Date x Cultivar x Fall	4	0.5	0.7365
Regression coefficient decomposition			
Total N	1	38.12	<.0001
Total N x Planting date	2	5.34	0.0055
Total N x Fall-N	2	2.74	0.067

Tested at 0.1 probability level

Table 8. Regression equations predicting GY as affected by planting date, cultivar and fall-N rate at NPRS.

	Fall-N	Havoc			Vandal		
Planting Date	kg N ha^{-1}	Equation	SE Intercept	SE slope	Equation	SE Intercept	SE Slope
Oct 16	0	3557 + 5.6950x	318	2.4273	4291 + 5.6950x	323	2.4274
	34	3568 + 7.2313x	474	3.1717	4159 + 7.2313x	461	3.1717
	67	4804 - 0.5613x^{ns}	555	3.1588	5149 - 0.5613x^{ns}	560	3.1588
Nov 4	0	2471 + 15.4171x	318	2.3719	2029 + 15.4171x	318	2.3719
	34	1960 + 16.9534	460	3.1619	1833 + 16.9534x	457	3.1619
	67	2899 + 9.1608x	552	3.1098	2282 + 9.1608x	555	3.1098
Nov 18	0	2894 + 8.9127x	317	2.3667	2722 + 8.9127x	317	2.3667
	34	2526 + 10.4490x	455	3.1224	2499 + 10.4490x	455	3.1224
	67	3559 + 2.6564x^{ns}	552	3.1064	3484 + 2.6564x^{ns}	552	3.1064

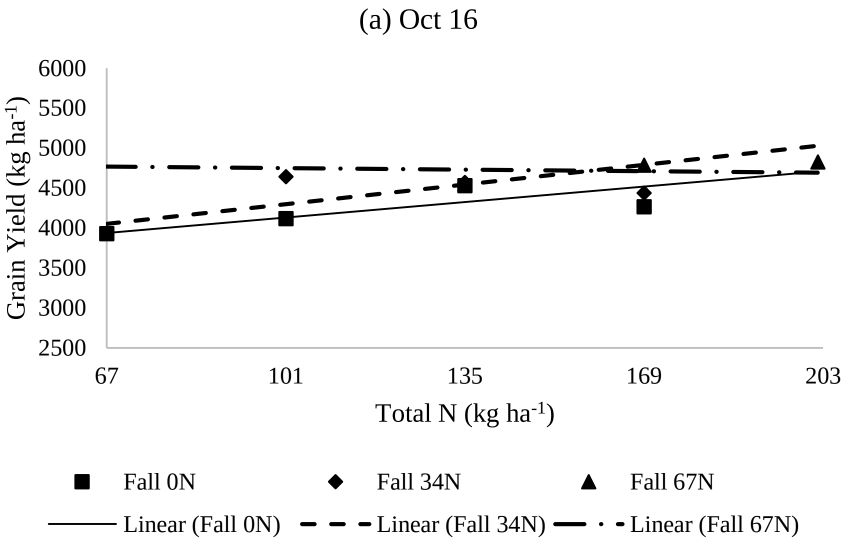
SE Standard error

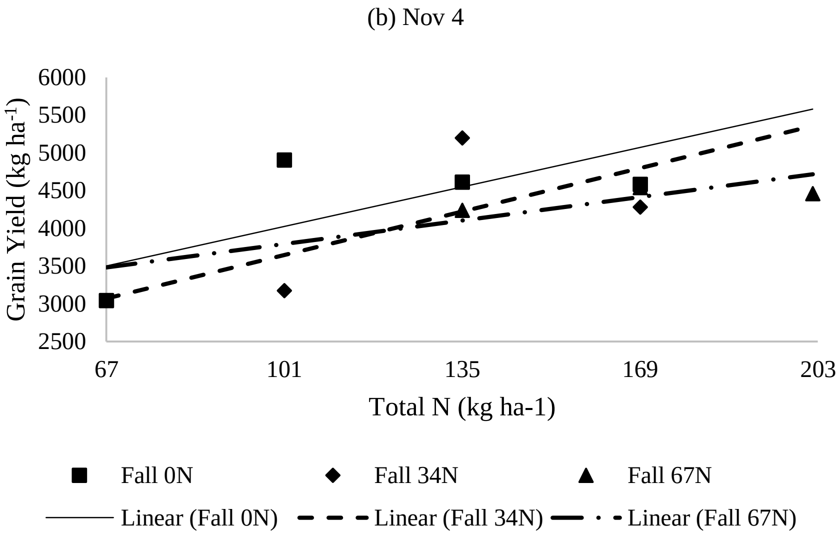
ns Slope not statistically different from zero.

Table 9. Orthogonal contrast of slopes shown in Table 8.

Slope Contrast	Significance
Oct 16 vs Nov 4	**
Oct. 16 vs Nov 18	ns
Nov 4 vs Nov 18	*
Fall_{0N} vs Fall_{34N}	ns
Fall_{0N} vs Fall_{67N}	*
Fall_{34N} vs Fall_{67N}	*

*, ** Significant at the 0.1 and 0.01 probability levels, respectively.
ns non significant





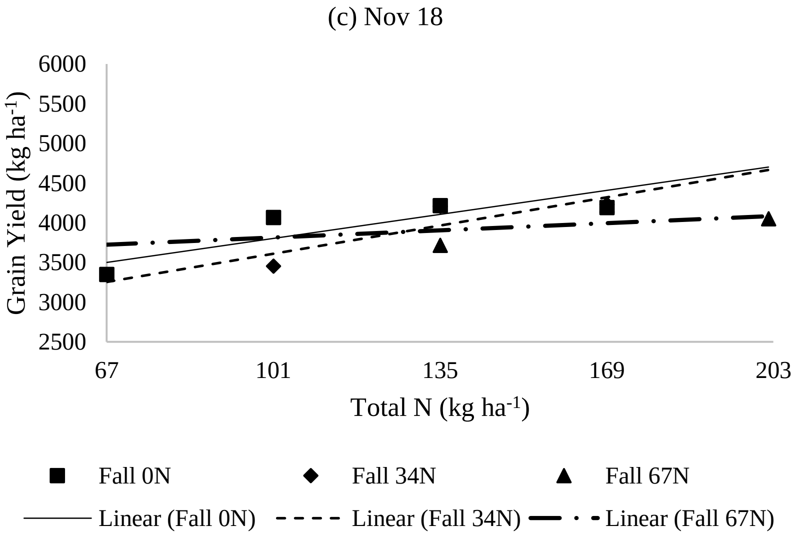


Figure 4. Grain yield of Havoc as a function of total N and affected by fall N-rate and planting dates Oct 16 (a), Nov 4 (b) and Nov 18 (c) at NPRS.

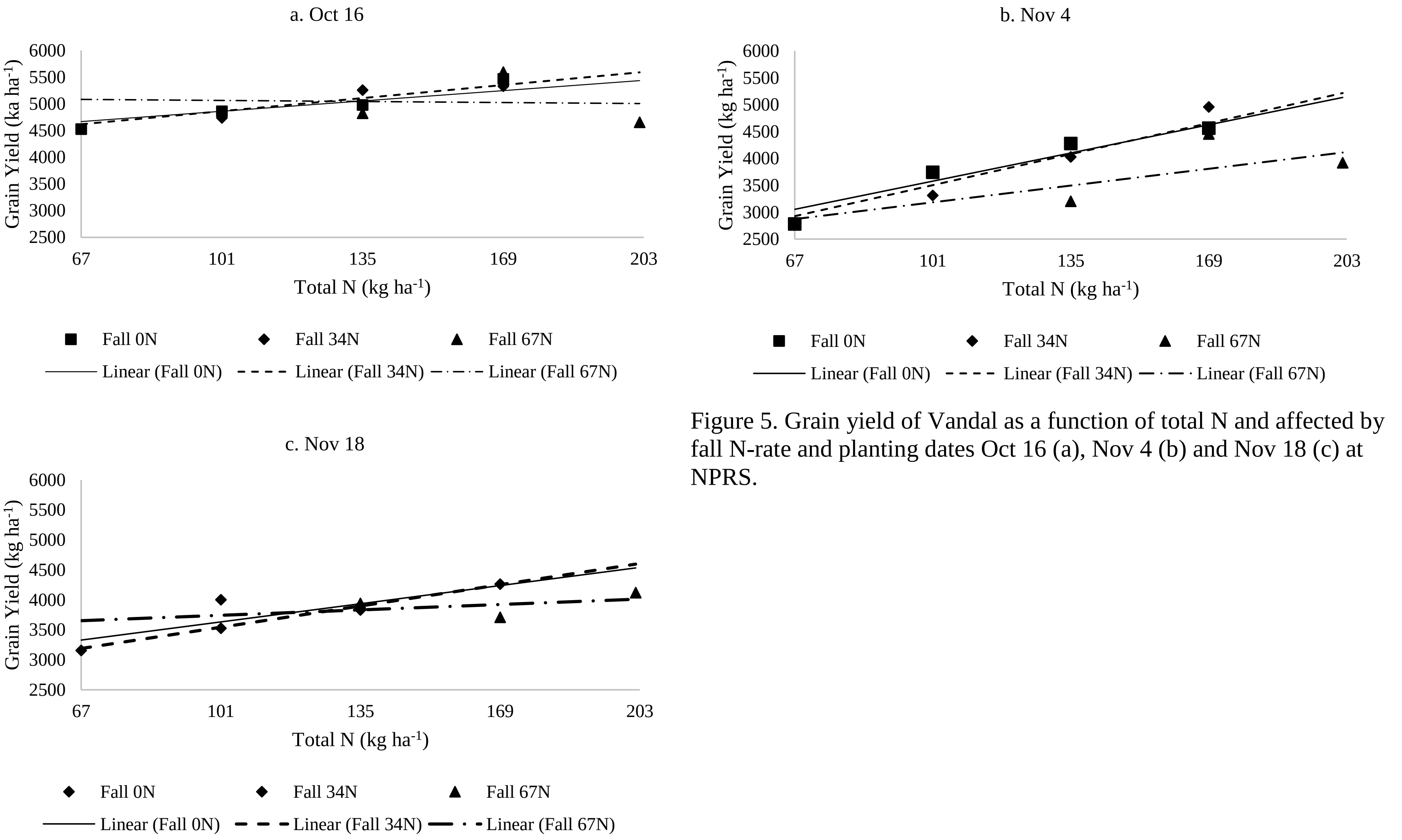


Figure 5. Grain yield of Vandal as a function of total N and affected by fall N-rate and planting dates Oct 16 (a), Nov 4 (b) and Nov 18 (c) at NPRS.

Pine Tree Research Station (PTRS)

Effect of planting date and cultivar on grain yield

At PTRS, GY was significantly ($P < 0.05$) affected by the main effects of cultivar and planting date and the interaction cultivar x planting date (Table 3). For Havoc, no significant GY response to planting dates was observed (Fig. 5a). For Vandal, mean GY decreased from 6554 to 4831 kg ha^{-1} as planting was delayed from Oct 17 to Nov 2, but increased to 5203 kg ha^{-1} on Nov 13 (Fig. 5b). Averaged across all planting date trials, mean GY of Vandal was 503 kg ha^{-1} more than Havoc.

Effect of N timing and rate on grain yield

At PTRS, the main effect of fall-N on GY was significant ($P < 0.10$) (Table 3). In addition, when averaged across spring-N rates, the effect of fall-N rate varied across planting date and cultivar, resulting in a significant cultivar x planting date x fall-N interaction ($P < 0.0001$). For treatments receiving, no fall N, GY generally decreased as planting date was delayed (Table 10). For Havoc sown on Nov 13, application of 34 and 67 kg N ha^{-1} in the fall significantly increased GY by 1160 and 1084 kg ha^{-1} compared to no fall-N.

Vandal showed an opposite response compared to Havoc, with a decrease in GY as planting date was delayed and with increased rates of fall applied N (Table 10). Although GY differences within planting dates did not differ statistically among fall-N levels, treatments receiving 67 kg N ha^{-1} in the fall were numerically lower compared to fall rates of 0 or 34 kg N ha^{-1}. These results suggest Vandal did not benefit from application of fall-N at any planting date, and split applications with fall-N rates greater than 34 kg N ha^{-1} may have detrimental effects on GY.

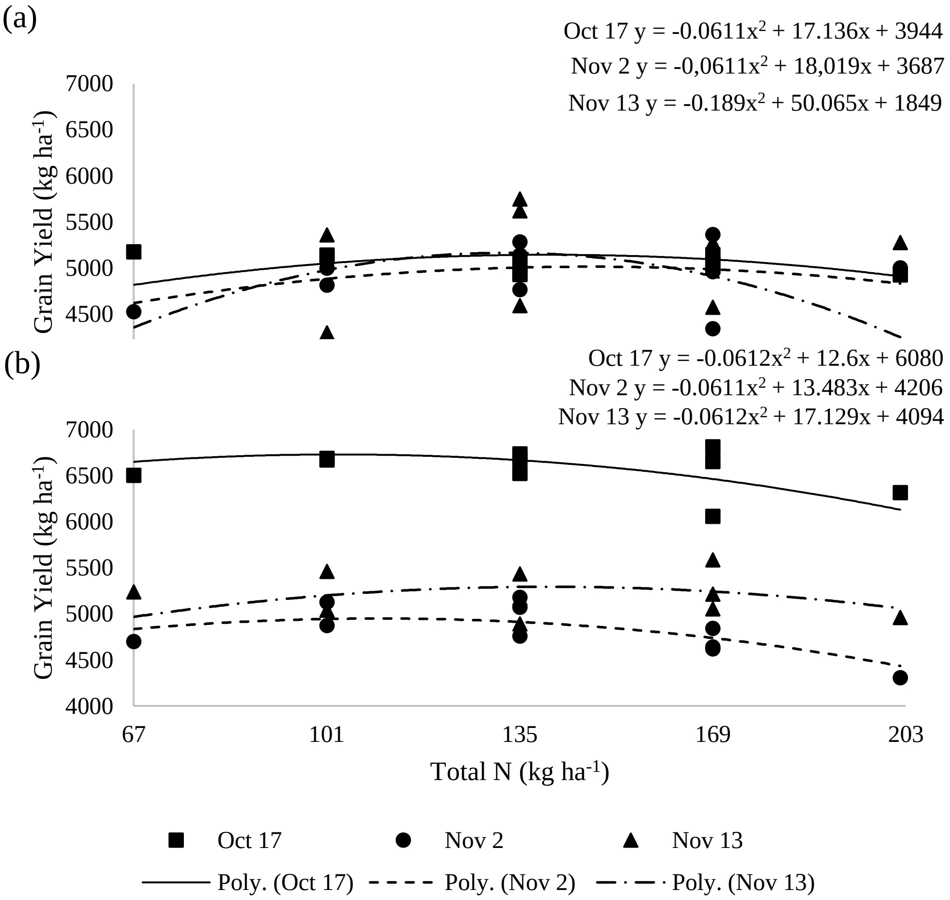


Figure 6. Grain yield of (a) Havoc and (b) Vandal as a function of total N rates and affected by planting date at PTRS.

Table 10. Grain yield as affected by cultivar, planting date and fall-N at PTRS.

Fall N treatment	Havoc			Vandal		
	Oct 17	Nov 2	Nov 13	Oct 17	Nov 2	Nov 13
	-- kg ha^{-1} --					
0	5130	4889	4302	6569	4966	5376
34	5042	4982	5462	6739	4824	5171
67	4961	5082	5386	6352	4703	5060
Check	5143	4343	4575	6652	4642	5215

LSD to compare means in the same cultivar and same planting date = 343 kg ha^{-1}
LSD to compare means in the same cultivar and different planting dates = 539 kg ha^{-1}
LSD to compare means of different cultivars and same planting dates = 338 kg ha^{-1}
LSD to compare means of different cultivars and different planting dates = 536 kg ha^{-1}

Regression Analysis

The regression analysis showed the predictor fall-N significantly ($P < 0.05$) affected the regression coefficients (β slopes) and thus influenced the prediction of GY ($R^2= 0.67$, $P < 0.0001$) (Table 11). Slopes were positive but not statistically different from zero for all planting date-cultivar trials at fall N-rates of 0 and 34 kg N ha^{-1}. At 67 kg N ha^{-1}, slopes were negative with GY significantly decreasing at a rate of 5 kg ha^{-1} per kg of spring applied N (Table 12).

For Havoc planted on Oct 17, no significant GY response to fall N was detected indicating N rates within this range either as split or spring only applications were able to maximize GY (Fig. 6a). For Nov 2, the rate of GY increase was greater for plots supplied with 34 kg N ha^{-1} in the fall compared to 0 kg N ha^{-1}, but this difference was not significant based on the slope contrast analysis (Table 14). Response lines for 67 kg N ha^{-1} in the fall and up to 88 kg N ha^{-1} in the spring had a larger GY response than those receiving spring only N ranging from 67 to 155 kg N ha^{-1}, as did application of 67 kg N ha^{-1} in the fall and up to 44 kg N ha^{-1} in the spring compared to 34 kg N ha^{-1} in the fall and up to 44 kg N ha^{-1} in the spring (Fig. 6b). For Nov 13, the lowest GY was observed for treatments receiving 0 kg N ha^{-1} in the fall which was significantly different from 34 and 67 kg N ha^{-1} fall-N rates. Based on the response lines, 34 and 67 kg N ha^{-1} fall-N rates did not differ statistically with the exception of a total N rate of 67 kg N ha^{-1} where a single application of 67 kg N ha^{-1} in the fall would possibly yield greater than application of 67 kg N ha^{-1} in the spring (Fig. 6c).

For Vandal planted on Oct 17, there were no statistical differences in GY among fall-N rates within the range of total N evaluated with the exception of a total N rate of 202 kg N ha^{-1}, which was higher yielding when applied in a spring only application (Fig. 7a). For Nov 2 and 13 planting dates, GY response was lower compared to Oct 21 (Fig. 7b and 7c) and there was no significant GY effect from fall applied N as planting date was delayed in any spring-N rate combination within the range of total N evaluated.

Regression analysis using surface analysis showed a significant quadratic fit for GY response of Havoc planted on Nov 13 ($R^2 = 0.48$) and Vandal on Nov 2 ($R^2 = 0.20$). Grain yield response was quadratic and linear to fall-N for Havoc planted on Nov 13 (Table 14) with the magnitude of GY increase greater with fall applied N at 1.1 kg ha^{-1} per kg N than for spring at 0.3 kg ha^{-1} per kg N. For Vandal planted on Nov 2, GY responded interactively to fall and spring-N with only the negative fall x spring-N interaction significant, indicating an inversely proportional GY response to both application times (fall and spring). Based on this model, the predicted optimal fall and spring-N rates to maximize GY were 53 and 79 kg N ha^{-1} for Havoc sown on Nov 13 and 25 and 86 kg N ha^{-1} for Vandal sown on Nov 2.

Optimum fall- and spring-N rates to maximize GY were 53 and 79 kg N ha^{-1} and 25 and 86 for Havoc (Nov. 13) and Vandal (Nov. 2), respectively (Table 14). Relative grain yield (RY) based on the time and rate used in this experiment and predicted by multiple regression equations showed the largest yield increases for Havoc planted on Nov 13 were greater than 80% with split N applications with either of fall-N at 34 or 67 kg N ha^{-1} rate (Table 15). For Vandal planted on Nov 3, the largest GY increases were also greater than 80% but with spring-N applications greater than 67 kg N ha^{-1} or split N applications with fall and spring-N rates equal to 67 kg N ha^{-1}. Optimal N rate and time could not be predicted for other planting date-cultivar trials, as they did not statistically fit quadratic functions.

Table 11. Stepwise regression analysis for grain yield of winter wheat as affected by cultivar, planting date and fall-N at PTRS.

Source of Variation	df	f-value	p-value
Intercept decomposition			
Cultivar	1	80.26	<.0001
Planting Date	2	64.83	<.0001
Fall-N	2	3.97	0.0203
Planting Date x Cultivar	2	68.59	<.0001
Planting Date x Fall-N	4	3.14	0.0154
Cultivar x Fall-N	2	9.62	<.0001
Planting Date x Cultivar x Fall	4	5.17	0.0005
Regression coefficient decomposition			
Total N	1	0.37	0.544
Total N x Fall-N	2	4.15	0.0171

Tested at 0.05 probability level

Table 12. Regression equations for wheat to predict grain yield and affected by planting date, cultivar and fall-N rates at PTRS.

		Havoc			Vandal		
Planting Date	Fall-N	Equation	SE Estimate	SE slope	Equation	SE Estimate	SE Slope
	kg N ha^{-1}						
Oct 17	0	5052 + 0.69x ^{ns}	193	1.288	6509 + 0.69x ^{ns}	193	1.288
	34	4696 + 2.5671x ^{ns}	307	2.036	6393 + 2.5671x ^{ns}	307	2.036
	67	5834 - 5.17373x	370	2.036	7224 - 5.17373x	370	2.036
Nov 2	0	4671 + 0.69x ^{ns}	193	1.288	4804 + 0.69x ^{ns}	193	1.288
	34	4635 + 2.5671x ^{ns}	307	2.036	4478 + 2.5671x ^{ns}	307	2.036
	67	5955 - 5.17373x	370	2.036	5575 - 5.17373x	370	2.036
Nov 13	0	4289 + 0.69x ^{ns}	193	1.288	5254 + 0.69x ^{ns}	193	1.288
	34	5116 + 2.5671x ^{ns}	307	2.036	4825 + 2.5671x ^{ns}	307	2.036
	67	6258 - 5.17373x	370	2.036	5933 - 5.17373x	370	2.036

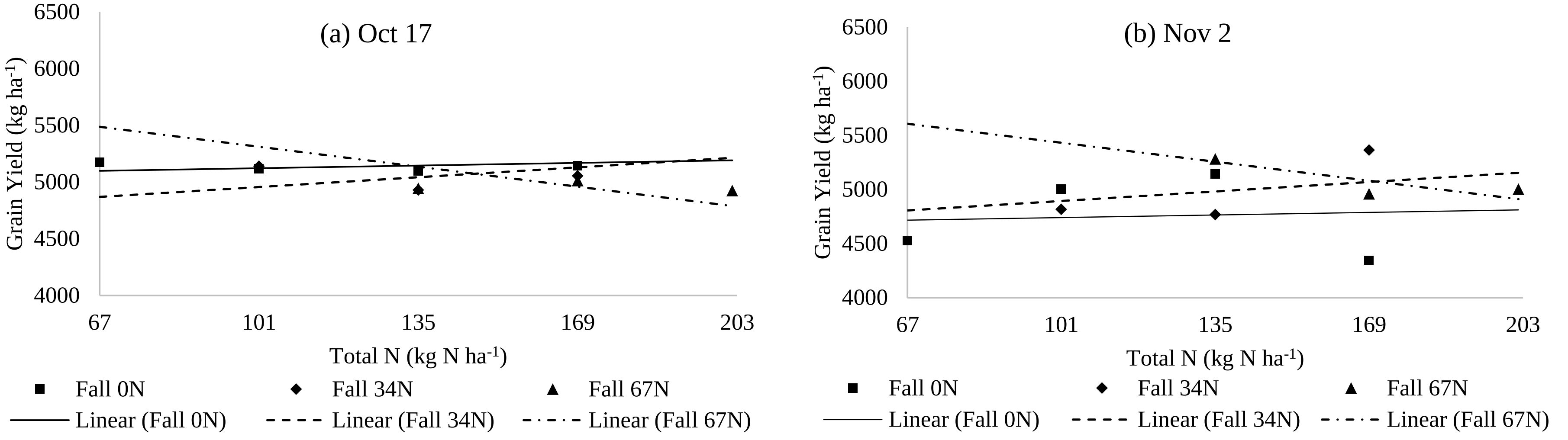
SE Standard error

ns Slope not statistically different from zero.

Table 13. Orthogonal contrast of slopes shown in Table 12.

Slope Contrast	Significance
$Fall_{0N}$ x $Fall_{34N}$	ns
$Fall_{0N}$ x $Fall_{67N}$	*
$Fall_{34N}$ x $Fall_{67N}$	**

*, ** Significant at the 0.05 and 0.01 probability levels, respectively.



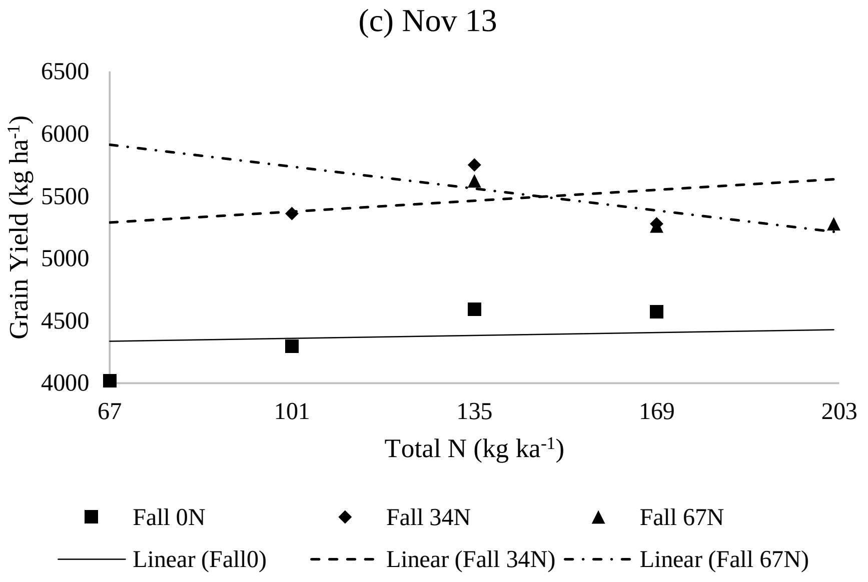
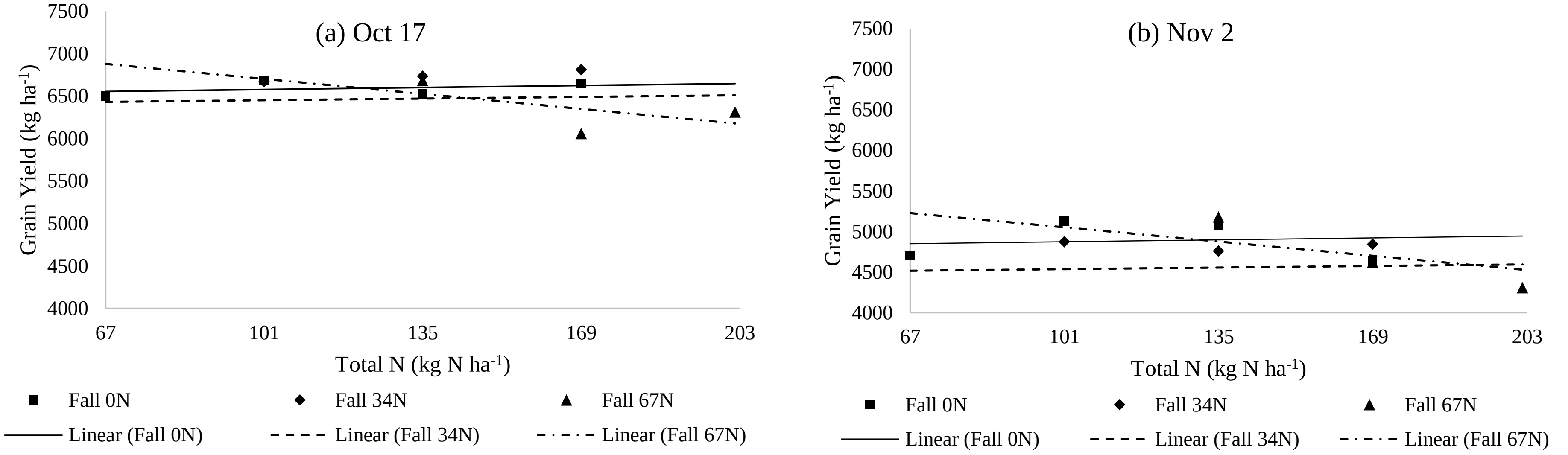


Figure 7. Grain yield of Havoc as a function of total N and affected by fall-N and planting dates (a) Oct 17, (b) Nov 2 and (c) Nov 13 at PTRS.



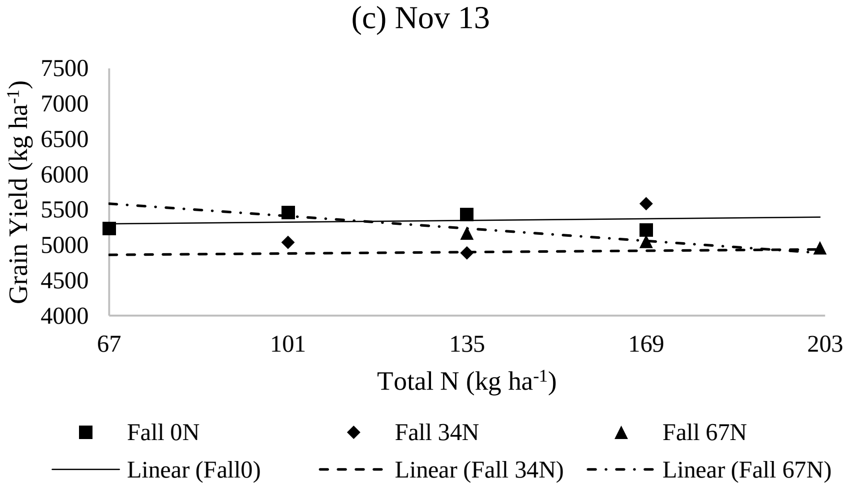


Figure 8. Grain yield of Vandal as a function of total N and affected by fall-N and planting dates (a) Oct 17, (b) Nov 2 and (c) Nov 13 at PTRS.

Table 14. Critical values and predicted relative grain yield (RY) based on quadratic response surface regression models of grain yield for cultivars Havoc and Vandal grown on a silt loam soil.

Cultivar	Planting Date	Intercept	Spring-N	Fall-N	Spring^2	Fall^2	Fall- x Spring-N	Critical values (kg ha^{-1})^a	Predicted RY at critical value (%)
Havoc	Nov 13	43.6	0.3230	1.1021***	-0.0010	-0.0082**	-0.0030	$53_F + 79_S$	85
Vandal	Nov 2	68.5*	0.1230	0.3728	-0.0001	0.0001	-0.0044*	$25_F + 86_S$	78

*, **, *** Significant at the 0.1, 0.01 and 0.001 probability levels

[a] Critical values estimated for a range of 0 to 67 kg N ha^{-1} in the fall (F) and 67 to 134 kg N ha^{-1} in the spring (S).

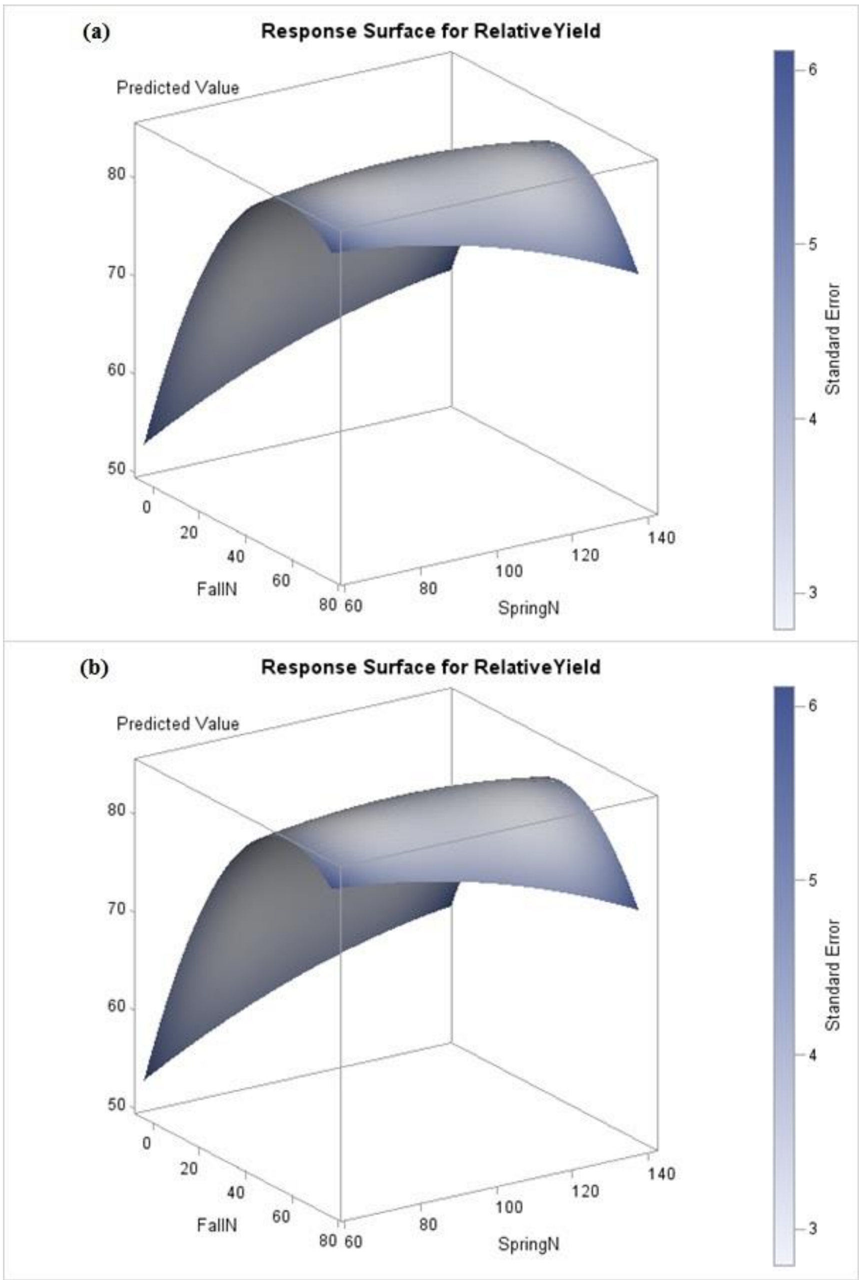


Figure 9. Surface response of yield as a function of split application of fall and spring-N of (a) Havoc planted on Nov 13 and (b) Vandal planted on Nov 2 at PTRS.

Rohwer Research Station (RWRS)

Effect of planting date and cultivar on grain yield

At RWRS, the main effects of planting date and cultivar and the interaction planting date x cultivar significantly affected GY (Table 4). For Havoc, GY was the lowest for the Oct 21 planting date (3435 kg ha^{-1}) and increased as planting date was delayed until Nov 3 (4715 kg ha^{-1}) and Nov 14 (4738 kg ha^{-1}) (Fig. 9a). For Vandal, GY decreased from Oct 21 (4899 kg ha^{-1}) to Nov 3 (4593 kg ha^{-1}) and then increased (5254 kg ha^{-1}) to Nov 14 (Fig. 9b). Overall, GY of Vandal was 619 kg ha^{-1} more than Havoc and GY response to timing and rate of N application increased as planting date was delayed for both cultivars (Table 17). The largest changes in GY were observed for the Nov 3 planting date for Havoc, where yields were 17 to 45 % greater compared to the Oct 21 planting date.

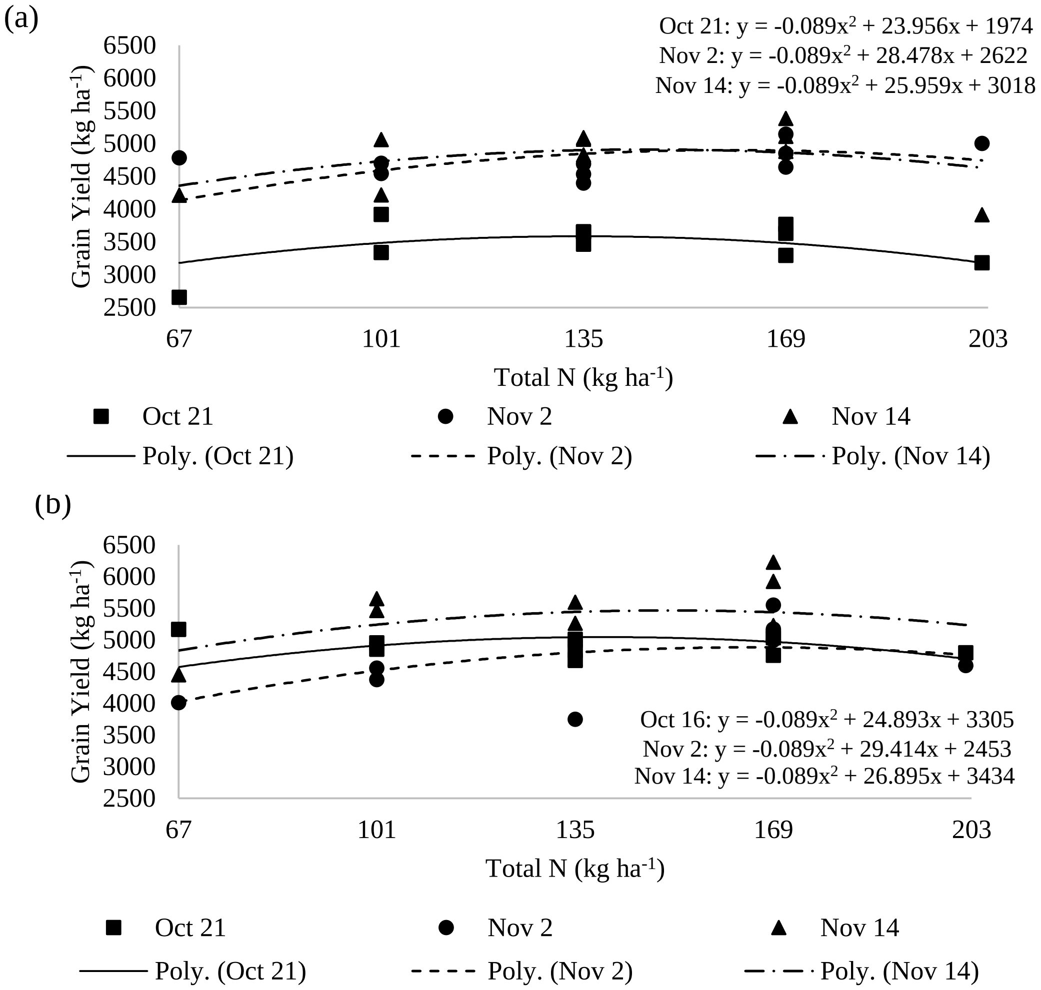


Figure 10. Grain yield of (a) Havoc and (b) Vandal as a function of total N rates and affected by planting date at RWRS.

Effect of N timing and rate on grain yield

The main effects of fall-N and spring-N and the interactions fall-N x spring-N, cultivar x fall-N, planting date x fall-N x spring-N and planting date x cultivar x spring-N significantly affected GY ($P < 0.05$) (Table 3). In addition, GY response to timing and rate of N application also varied across cultivar and planting dates and resulted in a significant 4-way interaction cultivar x planting date x fall-N x spring-N ($P < 0.05$).

For Havoc planted on Oct 21, GY ranged from 2653 to 3916 kg ha^{-1} (Table 15). The highest GY was obtained from 101 kg N ha^{-1} applied at late-winter and early-spring (0_{F} + 51_{LW} + 51_{ES}). No statistical differences were observed from the application of 135 and 169 kg N ha^{-1} either as two (F + LW and LW + ES) or three splits (F + LW + ES). Nevertheless, treatments which did not receive early spring N (34_{F} + 67 $_{LW}$ + 0_{ES} and 67_{F} + 67 $_{LW}$ + 0_{ES}) had lower GY compared to those with the last split delayed until Feekes 5. The lowest GYs were obtained from the single late-winter treatment (0_{F} + 67_{LW} + 0_{ES}) and the highest total N rate (67_{F} + 67_{LW} + 67_{ES}). Results indicate N applied both in fall and early-spring were important for maximizing GY at the earliest planting date.

Grain yield for Havoc planted on Nov 3 ranged from 4396 to 5143 kg ha^{-1}. The highest GY was obtained from the treatment receiving 169 kg N ha^{-1} in three splits (34_{F} + 67_{LW} + 67_{ES}). The lowest was obtained from the treatment receiving 134 kg N ha^{-1} in two splits (67_{F} + 67_{LW} + 0_{ES}), with no early spring N applied. Overall, no statistical GY differences were observed among N treatment combinations with the exception of between those resulting in the lowest and highest GY. Unlike Oct 21, GY from the treatment receiving 67 kg ha^{-1} as a single late winter application was statistically equal to other N treatment combinations.

Grain yield response to rate and timing of N application had a narrow range when Vandal was planted on Oct 21 (Table 15) with no statistical GY difference among N treatments. Grain yields for Vandal planted on Nov 3 ranged from 3749 to 5549 kg ha^{-1} and increased an average of 10 % with application of fall-N and 15 % with split-spring as oppose to single spring applications. The treatment with the highest GY was the high N-rate check ($0_F + 84_{LW} + 84_{ES}$). The lowest yielding treatments received either 134 kg N ha^{-1} in two equal splits ($67_F + 67_{LW} + 0_{ES}$) or a single late-winter N treatment ($0_F + 67_{LW} + 0_{ES}$). No statistical GY differences were observed for treatments receiving total N applications of 101 kg ha^{-1} or 169 kg N ha^{-1} in different rate and timing combinations. However, treatments receiving a total of 169 kg N ha^{-1} had higher GY compared to 134 kg N ha^{-1}. Overall, these results suggest that split spring-N was an important factor to maximize GY for Vandal on Nov 3.

Table 15. Grain yield of winter wheat as influenced by planting date, cultivar, fall-N and spring-N at RWRS.

N treatment				Havoc			Vandal		
Total N	F	LW	ES	Oct 21	Nov 3	Nov 14	Oct 21	Nov 3	Nov 14
	-------- kg ha^{-1} ------			-- kg ha^{-1} --					
169	0	84	84	3631	4851	5111	5061	5549	5926
67	0	67	0	2653	4784	4210	5166	4010	4451
101	0	51	51	3916	4699	5059	4955	4376	5464
135	0	67	67	3654	4691	5064	4678	4977	5598
101	34	67	0	3338	4543	4216	4855	4557	5650
135	34	51	51	3648	4536	4828	5009	4910	5266
169	34	67	67	3291	5143	5385	5034	5173	6229
135	67	67	0	3466	4396	5089	4835	3749	4703
169	67	51	51	3765	4639	4879	4759	4995	5230
202	67	67	67	3183	5001	3915	4799	4595	4695
Mean				3455	4728	4775	4915	4689	5321

LSD to compare means in the same cultivar and same planting date = 659 kg ha^{-1}

LSD to compare means in the same cultivar and different planting dates = 661 kg ha^{-1}

LSD to compare means in different cultivars and same planting dates = 654 kg ha^{-1}

LSD to compare means in different cultivars and different planting dates = 657 kg ha^{-1}

For Vandal sown on Nov 14, GY ranged from 4451 to 6229 kg ha^{-1}, with mean GY greater when 34 kg N ha^{-1} was applied in the fall. Treatments receiving 169 kg N ha^{-1} in two (0_F + 84_{LW} + 84_{ES}) or three splits (34_F + 67_{LW} + 67_{ES}) had the highest GY, while the single late-winter treatment was the lowest (0_F + 67_{LW} + 0_{ES}). There were no statistical GY differences among treatments receiving total N of 101 kg ha^{-1}. These results suggest that increases in GY are possible from both fall and increased spring-N rates when winter wheat is planted later than optimum. However, excessive N application was also shown to be harmful for GY production as the 202 kg N ha^{-1} rate had 25 % lower GY compared to 169 kg N ha^{-1}.

Regression analysis

Linear regression analysis indicated the main effect planting date and fall-N and the interactions planting date x fall-N and planting date x cultivar x fall-N significantly affected the regression coefficients (β slopes) and thus they were used to predict GY (Table 16). The overall model fit was statistically significant ($P < 0.0001$, R^2= 0.62). Overall, response lines indicated Havoc was affected by fall-N rates in all planting dates whereas Vandal was only affected on Nov 3 and Nov 14 (Table 17).

Five out of 6 planting date-cultivar-fall trials had no negative linear relationship between spring-N rates and GY. Despite a positive trend as spring-N increased with no fall-N treatment, contrast of the three slopes showed no statistical difference between spring and split-N applications except for both cultivars on the latest planting date (Table 18).

For Havoc planted on Oct 21, GY did not increase with applications of spring-N for any split N application, whereas spring-N treatments increased GY by 8 kg ha^{-1} per kg N applied (Fig. 10a). For Nov 3, GY increased by 9 kg ha^{-1} with a split compared to spring application (Fig. 10b). For Nov 14, GY decreased 17 kg per kg spring applied N when receiving the highest fall-N treatment (Fig 10c). Spring-N treatments and splits with 34 kg N ha^{-1} applied in the fall had positive slopes but did not differ statistically at any level of total N evaluated (Table 19). The rate of GY increase with 34 kg fall-N ha^{-1} was 17 kg ha^{-1} per kg N compared to 8 kg ha^{-1} per kg N with spring-N only treatments. Although the magnitude of the response was lower for wheat receiving no fall-N, a previous application of 34 kg N ha^{-1} would actually require application of 35 kg N ha^{-1} to increase 17 kg of GY. Thus, it would be more economical to apply N only in the spring. Grain yield decreased with split N treatments that received that highest fall rate (67 kg N ha^{-1}), with total N rates reaching 135 to 202 kg ha^{-1}, showing the negative effect of excessive N rates on winter wheat.

For Vandal planted on Oct 21, there were no statistical GY differences among fall-N treatments at any level of spring-N with total N rates from 67 to 202 kg N ha^{-1} in various combinations able to maximize GY (Fig 11a). For Nov 3, slopes were positive for all application times, however splits that received that highest fall-N rate yielded lower compared to the other N application timing (Fig. 11b). For Nov 14, a GY increase due to application of spring-N was only observed with no fall-N or splits receiving 34 kg N ha^{-1} in the fall (Fig. 11c).

Table 16. Stepwise regression analysis for grain yield (GY) of winter wheat as affected by cultivar, planting date, fall and spring-N rates at RWRS.

Source of Variation	df	F-value	P-value
Intercept decomposition			
Cultivar	1	0.16	0.6861
Planting Date	2	4.2	0.0163
Fall-N	2	1.66	0.1925
Planting Date x Cultivar	2	4.44	0.0129
Planting Date x Fall-N	4	3.41	0.0101
Cultivar x Fall-N	2	2.37	0.0958
Planting Date x Cultivar x Fall	4	2.49	0.0445
Regression coefficient decomposition			
Total N	1	20.31	<.0001
Total N x Planting Date	2	5.26	0.0059
Total N x Fall-N	2	4.89	0.0084
Total N x Planting Date x Fall-N	4	3.96	0.0041
Total N x Planting Date x Cultivar x Fall-N	9	2.62	0.0068

Table 17. Regression equations for wheat to predict grain yield and affected by planting date, cultivar and fall-N rates at RWRS.

Planting	Fall N	Havoc			Vandal		
Date	kg ha^{-1}	Equation	SE Estimate	SE slope	Equation	SE Estimate	SE Slope
Oct 21	0	2529 + 7.91963x*	407	3.2886	5173 - 1.76379x^{ns}	407	3.2886
	34	3520 - 0.69692x^{ns}	716	5.1997	4608 + 2.6505x^{ns}	716	5.1997
	67	4180 - 4.20374x^{ns}	888	5.1997	4888 - 0.53751x^{ns}	888	5.1997
Nov 3	0	4688 + 0.57829x^{ns}	407	3.2886	2902 + 15.46931x****	407	3.2886
	34	3539 + 8.90792x*	716	5.1997	3648 + 9.13405x*	716	5.1997
	67	3167 + 8.96723x*	888	5.1997	2330 + 12.55190x*	888	5.1997
Nov 14	0	3912 + 8.03751x*	407	3.2886	3765 + 13.51349x****	407	3.2886
	34	2470 + 17.34134x**	716	5.1997	4558 + 8.57429x^{ns}	716	5.1997
	67	7562 - 17.40436x**	888	5.1997	4896 - 0.11862x^{ns}	888	5.1997

SE Standard error

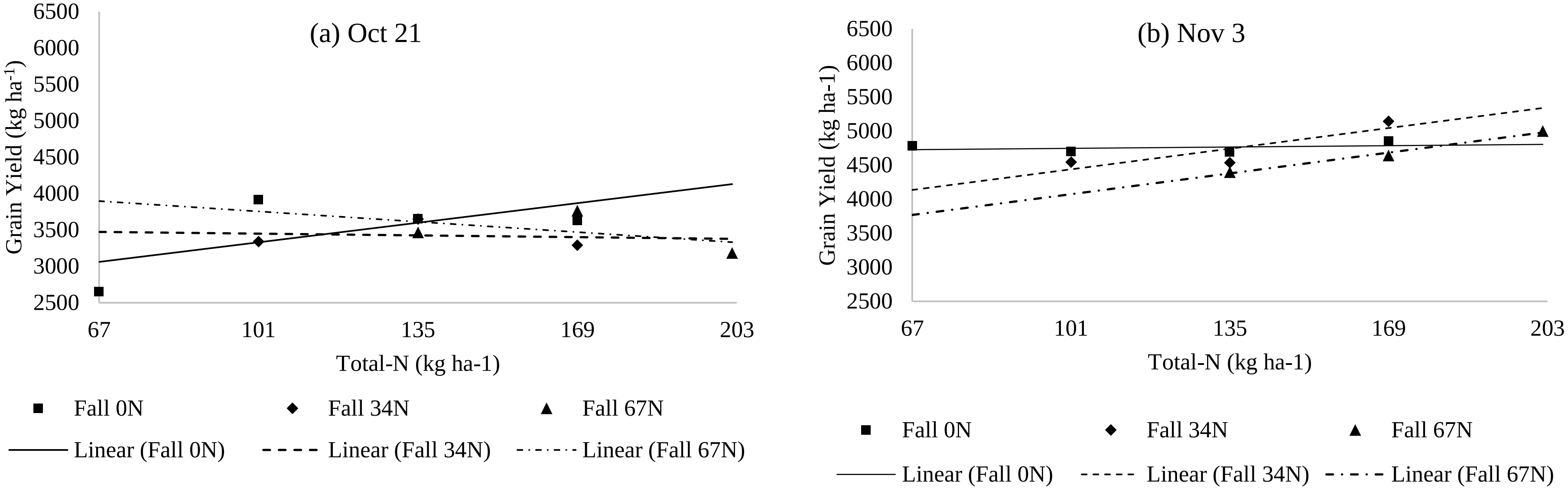
ns Slope not statistically different from zero.

*, **, *** Significant at the 0.1, 0.01, and 0.0001 probability levels, respectively.

Table 18. Orthogonal contrast for slopes of linear equations shown in Table 17.

	Havoc			Vandal		
Planting Date	Oct 21	Nov 3	Nov	Oct	Nov 3	Nov 14
$Fall_{0N}$ x $Fall_{34N}$	ns	ns	ns	ns	ns	ns
$Fall_{0N}$ x $Fall_{67N}$	ns	ns	***	ns	ns	*
$Fall_{34N}$ x $Fall_{67N}$	ns	ns	***	ns	ns	ns

*, **, *** Significant at the 0.05, 0.01 and 0.001 probability levels, respectively.



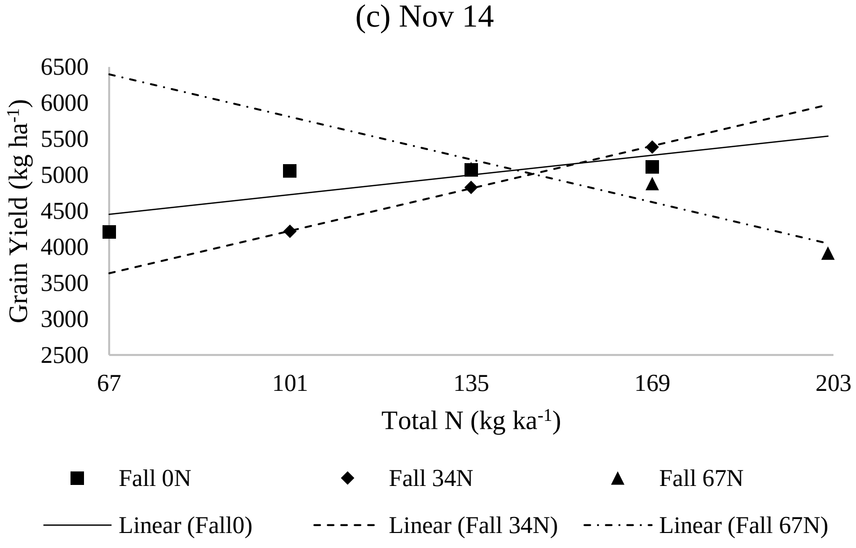
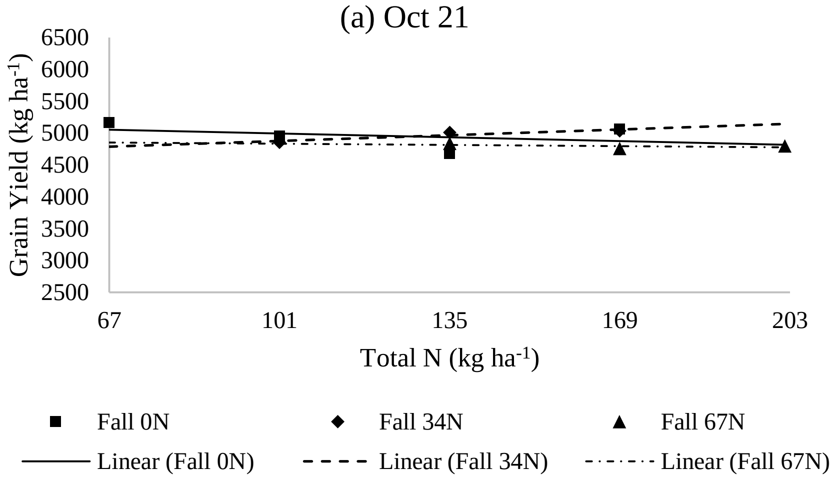


Figure 11. Grain yield of Havoc as a function of total N and affected by fall-N and planting dates (a) Oct 21, (b) Nov 3 and (c) Nov 14 at RWRS.



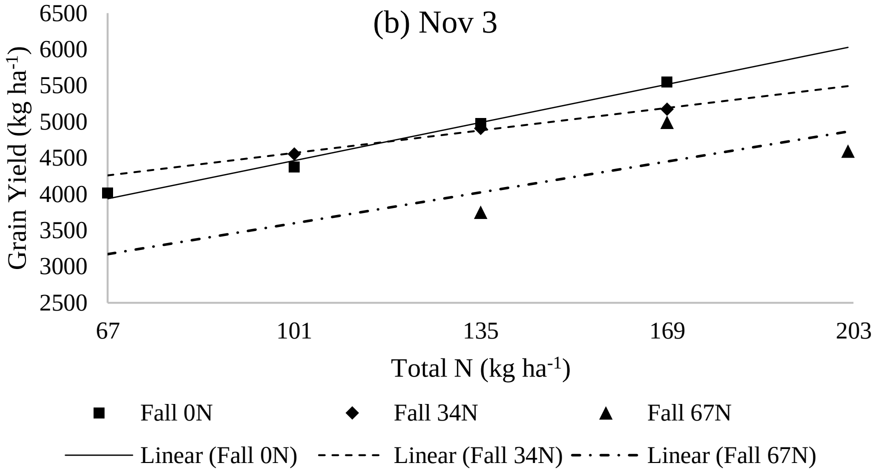
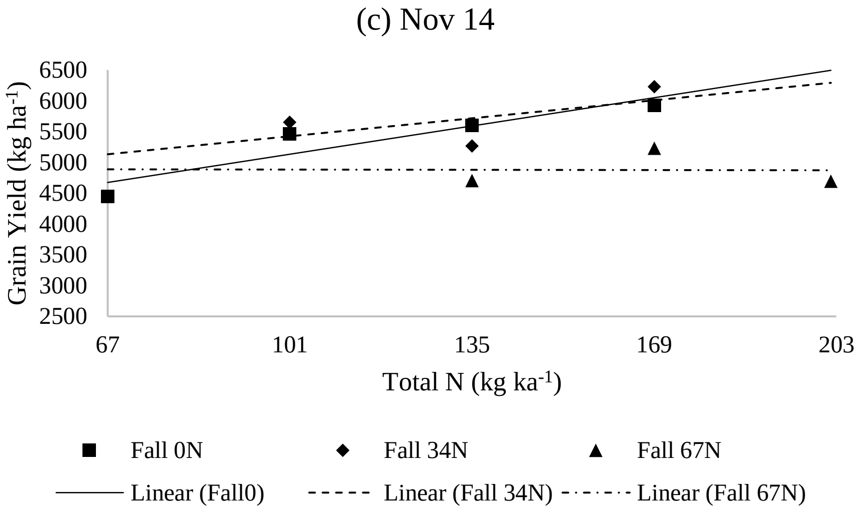


Figure 12. Grain yield of Vandal as a function of total N and affected by fall-N and planting dates (a) Oct 21, (b) Nov 3 and (c) Nov 14 at RWRS.



The results from surface response analysis (Table 19 and Fig. 12) showed 4 of 6 planting date-cultivar trials responded to both fall and spring-N applications. For Havoc planted on Nov 3 and Vandal planted on Oct 21, GY did not significantly fit either linear or quadratic functions, indicating the need for a higher order polynomial function or further experimentation. Grain yield of Havoc from Oct 21 responded linearly to both fall and spring-N, quadratically to spring-N and interactively to fall and spring-N with R^2 =0.40 (Fig. 12a). For the Nov 14 planting date, GY responded linearly for both fall and spring and interactively to fall and spring-N with R^2 = 0.40 (Fig. 12b). For Vandal planted on Nov 3, GY responded linearly to both fall and spring-N and quadratically to fall-N with R^2 = 0.48 (Fig. 12c). For Nov 14 planting date, GY responded linearly and quadratically to fall N and interactively to fall and spring-N with R^2 = 0.47 (Fig. 12d).

Although application of spring-N was important to maximize GY, there was a benefit of fall-N for late planting dates. For Havoc, GY response to spring applied N was more than 3.6 times greater than fall-N but decreased to 1.3 times as planting date was delayed from Oct 21 to Nov 14. For Vandal, GY response to spring-N was 2 times greater than fall-N but GY response to fall-N increased 3 times as planting date was delayed from Nov 3 to Nov 14. Conversely, response to spring-N decreased as planting date was delayed for both cultivars. Additionally, the negative fall x spring-N interaction indicated GY response to spring applied N is inversely proportional. Slopes obtained from 3 out of 4 planting date-cultivars trials were negative and statistically significant for the fall x spring interaction term.

Although GY of Vandal planted on Nov 3 and 14 decreased quadratically with fall-N application, application of a small amount of fall-N had a benefit for GY. For Vandal planted on Nov 14, the quadratic coefficient for fall-N was 2-fold greater than Nov 3 suggesting substantial GY decrease as fall-N increased. However, GY increased linearly with fall-N at a rate of 0.5 and 1.5 kg per kg of fall applied N when planted on Nov 3 and Nov 14, respectively. Nevertheless, optimum fall-N rate for Vandal was lower than that of Havoc but still needed to maximize GY. Optimum fall-N and spring-N rates for Havoc were 35 and 105 kg N ha^{-1} for Oct 21 to achieve 82% RY, 61 and 85 kg N ha^{-1} for Nov 14 to achieve 84% RY. For vandal, 33 and 129 kg N ha^{-1} for Nov 3 to achieve 87 % RY and 24 and 135 kg N ha^{-1} to achieve 94% RY, respectively.

Relative grain yield (RY) based on the N application times and rates used in this experiment and predicted by multiple regression equations shows that the largest yield increase for Havoc planted on Oct 21 was 81% with application of fall-N ranging from 0 to 67 kg N ha^{-1} and spring-N equal to 101 kg N ha^{-1}. For Nov 14, the largest yield increase was 91% with spring N application of 135 kg N ha^{-1}. For Vandal planted on Nov 3 predicted RY was 87% with split applications with fall-N and spring-N equal to 34 and 135 kg N ha^{-1}. For Nov 14, all N treatments were predicted to achieve RY greater than 100% with the largest increase of 140% also from split applications with fall-N and spring-N equal to 34 and 135 kg N ha^{-1}

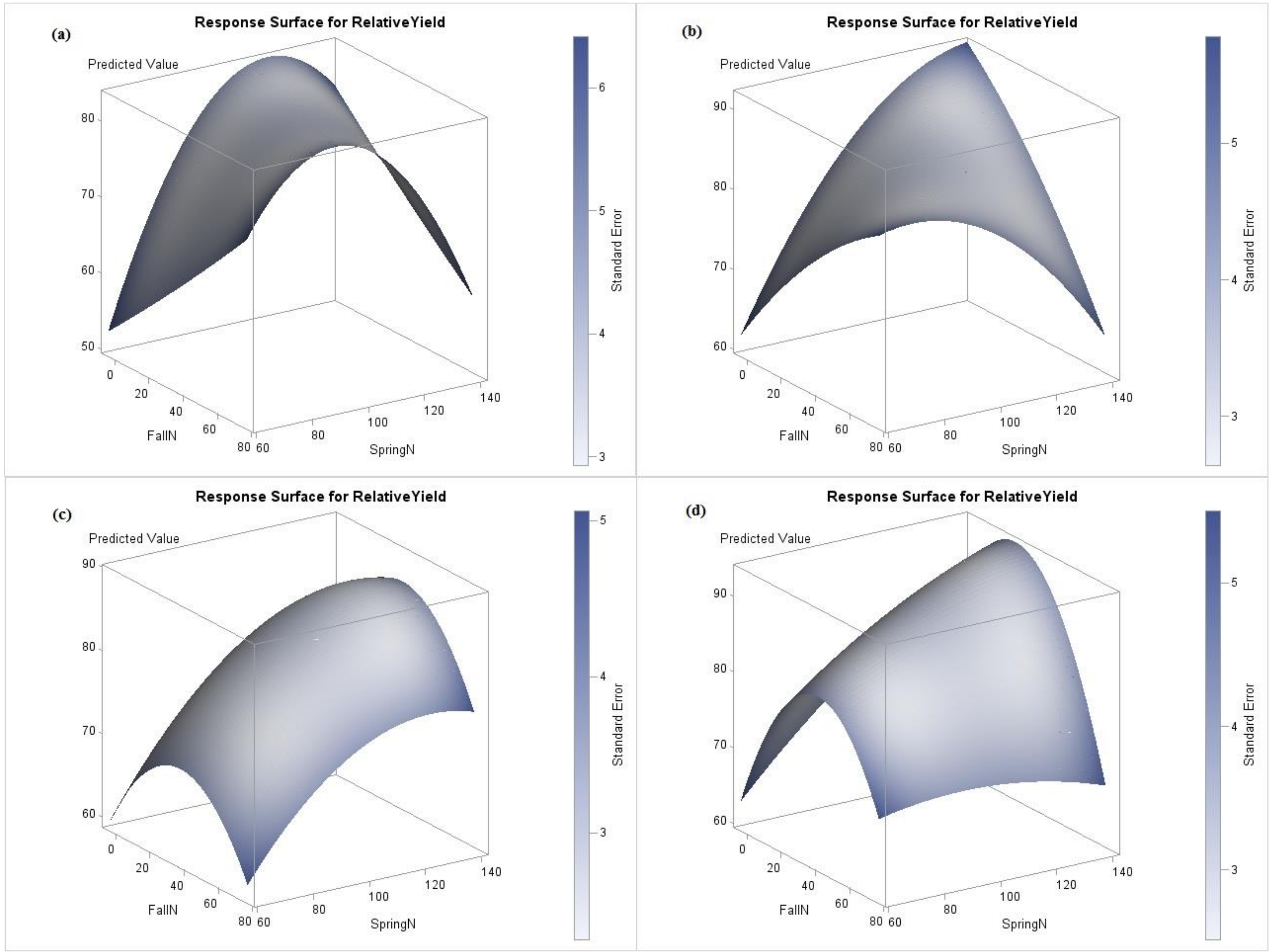


Figure 13. Response surface analysis for Havoc on (a) Oct 21 and (b) Nov 14 and Vandal on (c) Oct 21 and (d) Nov 14 at RWRS.

Table 19. Critical values and predicted relative yield (RY) of winter wheat grown in silt loam soil based on quadratic response surface regression models of grain yield for a data range of 0 to 67 kg N ha^{-1} in the fall (F) and 67 to 134 kg N ha^{-1} in the spring (S)

Cultivar	Planting Date	Intercept	Spring-N	Fall-N	Spring^2	Fall^2	Fall-N x Spring-N	Critical values (kg ha^{-1}) [a]	Predicted RY at critical value (%)
Havoc	Oct 21	-46.7	2.25**	0.62*	-0.0098**	0.0003	-0.0061**	$35_F + 105_S$	82
	Nov 3	-	-	-	-	-	-	-	-
	Nov 14	9.1	1.16*	0.83**	-0.0041	-0.0016	-0.0076***	$61_F + 85_S$	84
Vandal	Oct 21	-	-	-	-	-	-	-	
	Nov 3	17.8	0.9588*	0.4682*	-0.0037	-0.0063*	-0.0004	$33_F + 129_S$	87
	Nov 14	61	0.80	1.457***	-0.0020	-0.014**	-0.0059*	$24_F + 135_S$	140

*, **, *** Significant at the 0.1, 0.01 and 0.001 probability levels

[a] Critical values estimated for a range of 0 to 67 kg N ha^{-1} in the fall (F) and 67 to 134 kg N ha^{-1} in the spring (S).

Results for Yield Components

Effect of planting date and cultivar on yield components

Analysis of variance indicated that the interaction planting date x cultivar significantly affected kernel weight per spike (KWS), kernel number per spike (KNS) and spike density (SD) at all locations ($P<0.0001$), with the exception of KNS at PTRS (Table 20). For Havoc planted at NPRS, there was a 20% decrease in SD as planting date was delayed from October 16 to Nov 4 and a 13% increase from Nov 4 to Nov 18 (Table 21). For Vandal, SD decreased by 25% from October 16 to November 4 which was equal to November 18 (Table 21). For Havoc, the highest KWS was observed on the Nov 4 planting date. There was no statistical difference in KWS among planting dates for Vandal (Table 22). For KNS, Havoc showed a significant decrease as planting date was delayed, while no statistical differences were observed among planting dates for Vandal (Table 23).

At PTRS, KWS of Havoc was the highest for the Oct 17 planting date at 1.34 g and decreased to 1.13 g when planted on Nov 2 (Table 29) in agreement with the trend observed in GY (Table 11). Likewise, for Vandal, KWS was highest for Oct 17 and the lowest for Nov 2 and 13 again in agreement with observed GY. Both Havoc and Vandal showed a similar trend for KNS, with a reduction observed as planting date was delayed from Oct 17 to Nov 2 and 13.

At RWRS, KWS and KNS were higher for Vandal compared to Havoc, which was again in agreement with GY results (Table 25). For Havoc, the lowest KWS was observed on the earliest planting date and the highest on the second planting date, with no statistical differences observed among planting date for Vandal. Kernel number spike^{-1} of Havoc increased 20 % as planting date was delayed from Oct 21 to Nov 3 and 14 with a 7 % increase observed for Vandal. For Havoc, SD increased 10 % as planting date was delayed from Oct

21 to Nov 14 (Table 28). For Vandal, there was an initial decline in SD as planting date was delayed from Oct 21 to Nov 3, and then an increase as planting date was delayed further to Nov 14.

Effect of time and rate of N application on yield components

Spike density was only significantly affected by time and rate of N application at NPRS, increasing by 14 % with applications of spring-N at rates of 101 and 135 kg N ha^{-1} (Table 26). Kernel weight per spike and KNS were significantly affected by the 4-way interaction planting date x cultivar x fall-N x spring-N ($P<0.01$) (Table 22 and 27). When averaged across the effects of spring-N, Havoc planted on Oct 16 and receiving only spring-N produced greater KWS compared to split N applications. No statistical differences in KWS were observed on successive planting dates due to the addition of fall-N. For Vandal, treatments receiving fall-N produced greater KWS compared to spring only when planting was delayed to Nov 18. A similar pattern was observed for KNS for Havoc (Table 23 and 28). On average, spring-N application and split with fall N rate at 67 kg N ha^{-1} increased KNS by 4 kernels per spike compared to a split with fall-N rate equal to 34 kg N ha^{-1}. No statistical differences in KWS were observed on successive planting dates due to the addition of fall-N. For Vandal planted on Nov 4, KNS decreased as the rate of fall applied N increased. However, there was a decrease of 3 kernels per spike with only spring-N applications.

At PTRS, yield components were affected by both timing and rate of N application. The interaction fall x spring-N significantly affected KWS (Table 29). When averaged across cultivar and planting date the lowest KWS was obtained from the treatment receiving 169 kg N ha^{-1} in three splits ($67_{F} + 51_{LW} + 51_{ES}$), and the highest from application of 134 kg N ha^{-1} in two splits ($67_{F} + 67_{LW} + 0_{ES}$) (Table 32).

A three way significant interaction of cultivar x planting date x fall-N was observed for both KNS and SD. Kernel number spike^{-1} decreased as planting date was delayed for both cultivars (Table 30). Major differences were only observed for Vandal planted on Oct 17 where increased spring-N rates led KNS to decline. For SD, Havoc had an increase of 20% at the latest planting date of Nov 13 with the addition of fall-N (Table 31). At RWRS, analysis of variance indicated that time and rate of N application did not significantly affect any of the GY components evaluated.

Linear regression for yield components

Analysis of covariance showed that SD explained the greatest amount of the variation in total yield at all locations, with a positive relationship between the two traits. At NPRS, there was significant effect of planting dates and the interactions planting date x cultivar and planting date x fall-N on grain yield when controlling for SD with $R^2= 0.81$ ($P<.0001$) (Table 32; Fig. 13; Fig. 14). At PTRS, there was a significant effect of planting date and the interaction planting date x cultivar on grain yield when controlling for SD with $R^2 = 0.84$ ($P<.0001$) (Table 33; Fig. 15a and b). At RWRS, there was also significant effect of planting date and the interaction planting date x cultivar on grain yield when controlling for SD with $R^2 = 0.80$ ($P<.0001$) (Table 34; Fig 15c and d).

Table 20. Analysis of variance for yield components kernel weight per spike (KWS), kernel number per spike (KNS), and spike density (SD) for SRWW grown at Newport (NPRS), Pine Tree (PTRS), and Rohwer (RWRS).

		NPRS			PTRS			RWRS		
Source of Variation	df	KWS	KNS	SD	KWS	KNS	SD	KWS	KNS	SD
		------------------------------------- Pr > F -------------------------------------								
Planting Date	2	0.0279	0.4595	0.0026	<.0001	<.0001	0.4395	0.0222	0.0002	<.0001
Cultivar	1	0.9659	0.1364	0.2276	0.9300	0.9106	0.1442	<.0001	0.0028	0.0855
Fall-N	2	0.5133	0.2592	0.2212	0.5121	0.6896	0.2852	0.6208	0.3342	0.1523
Spring-N	3	0.5614	0.1043	<.0001	0.3063	0.1403	0.5245	0.0235	0.4850	0.2300
Cultivar x Planting Date	2	<.0001	0.0009	0.0002	0.0041	0.2197	<.0001	<.0001	<.0001	<.0001
Planting Date x Fall-N	4	0.0021	0.0203	0.4204	0.9492	0.802	0.2531	0.5663	0.5903	0.5892
Planting Date x Spring-N	6	0.0011	0.8268	0.5556	0.6726	0.0005	0.4124	0.6144	0.6216	0.8019
Cultivar x Fall-N	2	0.0976	0.0369	0.5593	0.9248	0.2832	0.0074	0.3123	0.551	0.8799
Cultivar x Spring-N	3	0.0700	0.0448	0.0822	0.8300	0.9787	0.8706	0.7436	0.2651	0.1857
Fall-N x Spring-N	4	0.0884	0.7249	0.2495	<.0001	0.5804	0.0563	0.9723	0.3383	0.2473
Planting Date x Fall-N x Spring-N	8	0.7300	0.5153	0.9897	0.9863	0.1585	0.9468	0.8294	0.7887	0.7649
Planting Date x Cultivar x Fall-N	4	0.1386	0.0557	0.6364	0.7657	0.0352	0.0008	0.4925	0.3248	0.2962
Planting Date x Cultivar x Spring-N	6	0.4838	0.2965	0.4062	0.9523	0.4157	0.4394	0.9769	0.4542	0.4023
Cultivar x Fall-N x Spring-N	4	0.0716	0.1437	0.1694	0.9845	0.7739	0.8752	0.4166	0.4334	0.7148
Planting Date x Cultivar x Fall-N x Spring-N	8	0.0049	0.0034	0.7257	0.9946	0.7507	0.5317	0.5532	0.9446	0.9641

Table 21. Spike density (spikes m^{-2}) for wheat cultivars Havoc and Vandal as influenced by planting date at NPRS.

Planting date	Havoc	Vandal
Oct. 16th	358	390
Nov. 4th	287	295
Nov. 18th	330	286

LSD to compare means in the same cultivar and different planting date = 41 spike m^{-2}
LSD to compare means in different cultivars and the same planting date = 27 spike m^{-2}
LSD to compare means in different cultivars and the different planting date = 39 spike m^{-2}

Table 22. Kernel weight per spike as influenced by planting date, cultivar, fall-N and spring-N planted at NPRS.

N treatment				Havoc			Vandal		
Total N	F	LW	ES	Oct.16th	Nov. 4th	Nov. 18th	Oct.16th	Nov. 4th	Nov. 18th
kg ha^{-1}				g			g		
169	0	84	84	1.10	1.50	1.23	1.25	1.23	1.45
67	0	67	0	1.35	1.45	1.15	1.43	1.23	1.28
101	0	51	51	1.13	1.58	1.25	1.38	1.18	1.30
135	0	67	67	1.38	1.55	1.20	1.28	1.40	1.28
101	34	67	0	1.15	1.50	1.23	1.35	1.34	1.25
135	34	51	51	1.13	1.45	1.08	1.33	1.33	1.55
169	34	67	67	1.13	1.63	1.28	1.28	1.18	1.35
135	67	67	0	1.28	1.38	1.20	1.23	1.28	1.35
169	67	51	51	1.28	1.53	1.33	1.20	1.33	1.45
202	67	67	67	1.10	1.53	1.23	1.13	1.18	1.38
Means				1.20	1.51	1.22	1.27	1.27	1.36

LSD to compare means in the same cultivar and same planting date = 0.17 g
LSD to compare means in the same cultivar and different planting date = 0.19 g
LSD to compare means of different cultivars and same planting date = 0.18 g
LSD to compare means of different cultivars and different planting date = 0.2 g

Table 23. Kernel number per spike (KNS) of winter wheat as influenced by planting date, cultivar, fall-N and spring-N planted at NPRS.

N treatment				Havoc			Vandal		
Total N	F	LW	ES	Oct.16th	Nov. 4th	Nov. 18th	Oct.16th	Nov. 4th	Nov. 18th
---------------- kg ha^{-1} ---------------				-------Kernel no $spike^{-1}$---------			----------Kernel no $spike^{-1}$----------		
169	0	84	84	37.1	35.6	35.4	36.2	36.1	34.7
67	0	67	0	39.1	34.6	33.2	35.6	34.9	33.3
101	0	51	51	39.8	36.8	36.1	36.2	33.7	33.7
135	0	67	67	42.5	37.5	35.1	35.1	37.1	33.7
101	34	67	0	36.1	36.7	35.6	35.7	36.8	35.0
135	34	51	51	39.1	37.2	29.0	36.7	36.9	40.6
169	34	67	67	35.7	39.7	39.3	36.8	34.6	35.7
135	67	67	0	40.9	34.7	33.9	32.8	37.6	36.4
169	67	51	51	38.8	39.1	37.9	34.2	38.2	37.5
202	67	67	67	39.3	38.8	37.1	33.5	35.7	36.5
Means				38.8	37.1	35.3	35.3	36.2	35.7

Means sharing the same lower case do not differ significant at LSD.

LSD to compare means in the same cultivar and same planting date = 4.2 g

LSD to compare means in the same cultivar and different planting date = 4.6 g

LSD to compare means of different cultivars and same planting date = 4.3 g

LSD to compare means of different cultivars and different planting date = 4.7 g

Table 24. Kernel weight per spike (KWS) of wheat as affected by planting dates and cultivars PTRS.

Planting Date	Cultivar	
	Havoc	Vandal
	------------------------------- g	-------------------------------
Oct. 17th	1.34	1.35
Nov. 2nd	1.13	1.19
Nov. 13th	1.27	1.19

LSD to compare means in the same cultivar and same planting date = 0.9 g
LSD to compare means in the same cultivar and different planting date = 0.9 g
LSD to compare means of different cultivars and same planting dates = 1.6 g
LSD to compare means of different cultivars and different planting dates = 1.5 g

Table 25. Kernel weight per spike, kernel number per spike and spike density as influenced by cultivar and planting date at RWRS.

	Havoc			Vandal		
Planting Date	Kernel weight spike^{-1}	Kernel no. spike^{-1}	Spikes m^{-2}	Kernel weight spike^{-1}	Kernel no. spike^{-1}	Spikes m^{-2}
Oct 21	0.76	24	460	1.13	28	438
Nov 3	1.00	31	469	1.16	30	399
Nov 14	0.93	29	510	1.16	30	455

LSD to compare KWS means in the same cultivar and different planting date = 0.05 g
LSD to compare KWS means in the different cultivar and same planting date = 0.08 g
LSD to compare KWS means in the different cultivar and different planting date = 0.08 g
LSD to compare KNS means in the same cultivar and different planting date = 1.3
LSD to compare KNS means in the different cultivar and same planting date = 2
LSD to compare KNS means in the different cultivar and different planting date = 2
LSD to compare SD means in the same cultivar and different planting date = 22 spikes m^{-2}
LSD to compare SD means in the different cultivar and same planting date = 38 spikes m^{-2}
LSD to compare SD means in the different cultivar and different planting date = 37 spikes m^{-2}

Table 26. Spike density as influenced by spring-N at NPRS.

Spring-N rate (kg ha^{-1})	Spike Density (spike m^{-2})
67	292
101	340
135	341

LSD = 23 spikes m^{-2}

Table 27. Orthogonal contrast for KWS averaged across spring-N shown in Table 22.

	Havoc			Vandal		
Planting Date	Oct 16	Nov 4	Nov 18	Oct 16	Nov 4	Nov 18
Fall$_{0N}$ x Fall$_{34N}$	**	ns	ns	ns	ns	Ns
Fall$_{0N}$ x Fall$_{67N}$	ns	ns	ns	**	ns	*
Fall$_{34N}$ x Fall$_{67N}$	ns	ns	ns	*	ns	Ns

*, ** Significant at the 0.1 and 0.01 probability levels, respectively.

Table 28. Orthogonal contrast for KNS averaged across spring-N shown in Table 23.

	Havoc			Vandal		
Planting Date	Oct 16	Nov 4	Nov 18	Oct 16	Nov 4	Nov 18
Fall$_{0N}$ x Fall$_{34N}$	**	ns	ns	ns	ns	**
Fall$_{0N}$ x Fall$_{67N}$	ns	ns	ns	ns	ns	*
Fall$_{34N}$ x	*	ns	ns	*	ns	ns

*, ** Significant at the 0.1 and 0.01 probability levels, respectively.

Table 29. Kernel weight per spike (KWS) as affected by fall and spring-N rates at PTRS.

N treatment				KWS
Total – N	F	LW	ES	
------ kg ha^{-1} -------				---- g ----
169	0	84	84	1.24
67	0	67	0	1.19
101	0	51	51	1.30
135	0	67	67	1.21
101	34	67	0	1.27
135	34	51	51	1.20
169	34	67	67	1.30
135	67	67	0	1.33
169	67	51	51	1.18
202	67	67	67	1.24

LSD = 0.07 g

Table 30. Kernel number per spike (KNS) of wheat as affected by planting dates, cultivar, and fall-N at PTRS.

Fall N treatment	Havoc			Vandal		
	Oct. 17	Nov 2	Nov 13	Oct. 17	Nov 2	Nov. 13
	---------- kernel no spike $^{-1}$----------			--------- kernel no spike $^{-1}$----------		
0	40	36	36	45	36	36
34	42	34	37	41	37	36
67	41	35	37	41	36	35
Mean	41	35	37	42	36	36

LSD to compare means in the same cultivar and same planting date = 2.9
LSD to compare means in different cultivars and the same planting date = 4.2
LSD to compare means in same cultivars and different planting date = 2.8
LSD to compare means in different cultivars and different planting date = 4.1

Table 31. Spike density of wheat as affected by planting date, cultivar, and fall-N at PTRS.

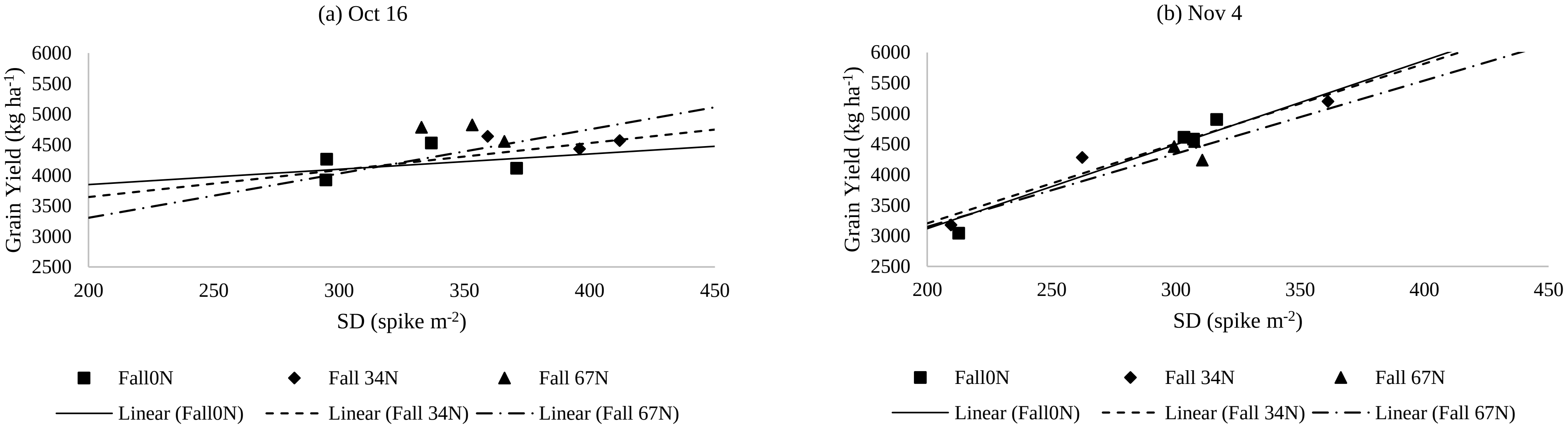
Fall N treatment	Havoc			Vandal		
	Oct 17	Nov 2	Nov 13	Oct 17	Nov 2	Nov 13
	--------------spikes m^{-2}-------------			-------------spikes m^{-2}-----------		
0	396	432	343	489	415	466
34	373	443	431	523	409	431
67	370	452	429	471	389	427
Mean	380	442	401	494	404	441

LSD to compare means in the same cultivar and same planting date = 41 spike m^{-2}

LSD to compare means in different cultivars and the same planting date = 62 spike m^{-2}

LSD to compare means in same cultivars and different planting date = 50 spike m^{-2}

LSD to compare means in different cultivars and different planting date = 66 spike m^{-2}


(a) Oct 16

(b) Nov 4

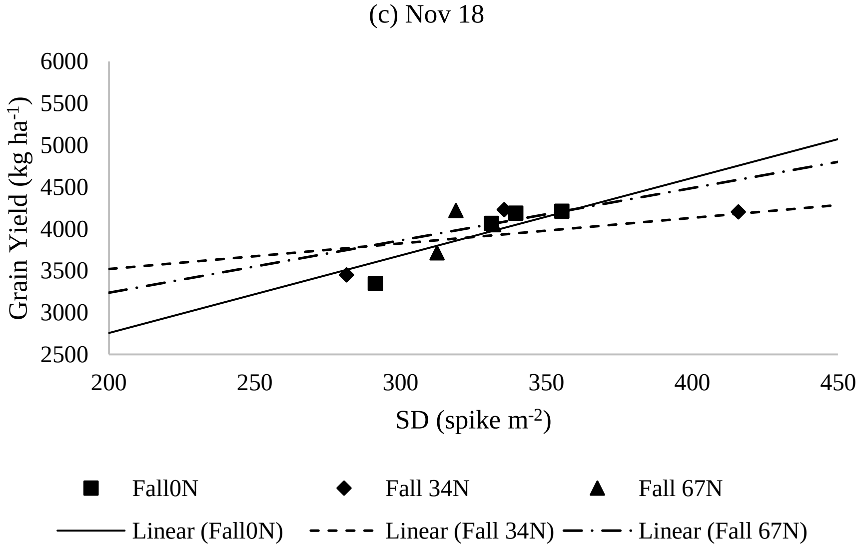
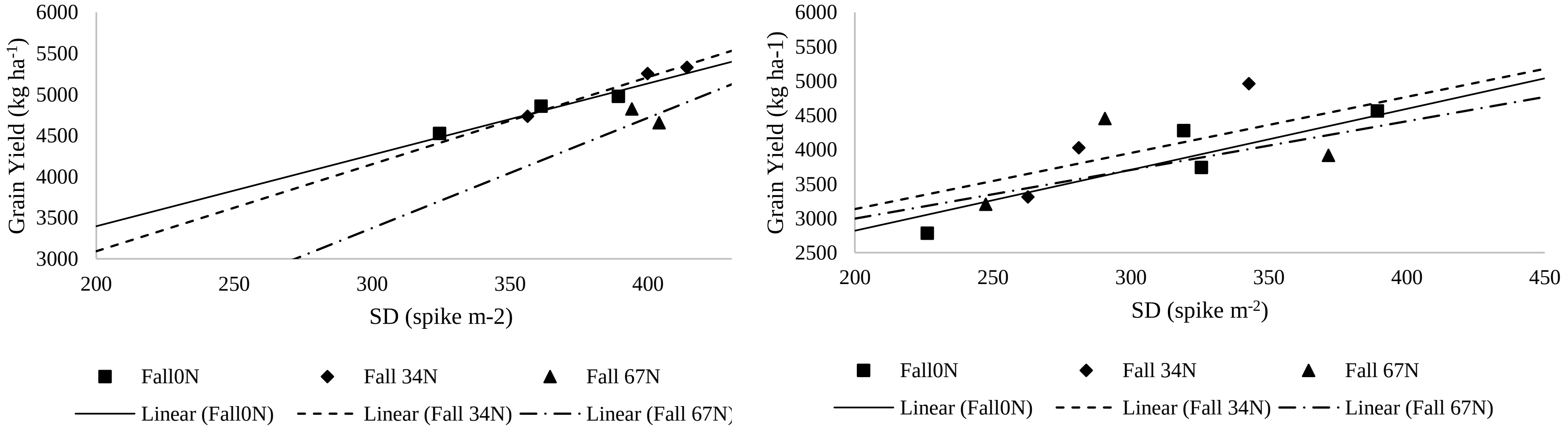

(c) Nov 18

Figure 14. Grain yield response to fall-N rates as a function of spike density (SD) for Havoc wheat planted on (a) Oct 16, (b) Nov 4 and (c) Nov 18 at NPRS.


(a) Oct 16

(b) Nov 4

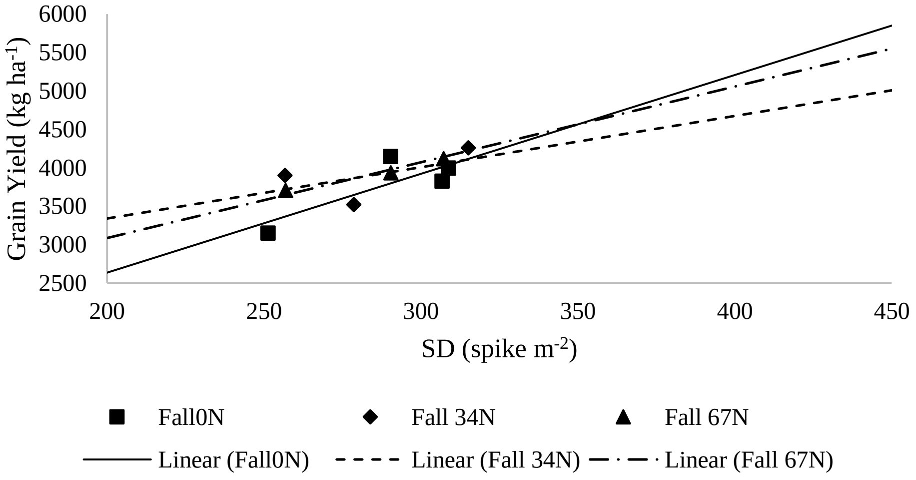

(c) Nov 18

Figure 15. Grain yield response to fall-N rates as a function of spike density (SD) for Vandal wheat planted on (a) Oct 16, (b) Nov 4, (c) and Nov 18 at NPRS.

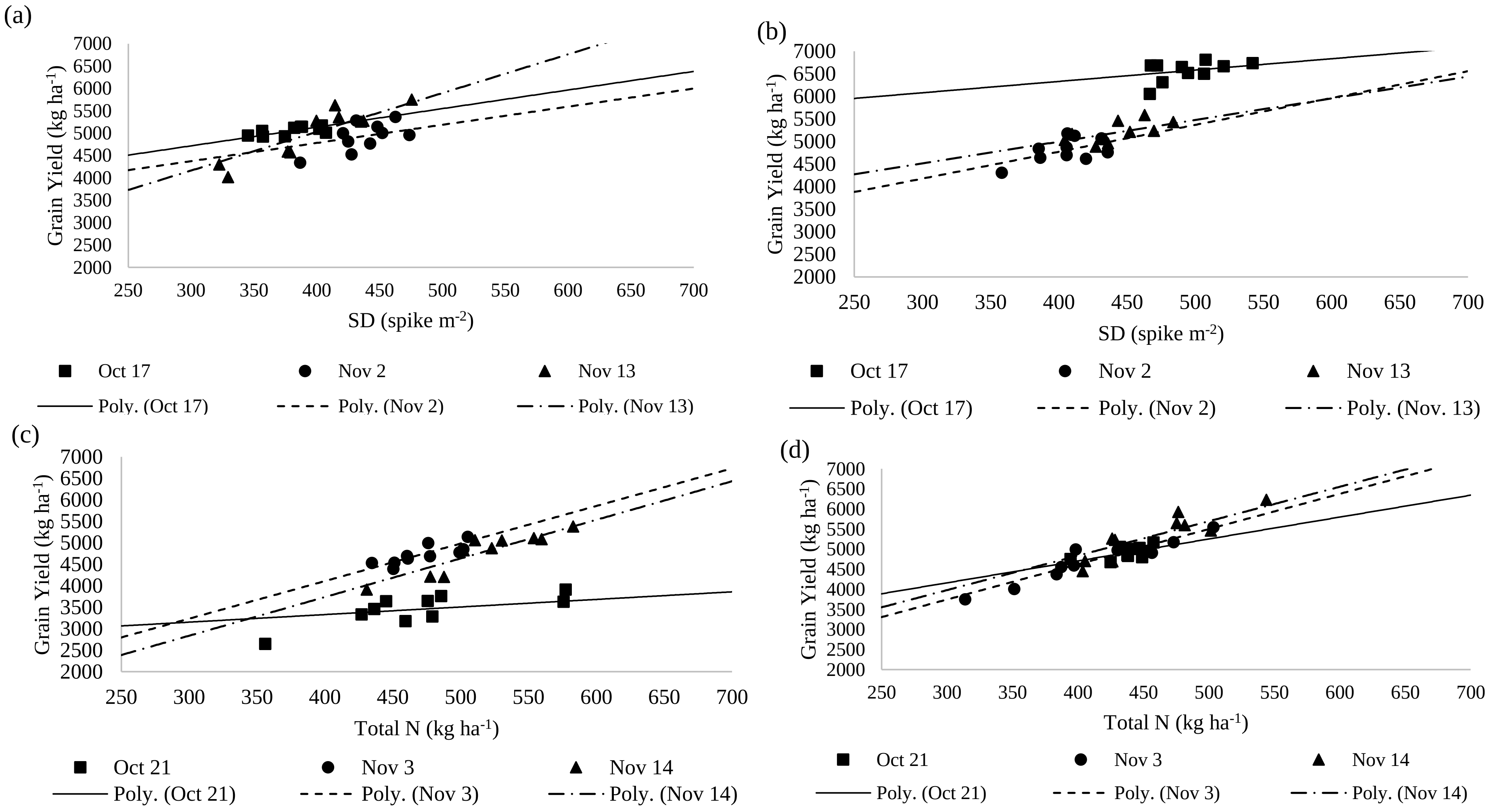


Figure 16. Grain yield of (a) Havoc and (b) Vandal as a function of spike density (SD) and affected by planting dates at PTRS. Grain yield of (c) Havoc and (d) Vandal as a function of SD and affected by planting dates at RWRS.

Table 32. Regression equations, slope significance and slope contrast for spike density (SD) as affected by planting dates and cultivars at NPRS.

Planting Date	Fall N kg ha^{-1}	Havoc			Vandal		
		Equation	SE Estimate	SE slope	Equation	SE Estimate	SE Slope
Oct 16	0	3344 + 2.51025x^{ns}	480	1.366184	1663 + 8.68533x	547	1.420826
	34	2761 + 4.41812x	774	1.89852	975 + 10.59319x	715	1.812037
	67	1856 + 7.23683x	687	1.730022	-648 + 13.41191x	758	1.774049
Nov 4	0	365 + 13.75438x	387	1.316463	1045 + 8.87549x	313	0.947673
	34	592 + 13.05223x	383	1.320873	1500 + 8.17334x	472	1.381061
	67	750 + 11.96994x	433	1.370268	1578 + 7.09105x	268	0.770843
Nov 18	0	909 + 9.24529x	794	2.392593	62 + 12.86181x	661	2.260707
	34	2910 + 3.05503x	414	1.159738	2005 + 6.67155x	637	2.214698
	67	1990 + 6.24309x	668	2.050814	1113 + 9.85961x	674	2.334019

ns Slope not statistically different from zero.

SE Standard error

Table 33. Regression equations, slope significance and slope contrast for spike density (SD) as affected by planting date, cultivar and fall-N at PTRS.

	Havoc			Vandal		
Planting Date	Equation	SE Estimate	SE slope	Equation	SE Estimate	SE Slope
Oct 17	3470 + 4.1579x	515	1.2898	5327 + 2.5152x	446	0.8941
Nov 2	3159 + 4.0548x	543	1.2729	2394 + 5.9514x	542	1.3081
Nov 13	1567+ 8.6577x	389	1.0767	3075 + 4.8040x	516	1.1007

Table 34. Regression equations, slope significance and slope contrast for spike density (SD) as affected by planting date, cultivar and fall-N at RWRS.

Planting Date	Havoc			Vandal		
	Equation	SE Estimate	SE slope	Equation	SE Estimate	SE Slope
Oct 21	2626 + 1.7631x	302	0.6297	2524 + 5.4564x	569	1.2942
Nov 3	614 + 8.7409x	677	1.4340	1114 + 8.7706x	442	1.0728
Nov. 14	145 + 8.9833x	557	1.0787	1406 + 8.5782x	550	1.1994

Discussion

The agro climatic factor plays a decisive role in the responsiveness of GY to rate and time of N application. Researchers have long recognized the importance of environmental factors, particularly rainfall in determining the effectiveness of split N applications. Results obtained by Welch et al. (1966), Gravelle et al. (1988), Zebarth and Sheard (1992) and Sowers et al. (1994) suggested GY response of winter wheat to time of N application to be mostly dependent on the weather for a particular season. Planting date is important for N management for winter wheat as it dramatically changes environmental parameters such as temperature and moisture during crop growth, and ultimately GY and fertilizer efficiency. The physiological development of winter wheat is primarily driven by the accumulation of heat units (°C day-hour) as opposed to calendar days (Li et al., 2012; Tayebi et al., 2010). Taruna et al. (2013) showed that winter wheat is exposed to different thermal regimes during the vegetative and reproductive phases when sown at different dates. For late planting dates, the authors reported a negative relationship between the duration of these phases and mean temperature mainly for the reproductive phase. For example, the days required for wheat to reach maturity decreased by 25 days or 3061 photo thermal units (°C day-hour) as planting date was delayed from Nov 5 to Dec 20. In Arkansas, high precipitation in the fall often forces farmers to delay planting date affecting the time allocated for the crop to grow and develop prior to the arrival of winter temperatures, which in turn provides less opportunity for heat units and biomass to accumulate. Therefore, synchronized growth with optimum environmental conditions and adapted cultivars will result in a greater GY return of the applied-N.

At NPRS and PTRS, temperatures dropped quickly following planting as opposed to the gradual decrease observed at RWRS (Table 2). Precipitation amounts were higher at RWRS and

NPRS compared to PTRS (Fig. 1). At NPRS, GY of both cultivars decreased as planting date was delayed from Oct 16 to Nov 18, but for Vandal the magnitude of GY loss was twice that of Havoc. At PTRS, only Vandal showed a yield decrease as planting date was delayed. Mid-maturity cultivars including Havoc break winter dormancy sooner, which can accelerate growth and the risk of frost injury if planted earlier than optimum. Late maturity cultivars including Vandal benefit from early planting dates by avoiding the risk of exposure of reproductive organs to high temperature stress during the summer. Based on the recommended planting dates by the University of Arkansas, planting dates were later than optimum at NPRS and PTRS, which could explain why Vandal, a full season cultivar which matures later than Havoc, was negatively impacted. Although planting dates at RWRS (Oct 21, Nov 3, and Nov 14) were within the range of optimum planting dates, the Oct 21 may be too early for Havoc as it showed a significant reduction in GY at the earliest date and greater than that of Vandal. In addition, Havoc planted on Oct 21 was particularly vulnerable to low N input, with the treatment receiving only a full dose of 67 kg N ha^{-1} in the late winter yielding an average of 40% less than other all other N combinations planted on Oct 21. Havoc may have not been able to take up balanced amounts of N when required, as opposed to split applications that improved the synchrony of N supply and demand.

It was hypothesized that fall N application could compensate for GY reduction resulting from a delayed planting date. At NPRS, there were no statistical yield differences among rate and time of N application even though Vandal had a GY reduction of more than 1000 kg ha^{-1} as planting date was delayed from Oct 16 to Nov 18. These results suggest that both spring N and split N application were able of maximize GY at NPRS. Soil total N at NPRS was greater (1241 mg N kg^{-1}) compared to PTRS (1023 mg N kg^{-1}) and RWRS (996 mg N kg^{-1}), which could explain the low response to split N applications compared to spring applications (Table 3). These results are in agreement with Kelley (1995) and Vaughan et al. (1990) who reported lower GY response to fertilizer-N for winter wheat grown in soils with high residual NO_3^- levels. These results are also in line with the findings of Vaughan et al. (1990) who found that 9 out of 19 site-years did not respond to either fall or spring-N in years of low precipitation and high residual NO_3^- in the soil. However, 10 out of 19 site-years significantly responded to both fall and spring-N in soil textures ranging from clay loams to loamy sands in Colorado when sufficient precipitation occurred to promote N loss. Although fall N was required for some site-years, spring applied N required 20% less N fertilizer to achieve the same grain yield as fall applied-N. However, this study did not evaluate the effect of split N applications.

Splitting N between fall and spring was required to maximize GY of Havoc planted on the latest date at PTRS. Conversely, split applications with fall-N rates of 67 kg N ha^{-1}, which resulted in total N rates from 135 to 202 kg N ha^{-1}, resulted in GY reductions for Vandal planted on Oct 17 of 217 and 387 kg ha^{-1} compared to spring and split applications, respectively. High rates of N application can lead to economic loss to farmers due to both a higher expenditure with fertilizer and a potential yield loss due to excessive growth. Moreover, plants with excessive growth are more susceptible to disease infection and winter-kill. Wang et al. (2011) reported GY decreases with N rates greater than 240 kg N ha^{-1}. They also showed that excessive N rates increased N accumulation in deeper soil layers, a potential for environmental contamination.

At RWRS, fall-N was required to maximize yield for Havoc planted on Oct 21 and Nov 13, and Vandal planted on Nov 3 and Nov 14. A combination of high monthly temperature and rainfall and lower residual soil NO_3^- may have contributed to GY response to split N applications. Nitrogen losses from the field by leaching and denitrification are favored by high precipitation and temperature, which could have affected plants growing without fall applied-N. Results from response surface analysis showed that the response to fall-N increased while the response to spring-N decreased as planting date was delayed for both cultivars (Fig. 12). This result supports our hypothesis suggesting that the requirement for fall-N increases as planting was delayed. In some plant date-cultivar trials, GY response to spring applied-N was inversely proportional to fall-N, suggesting a balancing effect of application time for GY response.

Currently, the University of the Arkansas System Division of Agriculture recommends fall applied-N for late planting dates and when following flooded-rice (Roberts and Slaton, 2014). However, our results suggest that even within the range of optimum planting dates at RWRS fall applied-N may have the potential to increase GY and a fall application should be considered in some cases. These results do not agree with those found by Slaton et al. (2004), who reported that fall applied-N was not needed to maximize GY of winter wheat even if following high carbon to nitrogen ratio crops. However, the authors did not evaluate the effect of planting dates, which is an important determinant for response to rate and time of N application.

The prediction of the optimum N rate and application time for RWRS was above those recommended by Sabbe (1978), who suggested a rate of 80 to 101 kg N ha^{-1} applied only in the late-winter for wheat to achieve 90 to 95% of relative GY. Allocating all N to be applied at late winter in soils where split and spring-N have similar GY potential is more advantageous than splits considering only one pass over the field is needed, which reduces the cost of application. On the contrary, applying all N at once where N is likely to be lost from the field through processes including leaching, volatilization and denitrification reduces crop N use efficiency.

Spike density is associated with the number of tillers formed prior do dormancy, which would be influenced by fall-N applications. Results by Slaton et al. (2004), who evaluated the effects of fall, spring, and split-N application in Arkansas reported increased tillering with fall-N application. Our study showed SD to explain the greatest amount of variation in total GY and was influenced by rate and time of N application at PTRS where fall N increased SD for Havoc planted on Nov 3. These results are supported by the findings of Kenarsari et al. (2014) and Rutkowska et al. (2008) who reported split N applications between Feekes 2-3 and 10 to increase the number of tiller m^{-2} since most tiller production occurs in the fall. Gravelle et al. (1988) reported increased tillering with a single N application at Feekes growth stage 2-3 compared to splits between Feekes 2-3, 10, and 10.5. A single application of 134 kg N ha^{-1} at Feekes 2-3 led to increased lodging, which ultimately resulted in GY losses. Conversely, the yield components KWS and KNS are determined later in the season and were affected by the rate and time of N application at NPRS and PTRS.

Conclusion

Soft red winter wheat production in eastern Arkansas is subjected to year-to-year fluctuations, which effect fertilizer-N management. In this study, split N application between fall and spring was shown to have the potential to increase GY when wheat is planted later than optimum and grown in silt loam soils (RWRS). Overall, N is prone to loss in such conditions of high precipitation and thus split N fertilizer application could be advantageous. Further replication of this study over years is encouraged to account for stochastic yearly weather events that influence wheat performance and response to N.

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