MANAGEMENT PRACTICES FOR IMPROVED WINTER SURVIVAL OF WINTER WHEAT IN NORTH DAKOTA

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Management Practices for Improved Winter Survival

of Winter Wheat in North Dakota

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ABSTRACT

Hard red winter wheat (winter wheat, *Triticum aestivum* L.) production has been historically low in ND due to cold winter temperatures resulting in winter injury and stand loss. The objective of this research was to determine if management practices could improve winter survival and yield of winter wheat. Field experiments were conducted at five locations. Due to high winter snowfall, there was little difference in snow depth and winter survival between previous crop residues. Planting at the recommended date always resulted in the highest winter survival compared to planting late. At Hettinger, soil temperatures reached nearly -15°C, and as a result, the less-hardy cultivar Hawken had only 50% winter survival. Differences in fertility treatment were not consistent across location during this study. ND soils are inherently high in P and K, so it is likely the high soil nutrient levels masked any potential benefit to seed-applied P and K.

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INTRODUCTION

North Dakota has one of the strongest economies in the country thanks in part to its strong and diverse agricultural sector. In 2010, ND ranked first in the production of eleven different commodities, including all types of wheat (NASS, 2011a). However, winter wheat planted area has historically been low compared to HRSW, with ND contributing only 1% of the total winter wheat production in the United States. Winter wheat area in ND has varied considerably during the last decade, from 32,000 to 255,000 planted ha (NASS, 2011b). Despite the low planted area, winter wheat provides many benefits over HRSW, such as: higher yield potential, lower inputs costs, reduced labor congestion because planting and harvesting occur during periods with fewer conflicting activities, reduced wind and water erosion of top soil, and provided cover for wildlife during key nesting periods of the season (Wiersma and Ransom, 2005).

According to NASS (2011c), winter wheat in ND had higher yield than HRSW in 2009 (3228 vs. 3094 kg ha^{-1}, respectively). Winter wheat provided an even greater yield advantage of 740 kg ha^{-1} over HRSW in 2010, yielding 3699 compared to 2959 kg ha^{-1}, respectively. Furthermore, winter wheat has out yielded HRSW every year from 2001-2010, averaging 2946 kg ha^{-1} compared to 2502 kg ha^{-1} for HRSW. In 2009 and 2010, winter wheat yields in ND out-paced the national winter wheat yield average of 2973 and 3147 kg ha^{-1}, respectively. Despite consistently higher yields than HRSW and above average US yields, winter wheat still fails to compete with HRSW for planted area in ND.

The biggest constraint to winter wheat production in ND is winter injury (winter kill). Unlike HRSW, which is planted and harvested in the same growing season, winter wheat is planted in the fall, overwinters, and matures during the following growing season.

For winter wheat to survive the winter (defined as the time period 21 Dec through 19 March), the crown region of the plant, located below the soil surface, must be protected from injurious temperatures that can kill the plant. Recommendations for protecting the crown from injury include: choosing a cultivar with good winter hardiness, planting into previous crop residue that can help retain snow during the overwintering season, and planting at the recommended date (Peel et al., 1997). However, even if these recommendations are followed, there is no guarantee winter injury will be avoided.

Winter injury can be a problem throughout ND, but it is especially problematic in western and central ND where colder temperatures and reduced snowfall typically occur. Yet, winter wheat is still grown in these areas and the extent of winter injury is variable from year to year. Furthermore, the recent increase in the cultivation of later-maturing crops is creating another challenge for winter wheat in ND. Since 1996, the soybean planted area in ND has quadrupled, and is poised to continue to rise and spread throughout the state (NASS, 2011a). Planting winter wheat following soybeans is problematic because most cultivars grown in ND are not harvested until after the optimal planting date for winter wheat has past, leading to a delayed planting (Wiersma et al., 2006). Additionally, soybean residue provides minimal stubble for snow catch.

To help reduce yearly variation in winter injury, it is beneficial to re-examining current management practices related to winter wheat planting date, cultivar selection and previous crop residue for snow catch. Additionally, new management practices should be explored, such as applying phosphorus or potassium fertilizer with the seed when planting is delayed, or when adequate snow-catching residue is absent, or winter-hardy cultivars are unavailable.

RESEARCH OBJECTIVES

The objectives of this research were to determine the differences in winter survival, yield, vigor, test weight, thousand-kernel weight, protein, spike count, and fall stand count of winter wheat based on i) planting date, ii) previous crop stubble, iii) cultivar, iv) subsurface drainage, and v) P and K placed with the seed. This research will be used to determine if management methods can improve winter survival and the other grain quality characteristics of winter wheat previously mentioned when planting is delayed or when it is planted into limited previous crop residue that provides minimal potential for snow catch.

LITERATURE REVIEW

Winter injury frequently causes serious stand and yield losses in winter wheat sown in regions like ND that have severe sub-freezing winter temperatures. Winter wheat cultivars vary in their degree of winter hardiness, with more cold tolerant cultivars typically capable of surviving lower winter temperatures for longer periods of time than less cold tolerant cultivars. While the winter hardiness of a cultivar is genetically controlled, management practices (i.e., planting date and previous crop residue) can also influence winter survival (Peel et al., 1997).

Winter Survival

Winter wheat requires a period of cold temperatures to undergo a transition of the apical meristem from vegetative to reproductive growth (Michaels and Amasino, 2000). This irreversible, prolonged exposure to cold temperatures is known as vernalization and is a useful adaption allowing plants that are planted in the fall to flower in the spring or summer. Vernalization temperatures generally range from 1 to 7°C, with some cereals being vernalized at temperatures as low as -6°C. Trione and Metzger (1970) conducted experiments with winter wheat at various temperature gradients and found 7°C during late winter or early spring to provide the maximum effectiveness for vernalization.

Vernalization of winter wheat is a slow physiological process requiring prolonged cool temperatures to be completed (Trione and Metzger, 1970). The length of time required to complete this process is cultivar dependent, but typically ranges from 2 to 10 weeks. On average, ND records air temperatures at or below 0°C on about 180 to 210 days per year (USGS, 2006). While the climate in ND provides ample days for vernalization of winter wheat, extreme sub-zero temperatures can negatively affect winter wheat’s ability to survive the cold winter months. Historically, North Dakota measures 35 to 65 days per year with air temperatures at or below -18°C, depending on geographical location.

For winter wheat to survive the winter, the crown of the plant must go through a hardening process in order to tolerate below-zero temperatures. One method to evaluate winter survival is to determine the minimum soil temperature at which winter wheat can survive. Wiersma and Ransom (2005) suggest well developed winter wheat seedlings that have properly hardened are capable of surviving soil temperatures as low at -15°C at the crown depth; however, that number will vary based on the cultivar. An LT_{50} value (defined as the temperature at which 50% of the plants die due to freezing injury) is another method used to express winter hardiness of a cultivar (Skinner and Garland-Campbell, 2008). Under controlled conditions, Skinner and Garland-Campbell found the average LT_{50} value of 26 winter wheat cultivars to be -15.1°C. Consequently, -15°C is a reasonable estimate for the soil temperature threshold for winter wheat survival.

Survival of the crown does not always ensure survival of the plant. Chen et al. (1983) found roots to be less winter hardy than the crown under a controlled environment, with roots killed at temperatures below -8°C. When favorable conditions returned, they found new roots were produced. Therefore, when winter temperatures exceed -8°C, the ability of winter wheat plants to resume growth and survive may be limited by the regrowth of new roots.

Soil has a high capacity to buffer changes in air temperature, but extreme winter temperatures in ND make some sort of additional insulation necessary to prevent winter injury in most years as the air temperature falls below the minimum required for survival. In winter wheat, the crown is located 3 cm or less below the soil's surface going into the winter months, and therefore is susceptible to colder temperatures when insulation is lacking.

Thickness of snow cover has been found to have a direct effect on its insulating ability to buffer the soil temperature. Aase and Siddoway (1979) found the soil temperature at a 3-cm depth on bare soil with no snow dropped below -16°C when the air temperature was below -22°C. However, when 6 to 7 cm of snow cover was present, the soil temperature at the 3-cm soil depth stayed above -16°C even when the air temperature dropped below -35°C. Furthermore, Worzella and Cutler (1941) measured soil temperature at 1-cm depth. They found in January, when 10-12 cm of snow cover was present, the air temperature declined to -29°C while the soil temperature remained near -5°C. Aase and Siddoway (1979) concluded from their research that approximately 7 cm of snow is sufficient to protect winter wheat from dying if air temperatures occasionally reach -40°C, provided plants are properly hardened and ice crusts are not present.

The primary way to influence the amount of snow cover is trapping snow by retaining standing previous crop residue (stubble). By carefully managing crop residue and rotations, winter injury can be reduced to levels that permit the production of a profitable winter annual crop. Bauer and Black (1990) found significantly greater post-winter plant populations of winter wheat with increased stubble height of the previous harvested crop. Averaged over all tested winter wheat cultivars, the lowest stubble height (0 cm) resulted consistently in lower plant populations, with as high as 100% loss to winter injury occurring in some years. Conversely, the highest stubble heights (20 and 36 cm) almost always resulted in the highest post-winter plant population.

The ability of snow cover to buffer soil temperature is evident when contrasting minimal soil temperatures under snow cover with various stubble heights. Minimum two-hour soil temperatures were recorded under four stubble heights (0, 5, 20 and 36 cm) at Mandan, ND over four winters from 1982-1986 (Bauer and Black, 1990). They reported yearly minimum soil temperature differences between the 0 cm and 36 cm stubble heights for the winters of 1982-83 through 1985-86 of 6.8, 13.8, 9.7 and 9.9°C, respectively. During three out of four winters, 5 cm of stubble was sufficient to collect snow and keep the soil 2°C warmer on average than no stubble.

Phosphorus

Phosphorus is an essential nutrient for plant growth and is crucial in energy storage and transfer in plants (Havlin et al., 2005). Energy captured during photosynthesis is stored in phosphate compounds and are later released for growth and reproductive processes. In cereal crops, P is known to increase root growth and tillering (Fageria, 2009). It has been hypothesized that placing P with the seed makes it readily available to the developing roots and results in a healthier plant (Sander and Eghball, 1999).

Knapp and Knapp (1978) reported many benefits to fall P fertilizer banded between the rows. The addition of P produced a significantly greater number of spikes m^{-2}. Their work also showed significant yield increases in 1976 and 1977, averaging 520 and 871 kg ha^{-1}, respectively, in P treatments. Greater winter survival was observed in wheat receiving P compared to treatments receiving none. Additionally, a yield increase of up to 60% has been reported in winter wheat with fall P fertilization compared with no P applied in the fall (Sweeney et al., 2000), while others have reported only a 20% yield increase (Sander and Eghball, 1999).

Field experiments with soft white winter wheat in WA reported favorable yield responses with P fertilization in the fall for a late planted crop. Lutcher et al. (2010) banded P fertilizer at three application rates (0, 5, and 15 kg P_2O_5 ha^{-1}) 5 cm below and 2.5 cm beside the seed. Compared to the control, overall grain yield was increased 4.4% and 7.6% at the 5 and 15 kg ha^{-1} rates, respectively. The addition of P fertilizer improved grain yield at six sites, with initial P soil test level of <12 mg kg^{-1} reported at four of the locations. Responses to P fertilizer on soils with >12 mg kg^{-1} of available P were limited to soils where root injury from soil-borne pathogens is typically problematic. Overall, their research indicates a consistent grain yield response on soils with initial P soil tests of <12 mg kg^{-1}.

In comparing methods of P application, Sander and Eghball (1999) found seed-applied liquid ammonium polyphosphate to be superior to knife applied P 15 cm deep one week prior to planting. Higher P uptake resulted when P was seed applied compared with knifing, with 21.3 and 20.3 kg ha^{-1} of total P taken up, respectively. Furthermore, seed-applied P produced on average 35 additional stems m^{-2} and 38 spikes m^{-2}.

Winter barley (*Hordeum vulgare* L.) has also been studied to determine the effectiveness of fall-applied P. Knapp and Knapp (1980) banded N and P at sowing time in treatment combinations of 0 and 22 kg N ha^{-1} and 0 and 22 kg P_2O_5 ha^{-1}. Spring observations of plots receiving P had a higher surviving plant stand than those receiving none. Barley yields responded positively to P fertilization both years, with an average increase of 370 and 1200 kg ha^{-1}, respectively. In addition, consistently higher yields were noted over two years when winter wheat was sown with 11, 22 or 34 kg P_2O_5 ha^{-1} (Sander and Eghball, 1999). Yield increases with fall-applied P at seeding ranged from 214 kg ha^{-1}

in 1987 to 645 kg ha^{-1} in 1988, with an average yearly increase of 403 and 550 kg ha^{-1}, respectively.

Phosphorus efficiency and grain yield can also be influenced by pH. Fiedler et al. (1989) recorded increased grain yields of up to 500 kg ha^{-1} in seed-placed P over broadcast P at low soil P levels, but the advantage of seed placed P became less pronounced as soil pH increased from 6.0 to 8.0 and soil test P increased. McConnell and colleagues (1986) reported increased grain yields at all locations with P additions. Yield increases ranged from 9% to 103% and 5% to 99% in the first and second years, respectively; however, most grain yield increase was the result of P fertilization as an essential plant nutrient for growth and not winter survival per se. This information outlines the advantages of P for increasing grain yield, but also suggests that pH and soil test P could both be potential factors that influence the effectiveness of applying P to winter wheat and increasing winter survival.

Potassium

Potassium is also an important nutrient in plants and ranks second in absorption by plants behind N (Havlin et al., 2005). It has many vital roles in crop plants including root growth, water and nutrient uptake, maintenance of turgor, and regulation of CO_2 absorption through leaf stomates (Fageria, 2009). Potassium is relatively immobile in the soil and must be placed close to the root system for maximum efficiency. Potassium deficiencies in plants lead to slow growth, poor root development and greater susceptibility to lodging.

Tennant (1976) found an increase in the total number of roots formed with increasing amounts of K, but only up to the standard application rate. Applications of K more than 156 kg ha^{-1} suppressed root production. When potassium was deficient, root formation was also affected. Tennant's work found that after 10 days of potassium deficiency, the deficient root system had three to five seminal roots compared with five to six for non-deficient treatments.

Webster and Ebdon (2005) found the interaction of K and N to be beneficial in cold tolerance of perennial ryegrass (*Lolium perenne* L.) in MA. The study found that low to moderate rates of N combined with annual rates between 245 and 441 kg K ha^{-1} provided maximum cold tolerance for perennial ryegrass. The lowest killing temperature of perennial ryegrass was -13.6°C and was achieved when 147 kg N ha^{-1} was applied with 245 kg K ha^{-1} yr^{-1}. While this study was conducted with a perennial crop, it still suggests K can be an important nutrient to maximize cold hardiness for plants capable of surviving cold winter temperatures. Information on K suggests that it is crucial to root formation, but application rates need to be closely monitored because excessive rates can suppress root formation. It also highlights the need for more research on potassium's role in winter survival and demonstrates the lack of research investigating its use in fall-sown crops like winter wheat.

Planting Date

Optimum planting dates for winter wheat vary by location. Planting too early in the season can diminish soil moisture reserves and increase the chances of diseases, such as wheat streak mosaic (*Potyviridae* virus) and barley yellow dwarf (*Luteovirus*) due to inadequate time for the green bridge to be broken (Peel et al., 1997). An early planting can also lead to excessive fall growth, which can reduce winter survival. Conversely, planting later than the recommended date can significantly impact grain yield and winter injury. Pittman and Andrews (1961) reported a marked decrease in yield in Alberta, Canada when planting before or after the recommended date. In their study, as little as a one-week difference in planting date produced large differences in winter survival. Similarly, intermediate-planting dates produced the highest yields compared to early and late plantings (Knapp and Knapp, 1978). Grain yield reductions of up to 15% or more in NE have been reported when the optimal planting date is not followed (Sander and Eghball, 1999). Furthermore, planting late can result in a reduction of up to 280 spikes m^{-2} (Blue et al., 1990).

When planting date is delayed, yield losses due to winter injury may be reduced by P fertilizer application. In a two-year study, Sander and Eghball (1999) found grain yields improved up to 20% with additions of P. Yield increases in P treatments resulted from increased number of spikes m^{-2}. Even at the optimal planting date, P applied with the seed provided superior yields. Blue et al. (1990) also reported beneficial results from P applied at a late planting. When no P was applied and planting date was delayed until the middle of October, grain yield was reduced by 34%. Conversely, grain yield was reduced only 5% with an application of 34 kg P ha^{-1} at the same planting date.

Immediate availability of P to the developing seedlings is thought to be the primary advantage of seed-placed P. Increasing the amount of available P in a delayed planting may enable a bigger, healthier root system to develop, which could make the developing seedling more winter hardy. Past research demonstrates the importance of root and plant development prior to winter and highlights the benefits of seed-placed P, even at optimal planting dates. While research is limiting, immediate availability of K when placed with the seed may also provide a similar advantage as P.

Subsurface Drainage

With above-normal amounts of precipitation in the Red River Valley beginning in the early 1990s, producers are searching for ways to remove excess moisture from their fields. Excessive precipitation creates saturated soils, thereby limiting crop root development and contributing to crop stress (Wright and Sands, 2001). Subsurface drainage is one tool for producers to partially manage excess soil moisture. By removing excess gravitational water from the soil profile and creating more air-filled pore spaces, subsurface drainage can lower the soil water table.

Additional research has shown other benefits of subsurface drainage. Wiersma et al. (2010) found soil temperatures in plots with subsurface drainage to be 3.5°C higher compared with the non-subsurface drained control, which could allow HRSW planting up to two weeks earlier than normal in the spring and more rapid germination. A slight increase in grain protein was detected for wheat and soybeans, although the grain yield of both neither improved nor diminished with subsurface drainage. Small visible differences were also reported in seedbed quality, with check plots being slightly wetter and having a poorer seedbed; however, the differences were never enough to delay seedbed preparation.

MATERIALS AND METHODS

Field experiments were conducted near Fargo, ND beginning in 2009 and near Fargo, Prosper, Lisbon, Hettinger and Williston, ND in 2010. From this point on, all locations will be referred to based on the harvested year (Fargo 2010 and Fargo, Prosper, Lisbon, Hettinger and Williston 2011). Table 1 lists the soil series, soil taxonomy and slope at each location.

Table 1. Soil series, taxonomy and slope at Fargo, Prosper, Lisbon, Hettinger and Williston, ND in 2010 and 2011.

Location	Soil Series†	Soil Taxonomy‡	Slope
			%
Fargo	Fargo–Ryan	Fine, smectitic, frigid Typic Epiaquerts	0-1
		Fine, smectitic, frigid Typic Natraquerts	
Prosper	Bearden–Lindaas	Fine-silty, mixed, superactive, frigid Aeric Calciaquolls	0-2
		Fine, smectitic, frigid Typic Argiaquolls	
Lisbon	Barnes –Svea	Fine-loamy, mixed, superactive, frigid Udic Haploborolls	3-6
	and	Fine-loamy, mixed, superactive, frigid Pachic Udic Haploborolls	
	Gwinner–Peever–	Fine, smectitic, frigid Pachic Vertic Argiudolls	
	Parnell	Fine, smectitic, frigid Vertic Argiudolls	0-3
		Fine, smectitic, frigid Vertic Argiaquolls	
Hettinger	Belfield–Savage–	Fine, smectitic, frigid Glossic Natrustolls	0-2
	Daglum	Fine, smectitic, frigid Vertic Argiustolls	
		Fine, smectitic, frigid Vertic Natrustolls	
Williston	Williams–	Fine-loamy, mixed, superactive, frigid Typic Argiustolls	0-3 *and*
	Bowbells	Fine-loamy, mixed, superactive, figid Pachic Argiustolls	0-6

† Soil data obtained from (USDA-NRCS, 2011).

‡ Soil taxonomy listed on individual lines based on hyphenated soil series name.

Winter wheat was planted in the fall of the first year and harvested the second year. Experiments were conducted as randomized complete block designs with a factorial combination of subsurface drainage (2 levels), previous crop residue (2 levels), planting date (2 levels), cultivar (2 levels) and fertilizer (6 levels), depending on location. Four replicates were used per location. The Fargo site is the only location where subsurface drainage was present. At this location the area is divided into eight units, of which four are subsurface drained (drained) and four of which are non-subsurface drained (undrained). All eight units have drain tile installed along with water table control structures (Agri-Drain Corp, Adair, IA), with four control structures open to drain the corresponding plot.

Previous crop residue of canola, HRSW, soybean, and fallow were used between the five locations. Two planting dates were compared to determine the influence on agronomic characteristics when winter wheat was planted at the optimal date or a late planting. Two winter wheat cultivars were chosen for the experiment based on their capacity for winter survival. The winter wheat cultivar Jerry, released from North Dakota State University in 2001, is a commonly grown cultivar in ND due to its 'good' winter hardiness, while Hawken, released from Agripro in 2007, is less commonly grown in the state and rated 'fair to poor' for winter survival (Ransom et al., 2009). Additionally, a fertilizer treatment of P and K was placed with the seed at planting. The fertilizer treatment was packaged separately but applied with the seed at planting by first emptying the contents of the seed packet into the cone of the seeder followed by the fertilizer packet. Soil samples were collected in the fall to determine the levels of N, P, K, pH and organic matter at each location (Table 2).

Table 2. Nitrogen, P, K, pH and organic matter levels by sampling depth at Fargo, Lisbon, Prosper, Williston and Hettinger in 2010 and 2011.

Location	Depth	N	P	K	pH	OM†
	cm	kg ha^{-1}	mg kg^{-1}	mg kg^{-1}		%
			2010			
Fargo‡	0-15	18	16 (VH) §	418 (VH)	7.8	4.7
	15-61	73	9 (M)	348 (VH)	7.9	3.4
			2011			
Fargo‡	0-15	8	17 (VH)	560 (VH)	7.8	5.4
	15-61	29	10 (M)	420 (VH)	7.9	4.2
Lisbon‡	0-15	9	10 (M)	360 (VH)	7.0	5.1
	15-61	23	6 (L)	220 (VH)	7.4	3.4
Prosper‡	0-15	13	28 (VH)	350 (VH)	7.7	4.5
	15-61	27	9 (M)	310 (VH)	7.9	3.3
Williston	0-15	38	72 (VH)	750 (VH)	6.6	2.8
	15-61	54	--	--	--	--
Hettinger	0-15	20	32 (VH)	610 (VH)	6.3	3.6
	15-61	30	8 (M)	390 (VH)	7.5	2.5

† OM = Organic matter

‡ Fertility values based on a compiled value across 8 blocks and 2 residues (Fargo 2010 and 2011) and 2 residues (Lisbon and Prosper 2011).

§ Letter(s) in parentheses represent a fertility scale based on the soil test (Peel et al., 1997). L = low, M = medium, VH = very high.

The experimental design at the Fargo site in 2010 and 2011 was a RCBD with a split-split-split plot arrangement, with subsurface drainage the main plot factor, previous crop residue the sub plot factor, planting date the sub-sub plot factor and cultivar and seed-placed fertilizer (treatment) the sub-sub-sub plot factor. Previous crop residue of canola and fallow were compared at this location. The previous canola crop was mechanically harvested so that at least 13 cm of previous crop residue (stubble) remained standing prior to winter wheat planting. The fallow ground was mechanically tilled throughout the summer so no previous crop stubble remained. The optimal planting date (early) aligned with the recommended planting date suggested by Peel et al. (1997), while the late planting date was about two weeks later. In 2010, P and K were applied with the seed to Hawken at a rate of 22 kg P_2O_5 ha^{-1}, 17 kg K_2O ha^{-1}, and 22 kg P_2O_5 ha^{-1} + 17 kg K_2O ha^{-1}. Rates were modified in 2011 to be consistent across all locations and were applied at 28 kg P_2O_5 ha^{-1}, 11 kg K_2O ha^{-1}, and 28 kg P_2O_5 ha^{-1} + 11 kg K_2O ha^{-1}. The cultivar Jerry did not receive fertilizer with the seed because of its good winter survival. A summary of the experimental design and treatments applied are shown in Table 3.

At Prosper and Lisbon in 2011, a RCBD with a split-split plot arrangement was used with previous crop residue the main plot factor, planting date the sub plot factor, and cultivar and seed-placed fertilizer the sub-sub plot factor. Previous crop residues of HRSW and soybeans were compared at the Prosper and Lisbon locations. The previous HRSW crop was mechanically harvested to leave at least 13 cm of previous crop stubble to trap snow throughout the winter. The soybeans were desiccated at least two weeks prior to winter wheat planting using saflufenacil (N'-[2chloro-4-fluoro-5-(3-methyl-2,6-dioxo-4-(trifluoromethyl)-3,6-dihydro-1(2H)-pyrimidinyl)benzoyl]-N-isopropyl-Nmethylsulfamide) at 50 g ai ha^{-1} plus 3.8 L methylated seed oil and 7.8 kg ammonium sulfate 379 L^{-1} water. After sufficient dry-down time, plants were cut off at ground level using a self-propelled sickle mower and the residue removed from the field. The mowing and removal process left no standing soybean crop stubble or residue on the soil surface.

Table 3. Design, factors and treatments for experiments conducted at Fargo, Prosper, Lisbon, Hettinger and Williston, ND in 2010 and 2011.

Location	Design	Factor	Treatment
Fargo	RCBD with split-split-split plot arrangement	Subsurface drainage	Drained Undrained
		Previous residue	Canola Fallow
		Planting date	Early Late
		Treatment†	Jerry (check) Hawken (check) Hawken + 28 kg P_2O_5 ha^{-1} ‡ Hawken + 11 kg K_2O ha^{-1} Hawken + 28 kg P_2O_5 ha^{-1} + 11 kg K_2O ha^{-1}
Prosper and Lisbon	RCBD with split-split plot arrangement	Previous residue	Wheat Soybean
		Planting date	Early Late
		Cultivar	Jerry Hawken
		Fertilizer treatment	Check 22 kg P_2O_5 ha^{-1} 17 kg K_2O ha^{-1} 22 kg P_2O_5 ha^{-1} + 17 kg K_2O ha^{-1} 17 kg P_2O_5 ha^{-1} 13 kg K_2O ha^{-1}
Hettinger and Williston§	RCBD with split plot arrangement	Planting date	Early Late
		Cultivar	Jerry Hawken
		Fertilizer treatment	Check 22 kg P_2O_5 ha^{-1} 17 kg K_2O ha^{-1} 22 kg P_2O_5 ha^{-1} + 17 kg K_2O ha^{-1} 17 kg P_2O_5 ha^{-1} 13 kg K_2O ha^{-1}

† Fertilizer treatments applied with the seed at planting. P_2O_5 source: monoammonium phosphate (analysis 11-52-0); K_2O source: potassium sulfate (analysis 0-0-50). Because MAP contained a small amount of N, all treatments received an equivalent amount of N applied with the seed as urea (analysis 46-0-0).

‡ Rates for 2010 fertilizer treatment shown. 2011 Hawken fertilizer treatments: check, 22 kg P_2O_5 ha^{-1}, 17 kg K_2O ha^{-1}, and 22 kg P_2O_5 ha^{-1} + 17 kg K_2O ha^{-1}, respectively.

§ Previous crop residue was field pea (*Pisum sativum* L. subsp. sativum) at both locations.

An RCBD with a split plot arrangement was used in Hettinger and Williston in 2011, with planting date the main plot factor and cultivar and seed-placed fertilizer the sub-plot factor. Plots were sown into previous field pea residue with less than 4 cm of standing crop stubble. The remaining design factors for these four locations were similar to those described previously at the Fargo location and are summarized in Table 2.

Plots consisted of seven rows with 18 cm row spacing and 7.6 m (Fargo, trimmed to 6.1 m), 5.2 m (Prosper and Lisbon, trimmed to 3.7 m), 8.5 m (Hettinger, trimmed to 7 m) and 4.9 m (Williston, trimmed to 4.3 m) in length. During the growing season, plots were trimmed from each end using a rotovator (Fargo, Lisbon and Prosper) or mower (Hettinger and Williston) to the lengths previously mentioned to create an alley. Border plots were planted on the two outermost columns of plots to ensure similar competition as interior plots. Germination tests were performed on both cultivars and were determined by taking 100 seeds from each cultivar and placing them on a moist paper towel for one week at room temperature. After one week, seeds with the coleoptile showing were considered viable and used to determine the percentage of viable seeds. All plots were sown at a rate of 2.97 million viable seeds ha^{-1}.

In 2010, winter wheat plots were sown using a New Holland TT75A tractor (New Holland Agri., Racine, WI) and a seven row Great Plains 3P605NT drill (Great Plains Mfg Inc., Salina, KS) with 18 cm row spacing. Both winter survival and vigor ratings were based on a visual score from 0 to 10, with 10 being the best. For winter survival, a score of 10 had no apparent winter injury, while a vigor score of 10 had dark green color and excellent spring growth. Plots were fertilized at a rate of 123 kg N ha^{-1} in the spring and applied as urea at least 7 days prior to a rainfall event. Broadleaf and grassy weeds were controlled with a single premix application of fenoxaprop (ethyl 2-[4-(6-chlorobenzooxazol-2-yl)oxyphenoxy] propanoate), bromoxynil (3,5-dibromo-4-hydroxybenzonitrile), phyrasulfotole (5-hydroxy-1,3-dimethylpyrazol-4-yl(2-mesyl-4-trifluoromethylphenyl) methanone), and mefenpyr safener [(diethyl 1(2,4-dichlorophenyl)-5-methyl-2-pyrazoline-3,5-dicarboxylate)] at 89 g, 140 g, and 40 g ai ha^{-1}, respectively, and supplemented with hand weeding when necessary. Important dates and measures for 2010 are summarized in Table 4.

Table 4. Dates of important measurements and field applications at Fargo, ND for the 2010 crop.

Measurement/Application	Date
2009	
Early winter wheat planting	18 Sept
Late winter wheat planting	28 Oct
2010	
Survival/vigor score	21 April
N fertilization	28 April
Weed control	18 May
Winter wheat harvest	21 July

In 2011, Fargo, Lisbon, and Prosper plots were sown using the same New Holland TT75A tractor and seven row Great Plains 3P605NT drill with 18 cm row spacing. At Hettinger and Williston, a similar New Holland TT75A tractor with a custom-made seven row no-till double-disc opener seeder (Fabro Enterprises Ltd, Swift Current, Sask. Canada) and a seven row custom made self-propelled cone seeder (Fabro Enterprises Ltd, Swift Current, Sask. Canada), respectively, were used for sowing both planting dates with 18 cm row spacing. Vigor ratings were determined based on the same visual score of 0 to 10. Stakes delineating 0.6 m of each plot and counting the number of plants within the given area in the fall and spring were used to determine winter survival (formula: [spring count / fall count]*100). Winter wheat plots were fertilized at a rate of 123 kg N ha^{-1} as urea at least 7 days prior to a rainfall event in the spring.

The same rate and premix of fenoxaprop, bromoxynil, phyrasulfotole, and mefenpyr safener was tank mixed with a fungicide premix of trifloxystrobin {((E,E)-alpha-(methoxyimino)-2-[[[[1-[3-(trifluoromethyl)phenyl]ethylidene]amino] oxy]methyl]-methyleste} and propiconazole {1-[[2-(2,4-dichlorophenyl)-4-propyl-1,3-dioxolan-2-yl]methyl]-1,2,4-triazole} at 91 g ai each ha^{-1} at Fargo, Lisbon and Prosper in 2010 to control broadleaf and grassy weeds and early-season diseases. An additional mid-season premixed application of prothioconazole [2-(2-(1-chlorocyclopropyl)-3-(2-chlorophenyl)-2-hydroxypropyl)-1,2-dihydro-3H-1,2,4-triazole-3-thione] and tebuconazole [(RS)-1-p-chlorophenyl)-4,4-dimethyl-3-(1H-1,2,4-triazol-1-ylmethyl)pentan-3-o] fungicide at 100 g ai each ha^{-1} plus 1.2 L nonionic surfactant 379 L^{-1} water was applied to control late-season diseases. Hand weeding was also necessary to control late-emerging weeds. At Hettinger, a premix of florasulam [N-(2,6-difluorophenyl)-8-fluoro-5-methoxy (1,2,4)triazolo(1,5-c)pyrimidine-2-sulfonamide] and fluroxypyr [((4-amino-3,5-dichloro-6-fluoro-2-pyridinyl)oxy)acetic acid, 1-methylhepty ester] was applied at 102 g and 5 g ae ha^{-1}, respectively, to control broadleaf weeds, 175 g ai ha^{-1} of prothioconazole was applied to control *Fusarium* Head Blight (*Fusarium* spp.), and 1051 g ai ha^{-1} of malathion [diethyl 2-dimethoxyphosphinothioyl sulfanylbutane- dioate] was used to limit grain aphids (*Sitobion avenae*). A single premix application of octanoic acid ester of bromoxynil (3,5-dibromo-4-hydroxybenzonitrile) and isooctyl (2-ethylhexyl ester) ester of 2-methyl-chlorophenoxyacetic acid was applied at 107 g ae each ha^{-1} to control broadleaf weeds at Williston. All herbicide, fungicide, and insecticide treatments were applied using a backpack sprayer and a handheld boom. Tables 5 summarizes important measurement and field application dates for 2011.

Stand counts were obtained in the fall by counting the number of plants in a random representative 30 cm area of rows two and six, averaging the number of plants from both rows, and then adjusting them to represent plants m^{-2}. Spike counts were taken after heading (Haun stage 11.4) and obtained by counting the number of spikes in a random representative 0.6 m area of rows two and six, then averaging the numbers and adjusting them to represent spikes m^{-2}. Spikes were only counted if they contained a viable head that would contribute to the overall yield.

Table 5. Dates of important measurements and field applications at Fargo, Prosper, Lisbon, Hettinger and Williston, ND for the 2011 crop.

Measurement/Application	Fargo	Prosper	Lisbon	Hettinger	Williston
	---------------------------------------Date---------------------------------------				
		2010			
Early winter wheat planting	22 Sept	20/22 Sept†	21 Sept	13 Sept	14 Sept
Late winter wheat planting	5 Oct	5 Oct	6 Oct	4 Oct	4 Oct
Stakes installed/fall survival count	22 Oct	3 Nov	4 Nov	23 Oct	24 Oct
		2011			
Spring survival count/vigor score	5 May	17 May	11 May	2 May	13 May
N fertilization	19 May	19 May	18 May	11 April	13 May
Weed control + fungicide	26 May	26 May	26 May	15 May	19 May
Fungicide‡	17/20 June	20 June/1 July	17/27 June	29 June	--
Insecticide	--	--	--	2 July	--
Winter wheat harvest	5 Aug	11/16 Aug§	3 Aug	9 Aug	4 Aug

† Reps 3 and 4 were planted two days later due to mechanical issues with the seeder.

‡ Some application dates were split to accommodate the two planting dates.

§ Reps 1 through 3 were hand harvested on the first date due to excessive soil moisture at time of harvest.

In 2010, winter wheat was harvested using a Hege 125B Series combine (Hans-urlich Hege, West Germany). In 2011, Fargo, Lisbon, and Prosper were harvested using a Wintersteiger Classic plot combine (Wintersteiger Ag, Ried, Austria). Due to excessive rainfall at Prosper, the first three reps were hand harvested by cutting plots with a self-propelled sickle mower and hand feeding them into the combine. The final rep was mechanically harvested several days later. At Hettinger and Williston, winter wheat was harvested with a Kincaid 8XP plot combine (Kincaid Equipment Manufacturing, Haven, KS) and a Wintersteiger Elite plot combine (Wintersteiger Ag, Ried, Austria), respectively.

Once harvested, the seed was dried (if necessary) and cleaned (Clipper Office Tester and Cleaner, Seedburo Equipment Co., Chicago, IL). In 2011 at Fargo and Hettinger, moisture, test weight and yield were determined with a Grain Gauge weighing system (Wintersteiger Ag, Ried, Austria) installed on the plot combine. At the remaining locations, moisture and test weight were recorded using a GAC 2100 moisture tester (DICKEY-John Corp., Minneapolis, MN) and yield was calculated by weighing the plot sample with a scientific scale (RS-232, Scientech Inc., Gaitherseberg, MD) and adjusting to a moisture content of 13.5%. At all locations, plot lengths were recorded at harvest time and yield adjusted using the individual length of each plot. All seven rows of each plot were harvested.

Grain protein was measured using a 0.5 kg sub-sample of seed from each plot on a Diode Array 7200 NIR Analyzer (Perten Instruments, Springfield, IL). Thousand kernel weights were calculated by counting five hundred seeds with a seed counter (Model 850-3, International Marketing and Design Corp., San Antonio, TX) and weighing the seeds with the RS-232 Scientech Scale. Weights were then multiplied by two to obtain the thousand-kernel weight for each sample.

During the winter of 2009-10, average snow depths were measured in the canola residue and fallow at Fargo. Twenty-four snow depth measurements were made six times throughout the winter in each of the residue treatments and recorded in the center of the plot using a height stick. From the individual measurements, an average was determined for each sampling date for the canola residue and fallow.

Soil and ambient temperatures were measured at all locations during the winter of 2010-11. Two dual soil temperature sensors (Hobo Model U23-002, Onset Computer

Corporation, Pocasset, MA) were installed in the fall at each location. At the locations near Fargo, Lisbon, and Prosper, one sensor from each data logger was placed in each crop residue. One sensor was located at the crown depth (about 3 cm) while the other was placed just below the soil surface. Residue was not compared at the locations near Williston and Hettinger, so two sensors were placed at each of the two depths. Ambient air temperature sensors (Hobo Model U23-001, Onset Computer Corporation) at each location were placed about 0.6 m above the soil surface. Soil and ambient temperatures were logged every 30 minutes and readings at each location were averaged to generate a daily average temperature. When ambient or soil temperature data was unavailable, weather data was collected from the nearest automated weather station using NDAWN (2012).

Data were analyzed using a mixed linear model (PROC MIXED) with SAS 9.2 (SAS Institute, Cary, NC). Location and replicates were considered a random effect while remaining factors were considered fixed. For analysis across location, environment was considered a random effect. Main effects and interactions were tested using the appropriate error terms. Means were separated using a paired t-test at the 5% level of significance.

RESULTS AND DISCUSSION

Winter 2009-10 Weather Data

Total snowfall was above normal for southeastern ND during the winter of 2009-10 (Fig. 1). Fargo received between 1 and 1.3 m of snowfall during the winter, with snow accumulations primarily beginning at the end of December.

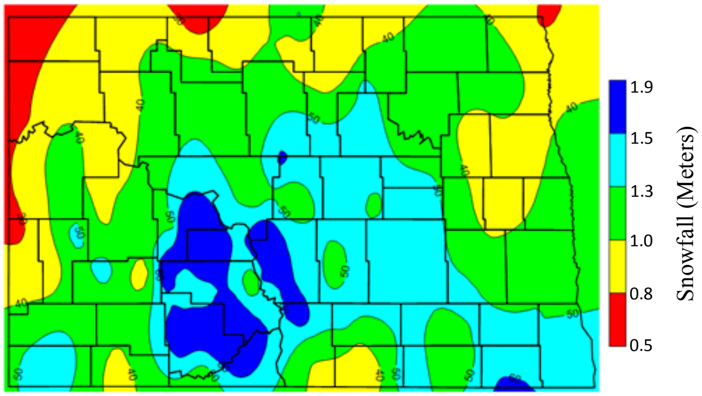

Fig. 1. Total Snowfall in ND in 2010. (Data from NWS Cooperative Network; Image from ND State Climate Office 2011.)

At an automated weather station in Fargo about 1.6 km from the research site, the average daily bare soil temperature did not drop below 0°C until 9 Dec 2009, while the coldest average daily reading of -10°C occurred exactly one month later (NDAWN, 2012). The average daily turf soil temperature did not fall below 0°C until 12 Dec 2009. The average daily temperature only dropped as low as -3°C on 25 Feb 2010, but for 16 days during February, the turf soil temperature averaged -2°C.

Snow depth differences between canola residue and fallow were recorded six times throughout the winter months. Fig. 2 shows that at the first reading on 21 Dec 2009, plots with canola residue had trapped nearly twice as much snow as the non-residue plots (11.7 vs. 6.0 cm). On 19 Feb 2010, the canola residue had trapped 40.4 cm of snow compared to only 33.0 cm in the fallow. After this reading, the snow depth in the canola residue declined while the fallow remained similar. This is likely due to the presence of canola stubble which absorbed sunlight and caused the snow to compact as the air temperature warmed.

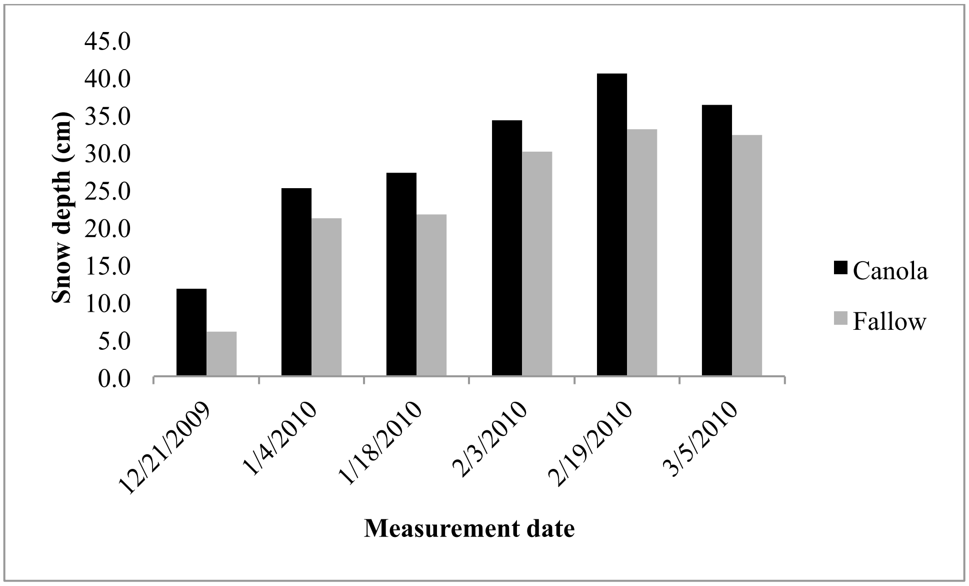

Fig. 2. Snow depth measurements in winter wheat grown at Fargo, ND in 2010.

Winter 2010-11 Weather Data

Most of North Dakota received above-normal or record amounts of snowfall during the winter of 2010-2011. The high snowfall totals in most locations were enough to moderate the soil temperature and prevent large temperature variations, even when ambient temperatures reached extreme levels. At all locations, minimal differences were detected in the average winter soil temperature at the crown and soil surface; therefore, readings were averaged and referred to as crown-depth temperatures. Snowfall totals and soil and ambient temperature information will be discussed separately for each location.

At the location near Fargo, the coldest 30-minute ambient temperature recorded was -35.6°C on 21 Jan 2011. The coldest 30-minute soil temperature of -4.7°C was recorded at the soil surface, in winter wheat plots sown into fallow, on 13 Dec 2010, while the lowest temperature recorded in canola residue was -3.2°C on 2 Feb 2011. Daily average ambient temperatures and daily average soil temperatures for canola residue and fallow from 25 Oct 2010 to 1 May 2011 are shown in Fig. 3.

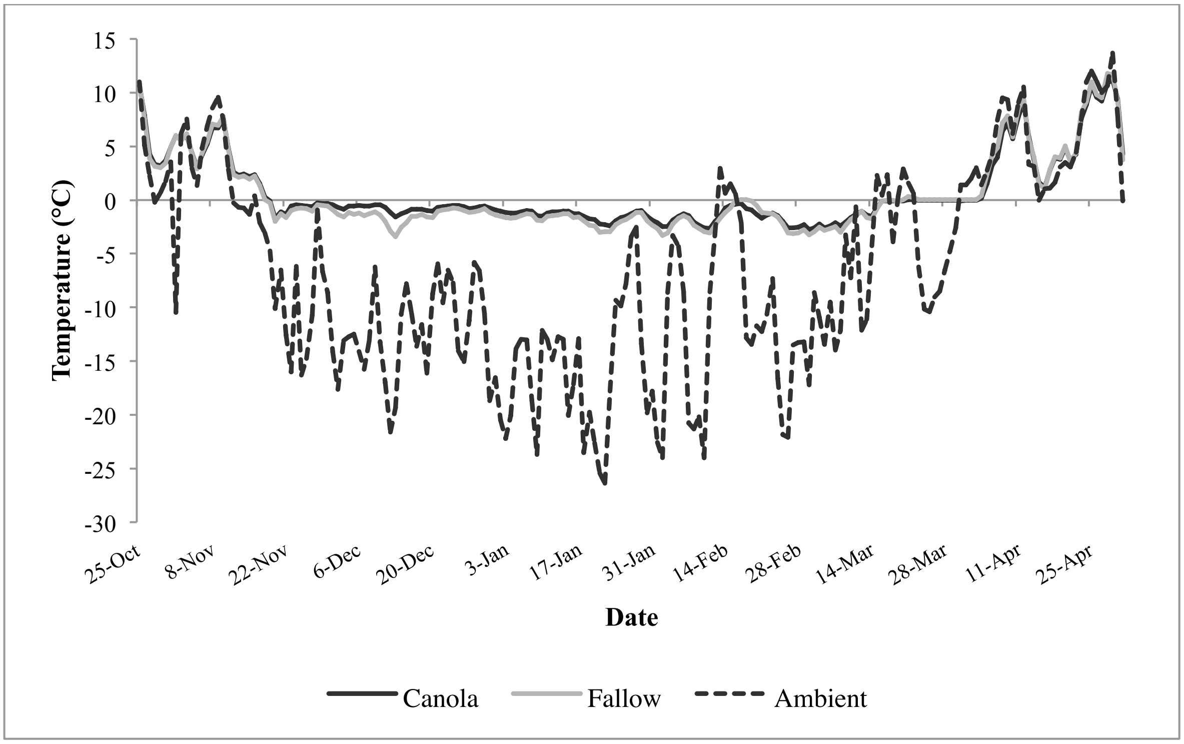

Fig. 3. Ambient and crown-depth soil temperature in canola residue and fallow at Fargo, ND in 2011.

As shown in Fig. 3, negligible differences were reported between soil temperatures in canola residue and fallow. This is primarily due to receiving over 2.2 m of snowfall during the winter that provided sufficient cover regardless of previous crop residue (Fig. 4). Additionally, only minimal differences were found in the average winter soil temperature in canola residue and fallow, with an average winter soil temperature from 25 Oct 2010 to 1 May 2011 of 0.7°C and 0.4°C, respectively.

The relationship between soil temperature and ambient temperature followed a similar trend at the site near Prosper (Fig.5). Despite the ambient temperature dropping below -20°C numerous times from December through February, the soil temperature in wheat and soybean residue never got below -4°C as a result of more than 2.2 m of snowfall in the region (Fig. 4). The coldest 30-minute ambient temperature of -36.9°C was recorded at Prosper on 21 Jan 2011; however, the minimum soil temperature of -3.6°C recorded at the soil surface on soybean residue occurred one day prior. The coldest half-hour soil temperature of -3.0°C in wheat residue was not observed until the final day of monitoring (1 May 2011) and was likely due to the lack of snow present in the residue. Similar to the Fargo location, very minimal differences were found between the average soil temperature in wheat and soybean from 4 Nov 2010 to 1 May 2011, at 0.4°C and 0.3°C, respectively.

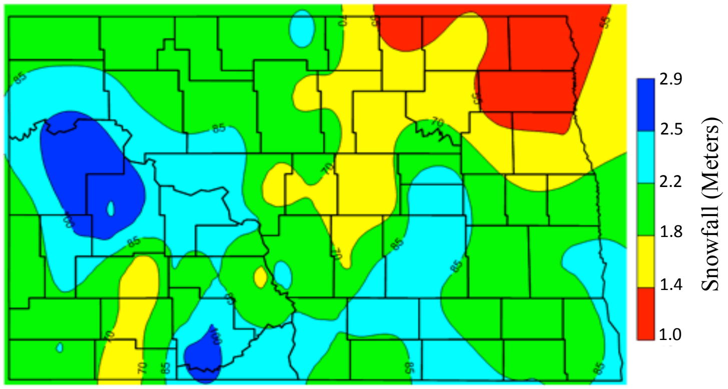

Fig. 4. Total snowfall in ND in 2011. (Data from NWS Cooperative Network; Image from ND State Climate Office 2011.)

The site near Lisbon, also located in eastern ND, followed a similar trend to the other eastern locations (Prosper and Fargo), with small differences in soil temperatures between wheat and soybean residue despite very cold winter temperatures (Fig. 6). The ambient air temperature sensor installed onsite malfunctioned, but on 21 Jan 2011, a minimum one-hour ambient temperature of -30°C was recorded at an automated weather station near Lisbon, about 16 km away (NDAWN, 2011). A minimum 30-minute soil temperature of -4.7°C was recorded at the soil surface in soybean residue on 1 Dec 2010, although a colder minimum temperature of -6.0°C was recorded in wheat plots on 20 Feb

2011. While the wheat residue contained standing stubble to catch snow and insulate the soil, the region received sufficient snowfall of more than 1.8 m that having standing stubble did not provide a major advantage compared to soybean residue (Fig. 4). From 4 Nov 2010 to 1 May 2011 the average soil temperature in the wheat and soybean stubble was similar, averaging 0.4°C and 0.3°C, respectively. During the same time period, the ambient temperature averaged -7.5°C.

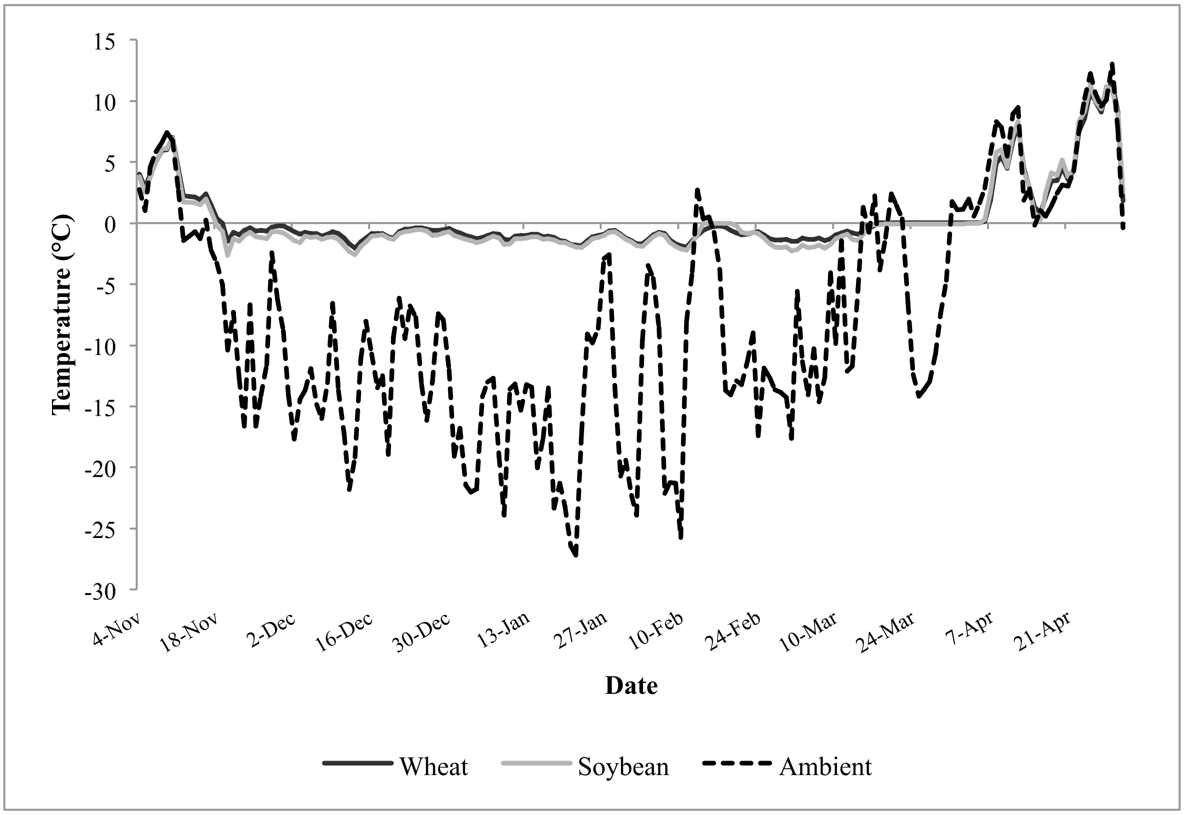

Fig. 5. Ambient and crown-depth soil temperature in wheat and soybean residue at Prosper, ND in 2011.

The western location near Hettinger, which received around 1.4 m of snowfall throughout the winter (Fig. 4), lacked sufficient snowfall to provide the level of insulation that was found at the previous locations (Fig. 7). On 1 Jan 2011, the minimum 30-minute soil temperature of -14.9°C was recorded, and thus some degree of winter injury would have been expected. Ambient temperature averaged -5.5°C from 25 Oct 2010 through 1

May 2011 and reached a minimum of -34.4°C on 25 Feb 2011. During the same time period, the soil temperature averaged -2.1°C.

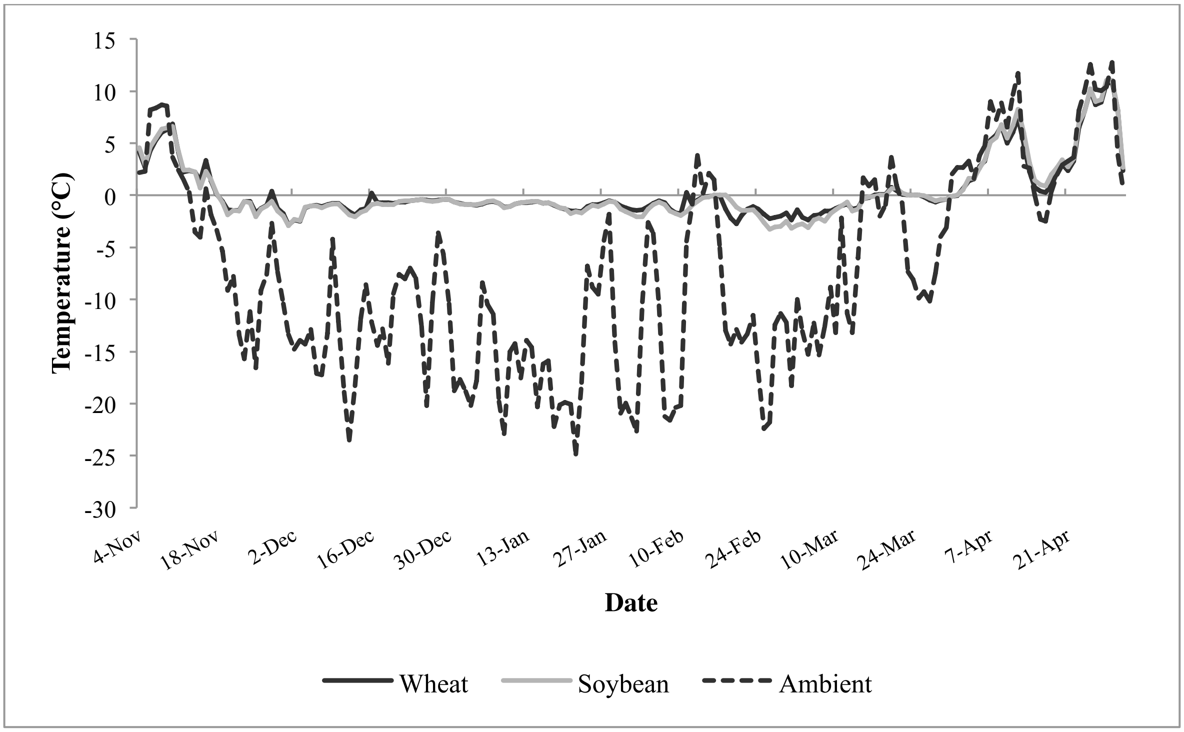

Fig. 6. Ambient and crown-depth soil temperature in wheat and soybean residue at Lisbon, ND in 2011.

Williston, also located in western ND, received a record amount of snowfall during the 2010-2011 winter, measuring over 2.5 m of snowfall (Fig. 4). The abundant snowfall in the northwestern portion of the state was sufficient to insulate the soil and prevent the soil temperature from dropping below -5°C for most of the season, with the exception of late February through the middle of March when melting was occurring (Fig. 8).

The minimum 30-minute ambient temperature of -32.5 was recorded on 1 Feb 2011, the same day the coldest average daily temperature of -30.0°C was also reported. Despite the extremely cold temperatures, the soil temperature did not drop below -4°C until 21 Feb 2011. The coldest 30-minute soil temperature -10.7°C wasn't registered until 26

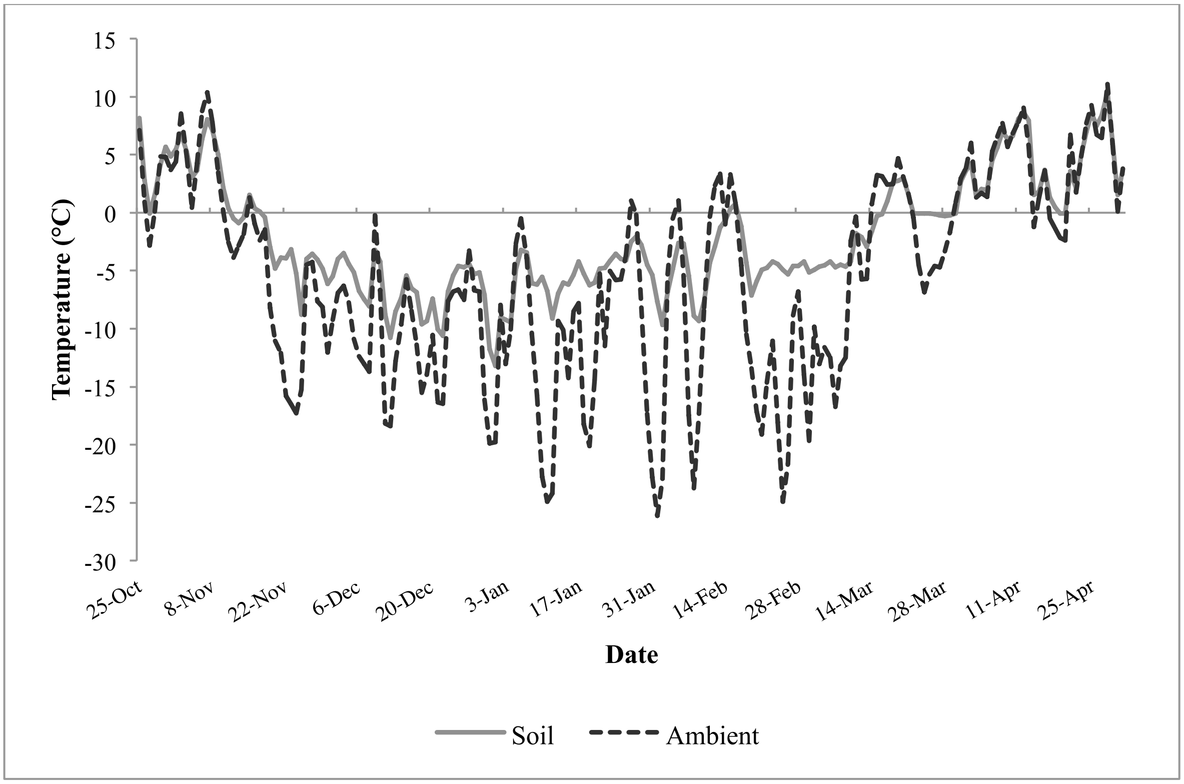

Fig. 7. Ambient and crown-depth soil temperature in pea residue at Hettinger, ND in 2011.

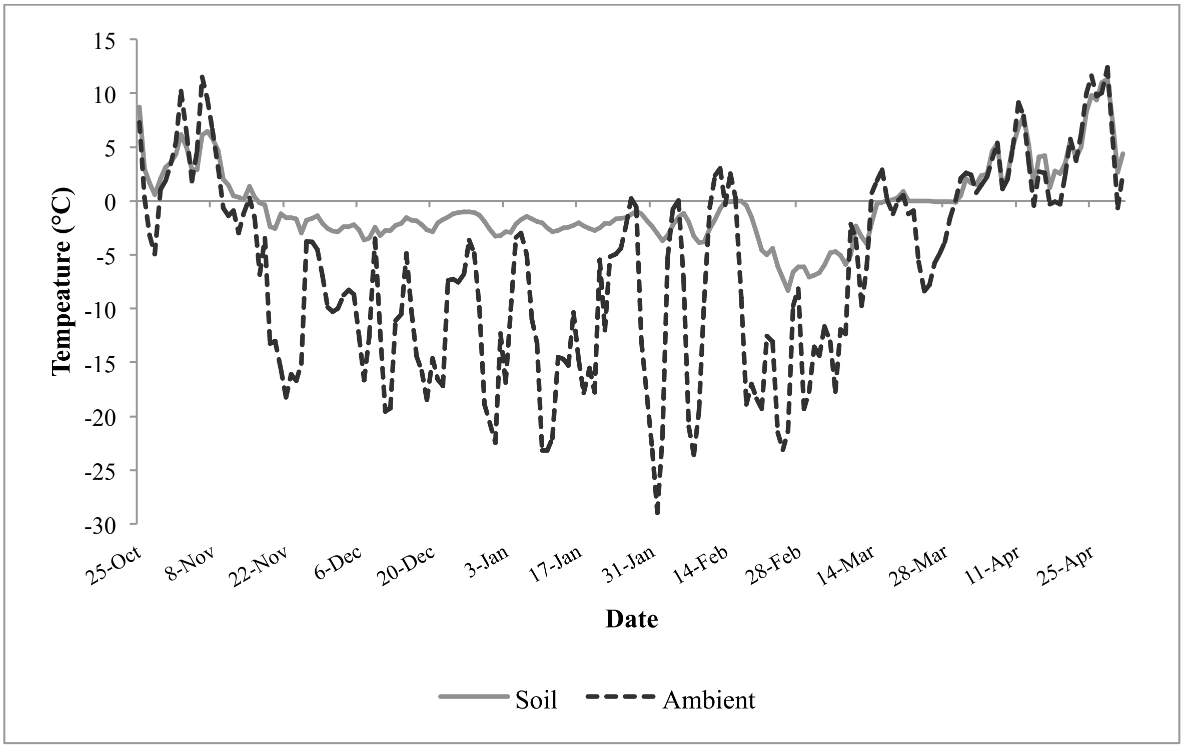

Fig. 8. Ambient and crown-depth soil temperature in pea residue at Williston, ND in 2011.

Feb, when the average daily temperature dropped below -21°C. From 25 Oct 2010 through 1 May 2011, the soil temperature averaged -0.5°C while the ambient temperature averaged -6.4°C.

With the exception of Hettinger, all locations in 2011 had very good snowfall to insulate the soil and moderate the soil temperatures. At Hettinger, the soil temperature approached -15°C, the suggested critical temperature for winter wheat survival. Therefore, good winter survival was expected at all locations except Hettinger.

Combined Analysis

Six site years of data are available for this experiment (Fargo in 2010 and Fargo, Lisbon, Prosper, Williston and Hettinger in 2011). Throughout these six environments, an RCBD with three design arrangements were used (split-split-split in Fargo both years, split-split in Lisbon and Prosper 2011, and split plot in Williston and Hettinger in 2011). Due to the multiple design arrangements, combined analysis was limited to like arrangements, leaving only two environments combinable per design. Having only two environments per design resulted in a decrease in the number of error degrees of freedom for each factor (i.e. degrees of freedom for rep x residue used to test residue at Lisbon was 3 [(4-1)(2-1)] while the error degrees of freedom for residue x location used to test residue for the combined analysis at Lisbon and Prosper was 1 [(2-1)(2-1)]). This loss of error degrees of freedom in the combined analyses resulted in multiple factors becoming non-significant even when both locations had significant differences in the measured traits. This same trend occurred for the remaining two combined analyses.

Due to the large loss of significant factors, it was decided that a presentation of individual locations was the best approach. While this approach will make it harder to make inferences about winter wheat throughout the state, the individual locations will better represent the responses to the various treatments tested. Throughout this thesis, a table showing the response of the main factors to treatments for the combined analyses will be presented for each combinable design but will not be discussed.

Fargo 2010

The Fargo site is designed specifically to test the effects of subsurface drainage on crops in the Red River Valley, and it is the only location with this capacity in the region. Winter wheat was grown with subsurface drainage at Fargo in 2010 and 2011. While thousand-kernel weight and yield were non-significantly different between drainage treatments during 2010, the trend indicates an increase in kernel size and yield when winter wheat is grown on subsurface drainage (Table 6). Winter wheat was significantly more vigorous on undrained soil. This is unusual because it was expected that the drained soil would have better vigor due to the removal of excess soil moisture. To determine if vigor scores were influenced by abiotic conditions in the spring, individual scores were plotted based on their location within the field. No pattern within the field was detected that would suggest excessive water or any other abiotic factor caused lower vigor scores within a concentrated area of the field, so there is no explanation as to why drained plots had lower vigor. In this case, it can be concluded that vigor score was a poor indicator of yield, as the trend indicated that drained plots out-yielded the undrained by 429 kg ha^{-1}.

Protein was two-tenths of a percent higher on undrained soil compared to the drained (Table 6). This is likely due to the lower yield that occurred in the undrained soil, which resulted from reduced starch filling during grain development. Wheat yield and protein are known to follow an inverse relationship, so it is likely the reduction in yield produced the significant protein advantage in the undrained soil (Brown et al., 2005).

Table 6. Drainage effect on vigor, thousand-kernel weight, protein and yield at Fargo, ND in 2010.

Drainage	Vigor	TKW†	Protein	Yield
	0-10‡	g	%	kg ha^{-1}
Drained	6.17 b§	35.5a	13.5 b	4207a
Undrained	6.63a	34.6a	13.7a	3778a

† TKW = thousand-kernel weight.

‡ Based on a visual score, with 10 being the most vigorous.

§ Means followed by the same letter in the same column are not significantly different (*p*≤0.05) using a paired t-test.

There was a significant interaction for drainage x planting date for the visual survival rating (Table 7). For drainage treatment, the undrained plots at the late planting date had better vigor than those that were drained. This reduction in survival is unusual because the fall of 2009 was wet and the late planting was significantly delayed. Unfortunately, fall stand counts were not taken due to the late planting, but it is possible the undrained had a lower plant stand going into the winter and this reduced competition for resources allowed the plants to resume growth more readily in the spring.

Table 7. Drainage x planting date interaction for survival at Fargo, ND in 2010.

Date	Drained	Undrained
	----------------0-10†	-----------------
Early	8.6a‡	8.1a
Late	6.8 b	7.5 b *
Mean	7.7	7.8

† Based on a visual score, with 10 being the most vigorous.

‡ Means followed by the same letter in the same column are not significantly different (*p*≤0.05) using a paired t-test.

* Denotes significance (*p*≤0.05) across rows.

The early planting date in both the drained and undrained soil had survival ratings over eight (8.6 and 8.1, respectively) on a 0-10 scale (Table 7). Good winter survival was expected as the southern Red River Valley region recorded over 1.3 m of snowfall during the winter season (Fig. 1). The significantly higher survival in the early planting confirms

Pittman and Andrews (1961) finding that each week delay from optimum in winter wheat planted resulted in a progressive decrease in winter survival.

Test weight was significantly different for the drainage x fertility treatment interaction, with Hawken and Hawken +P having significantly lower test weight in the undrained plots (Table 8). While the other treatments did not show significant differences, they all showed a trend for reduced test weight when the soil was undrained. Brodshaug (2011) measured the soil water table at this location during the 2010 growing season and reported the water table to be mostly higher in the undrained soil, especially following large rainfall events. This additional moisture from large rainfalls likely caused additional stress to the winter wheat in undrained plots. Musgrave (1994) reported up to a 51% reduction in test weight of winter wheat under waterlogged conditions.

Table 8. Drainage x fertility treatment interaction for test weight at Fargo, ND in 2010.

Treatment	Drained	Undrained
	--------------kg m^{-3}	-------------
Jerry	749.5a	748.1a
Hawken	737.6 b	714.6 b *
Hawken +P	729.0 b	704.7 c *
Hawken +K	735.5 b	715.7 b
Hawken +P+K	730.5 b	713.3 bc
Mean	736.4	719.3

†Means followed by the same letter in the same column are not significantly different ($p \leq 0.05$) using a paired t-test.
*Denotes significance ($p \leq 0.05$) across rows.

Jerry had higher test weight than all of the Hawken treatments in both the drained and undrained treatments (Table 8). A significant outbreak of stripe rust (*Puccinia striiformis*) occurred at this location during the summer of 2010, and visual observations indicated that Hawken was more susceptible than Jerry. In the undrained soil, Hawken +P had significantly lower test weight than all Hawken treatments except +P+K. It was expected that P would increase or maintain a similar kernel size as the untreated check, but the fall soil test showed a very high level of P (16 mg kg^{-1}) already present in the upper 15 cm of the soil. Even with the high levels of P already present in the soil, it was not expected that additional P with the seed would result in negative effects on test weight. This finding is contrary to Knapp and Knapp (1978) who found banding P fertilizer with winter wheat at planting increased test weight compared to those treatments receiving no banded P.

Winter wheat was sown into canola residue and fallow at Fargo. No significant difference was found for survival, test weight and thousand-kernel weight (Table 9). The 1.3 m of snowfall received at Fargo during the winter was enough to reduce winter injury of winter wheat. Snowfall was received before temperatures dropped considerably for the winter, and, therefore, the soil remained sufficiently warm throughout the winter so that there were no significant differences in winter survival. Vigor, however, was found to be significantly better in the canola residue. This is likely due to the presence of standing previous crop stubble in the canola residue, which helped keep the minimum soil temperature warmer by retaining and holding more snow throughout the winter season, when high winds can remove snow from fallow fields.

Table 9. Residue effect on survival, vigor, test weight, protein, and thousand-kernel weight at Fargo, ND in 2010.

Residue	Survival	Vigor	TW†	Protein	TKW†
	----------0-10 ‡----------		kg m^{-3}	%	g
Canola	7.84a§	6.80a	731a	13.3 b	35.2a
Fallow	7.64a	6.01 b	725a	13.9a	34.9a

† TW = test weight, TKW = thousand-kernel weight.
‡ Based on a visual score, with 10 being the best.
§ Means followed by the same letter in the same column are not significantly different ($p \leq 0.05$) using a paired t-test.

A significant protein advantage occurred in winter wheat grown on fallow (Table 9). Because grain yield in the fallow and canola residue were nearly identical (4018 vs. 3967 kg ha^{-1}), the higher protein in the fallow might be due to the additional time for N mineralization to occur during the fallow season, which allowed more N availability for winter wheat during the growing season. Wienhold and Halvorson (1999) reported higher N-mineralization rates in conventionally tilled fallow soils compared to soils that were cropped the previous season.

The Fargo locations in 2010 and 2011 differed from the other locations in 2011 because their treatments involved two cultivars and three fertility treatments (+P, +K or +P+K) placed with the seed. Jerry, currently the most widely grown winter wheat cultivar in ND, was grown on 38% of the acres in ND in 2011 and was included without fertilizer treatment because of its good winter hardiness (NASS, 2011b). Hawken was combined with the fertilizer treatments to determine if fertilizer treatment might increase the winter survival levels of this less winter hardy cultivar to that of Jerry.

Jerry grown on canola residue out-yielded the fallow, while residue had the opposite effect on Hawken with no seed-placed fertilizer treatment when examining the residue x fertility treatment interaction (Table 10). It was expected that winter wheat would yield better when grown on canola residue, as planting into standing previous crop stubble is already recommended to producers (Peel et al., 1997; Wiersma et al, 2006). The higher yield in the untreated check of Hawken, along with a trend for increased yield with two of the remaining Hawken treatments grown on fallow, indicate that an additional factor reduced the yield on canola residue. During winter wheat growth in the fall, volunteer canola plants emerged in the canola residue and may have contributed to the reduced yield prior to being controlled. Canola residue has also been reported to have phytotoxic effects on wheat seedling growth (Wanniarachchi and Voroney, 1997), which could also have contributed to the reduced yield on canola residue.

The cultivar Jerry significantly out yielded all other treatments in both residues (Table 10). In the fallow, there were no differences in Hawken plus fertility treatment, while Hawken +P+K significantly out yielded all other Hawken treatments in the canola residue. Knapp and Knapp (1978) and Lutcher et al. (2010) reported higher grain yields with added fall P, but it is not clear why the Hawken +P+K treatment out yielded the individual +P and +K treatments because fall soil tests indicated very high levels of both P and K (16 and 418 mg kg^{-1}, respectively in the upper 15 cm) prior to the addition of the seed-placed fertilizer.

Table 10. Residue x fertility treatment interaction for yield at Fargo, ND in 2010.

Treatment	Canola	Fallow
	-----------kg ha^{-1}-----------	
Jerry	4698a†	4388a *
Hawken	3733 c	4029 b *
Hawken +P	3724 c	3831 b
Hawken +K	3677 c	3933 b
Hawken +P+K	4001 b	3910 b
Mean	3967	4018

† Means followed by the same letter in the same column are not significantly different ($p \leq 0.05$) using a paired t-test.
* Denotes significance ($p \leq 0.05$) across rows.

Thousand-kernel weight differed significantly for the date x residue x fertility treatment interaction (Table 11). Across planting date, the fertility treatments maintained a consistent thousand-kernel weight with the exception of the Hawken +P treatment planted late on fallow. While most other treatments planted late into fallow suggested a trend for reduced thousand-kernel weight, no explanation can be offered as to why Hawken +P was more negatively affected, as the combination of +P and +K suggests the opposite trend.

For both residues and planting dates, Jerry had significantly higher thousand-kernel weights than Hawken (Table 11). This was to be expected as Jerry typically produces a larger kernel than Hawken in ND variety trial testing (NDSU Extension, 2009). The late planting on fallow was the only previous crop residue treatment that had significant differences in fertility treatments with Hawken. Hawken +P produced a significantly lower thousand-kernel weight than the Hawken +P+K treatment. Lutcher et al. (2010) reported no significant difference in thousand-kernel weight across years and locations with added P, with no consistent trend indicating a positive or negative impact on thousand-kernel weight with added P.

Table 11. Planting date x residue x fertility treatment interaction for thousand-kernel weight at Fargo, ND in 2010.

	Early		Late	
Treatment	Canola	Fallow	Canola	Fallow
	------------------------------g------------------------------			
Jerry	39.0a†	38.1a	38.3a	38.5a
Hawken	33.1 b	33.1 b	35.5 b	34.4 bc
Hawken +P	33.1 b	34.2 b	36.2 b	33.6 c *
Hawken +K	33.3 b	33.5 b	35.0 b	34.7 bc
Hawken +P+K	33.9 b	33.1 b	35.0 b	35.8 b
Mean	34.5	34.4	36.0	35.4

† Means followed by the same letter in the same column are not significantly different ($p \leq 0.05$) using a paired t-test.

* Denotes significance ($p \leq 0.05$) across rows by planting date.

Planting date effects on winter wheat were assessed at Fargo, ND in 2010. For planting date, an early planting date refers to the recommended (optimal) planting date for the location, while a late planting was planted about two weeks later. Thousand-kernel weight at Fargo in 2010 was significantly higher in the late planting (Table 12). This finding is contrary to Blue et al. (1990) who found kernel weight decreased as planting date was delayed. Visual observations of the stripe rust outbreak previously mentioned indicated a higher incidence at the earlier planting. Stripe rust accelerated the grain filling process and likely caused the reduced kernel weight. For protein and yield, there was no difference between planting dates, but the trend supports the inverse relationship commonly reported between protein and yield.

A significant planting date x fertility treatment interaction occurred for survival, vigor and test weight (Table 13). As expected, the early planting date had significantly higher survival and vigor than the late planting for all fertility treatments. For test weight, all treatments except Jerry produced significantly higher test weight in the late compared to the early planting. Jerry maintained a consistent test weight across planting date, while the stripe rust infection, primarily on the early planted Hawken, likely lead to the greater reduction in test weight for the early planting.

Table 12. Planting date effect on thousand-kernel weight, protein and yield at Fargo, ND in 2010.

Date	TKW†	Protein	Yield
	g	%	kg ha^{-1}
Early	34.4 b‡	13.3a	4227a
Late	35.6a	13.9a	3758a

† TKW = thousand-kernel weight

‡ Means followed by the same letter in the same column are not significantly different ($p \le 0.05$) using a paired t-test.

Table 13. Planting date x fertility treatment interaction for survival, vigor and test weight at Fargo, ND in 2010.

	Survival		Vigor		Test Weight	
Treatment	Early	Late	Early	Late	Early	Late
	--------------------------0-10†-------------------------				---------kg m^{-3}--------	
Jerry	8.4a†	7.6a‡ *	7.1 c	5.4a *	749.7a	747.9a
Hawken	8.3a	7.3ab *	7.4 bc	5.1a *	713.4 b	738.8ab *
Hawken +P	8.5a	6.8 c *	7.9a	5.1a *	703.0 c	730.7 b *
Hawken +K	8.3a	7.1 bc *	7.5ab	5.4a *	713.2 b	738.1 b *
Hawken +P+K	8.3a	6.7 c *	7.8ab	5.2a *	710.4 bc	733.4 b *
Mean	8.3	7.1 *	7.6	5.2 *	717.9	737.8 *

† Based on a visual score, with 10 being the best.

‡ Means followed by the same letter in the same column are not significantly different ($p \le 0.05$) using a paired t-test.

* Denotes significance ($p \le 0.05$) across rows by variable.

In the late planting, Jerry and Hawken without fertilizer had higher winter survival than all fertility treatments except Hawken +K (Table 13). This implies P placed with the seed did not increase winter survival and is contrary to Knapp and Knapp (1978) who found that fall P fertilization reduced winter injury. For vigor scores in the early planting, the same treatments that reduced winter survival for the late planting had higher vigor ratings than the untreated checks of Jerry. This suggests that when adequate P and K is present in the soil, additional P and K applied with the seed provides no benefit to winter survival but may increase spring vigor, as Hawken +P had significantly more vigor than Hawken without in the early planting.

As expected, Jerry had the highest test weight in both planting dates (Table 13). Furthermore, Hawken +P in the early planting produced the lowest test weight. This finding also contradicts the research by Knapp and Knapp (1978) who reported that fall P fertilization of 20 kg P_2O_5 ha^{-1} with and without 22 kg N ha^{-1} either had no effect on test weight or increased it. In their study, both soils had a medium P level prior to fall fertilization (45 and 60 kg ha^{-1}, respectively).

Fargo 2011

In the second year of the study at Fargo, there was no significant difference in survival, vigor, spike count, thousand-kernel weight and yield between drainage treatments (Table 14). The vigor ratings in 2011 were nearly identical for drainage, while spike count and thousand-kernel weight indicated a trend for additional spikes and larger kernels in the undrained soils. Winter survival was very good at Fargo even though air temperatures were low because of high amounts of snowfall. Having survival values great than 100% indicates that additional plants germinated and emerged after counts were taken in the fall, or seedlings did not fully germinate in the fall but were able to survive below the soil surface and continue growth in the spring. While survival and yield were not significant different at this location, it can be concluded that survival was not a good indicator of end-of-the-season yield, as the highest survival rating and yield did not suggest a similar trend.

The drainage x fertility treatment interaction for protein resulted in the Hawken treatments having significantly higher protein in the drained compared to the undrained soils, while protein for Jerry was similar across drainage treatment (Table 15). In 2011, Fargo received 360 mm of rainfall from April through July, with 100 mm of monthly rainfall or more recorded in all months except April (NDAWN, 2012). The drained plots likely benefited from subsurface drainage during those months and resulted in reduced losses of N to denitrification. Wiersma et al. (2010) found that grain protein increased linearly in HRSW as the drainage coefficient increased, suggesting that drainage may have reduced losses to denitrification. Comparing across fertility treatments, this interaction shows that Jerry had significantly lower protein than all the Hawken treatments. The higher protein in the Hawken treatments is expected as ND winter wheat varieties trials confirms that Hawken tends to have higher protein than Jerry (NDSU Extension, 2009).

Table 14. Drainage effect on survival, vigor, spike count, thousand-kernel weight and yield at Fargo, ND in 2011.

Drainage	Survival	Vigor	SCNT†	TKW†	Yield
	%	0-10‡	spikes m^{-2}	g	kg ha^{-1}
Drained	106.3a§	7.21a	720a	25.9a	3595a
Undrained	94.1a	7.27a	740a	26.7a	3860a

† SCNT = spike count, TKW = thousand-kernel weight.

‡ Based on a visual score, with 10 being the best.

§ Means followed by the same letter in the same column are not significantly different ($p \leq 0.05$) using a paired t-test.

Table 15. Drainage x fertility treatment interaction for protein at Fargo, ND in 2011.

Drainage	Drained	Undrained	
	-----------------	%----------------	
Jerry	14.8 b	14.7 b	
Hawken	15.9a	15.2a	*
Hawken +P	15.8a	15.0a	*
Hawken +K	15.8a	15.1a	*
Hawken +P+K	15.8a	15.0a	*
Mean	15.6	15.0	*

† Means followed by the same letter in the same column are not significantly different ($p \leq 0.05$) using a paired t-test.

* Denotes significance ($p \leq 0.05$) across rows.

There was no significant difference in winter survival and spike counts between canola residue and fallow (Table 16). Spike counts were taken to determine if additional tillers were produced for any of the applied treatments. Evaluations were taken at anthesis (Haun stage 11.5) and spikes were only counted if they contained at least four spikelets.

The data indicates that more spikes were produced in canola stubble compared with fallow. Survival was excellent due to high snowfall amounts.

Table 16. Residue effect on stand count, survival, vigor, spike count, test weight, protein, thousand-kernel weight and yield at Fargo, ND in 2011.

Residue	Survival	Vigor	SCNT†	Protein	TKW†	Yield
	%	0-10‡	spikes m^{-2}	%	g	kg ha^{-1}
Canola	101a§	7.70a	746a	15.2 b	26.4a	3759a
Fallow	100a	6.78 b	714a	15.4a	26.0 b	3712a

† SCNT = spike count, TKW = thousand-kernel weight.

‡ Based on a visual score, with 10 being the best.

§ Means followed by the same letter in the same column are not significantly different ($p \leq 0.05$) using a paired t-test.

Results for protein were similar to Fargo in 2010, with winter wheat grown on fallow having two-tenths of a percent protein advantage (Table 16). Winter wheat grown on previous canola residue had plants that were significantly more vigorous in the spring. While previous research on winter wheat does not provide data describing spring vigor or examining differences among treatments, it is often linked with the discussion on winter survival and therefore implies the two are linked. Canola residue had a higher minimum temperature (-3.2 vs. -4.7°C), which likely lead to the vigor differences. Thousand-kernel weight was also four-tenths of a gram heavier in the canola residue plots than the fallow plots (26.4 vs. 26.0 g, respectively). This was also likely linked to the significantly higher vigor, which allowed the plants to initiate growth earlier in the spring. Despite larger kernels and better vigor, yields were not significantly higher in the canola residue.

In both drainage treatments, winter wheat grown on canola residue produced higher test weight than on fallow for the drainage x residue interaction (Table 17). The higher test weight on canola residue is likely due to a significantly higher thousand-kernel weight on canola residue previously discussed (Table 16). There was no significant difference in test weight for canola residue or fallow across drainage treatment.

Table 17. Drainage x residue interaction for test weight at Fargo, ND in 2011.

Residue	Drained	Undrained
	---------------kg m^{-3}--------------	
Canola	647.3a†	667.0a
Fallow	641.1 b	655.4 b
Mean	644.2	661.1

† Means followed by the same letter in the same column are not significantly different ($p≤0.05$) using a paired t-test.

Stand counts were significantly different for the residue x fertility treatment interaction, with Hawken having a significantly higher fall stand count when planted into fallow (Table 18). While not significant, the untreated check of Jerry showed a similar response. A reverse trend developed in the Hawken treatments with seed-placed fertilizer. Because no consistent trend developed and stand counts in the fall were lower than the seeding rate, the difference was likely due to stand establishment. With no residue or stubble remaining on the surface, fallow provides a better seedbed, while canola residue may delay seed germination due to less seed-to-soil contact. This is likely the cause as harvest yields were similar at the end of the season (Table 14).

Table 18. Residue x fertility treatment interaction for stand count at Fargo, ND in 2011.

Treatment	Canola	Fallow	
	------------plants m^{-2}------------		
Jerry	122 c†	136 b	
Hawken	141 bc	174a	*
Hawken +P	159 b	155ab	
Hawken +K	166 b	161ab	
Hawken +P+K	195a	169a	
Mean	157	159	

† Means followed by the same letter in the same column are not significantly different ($p≤0.05$) using a paired t-test.
* Denotes significance ($p≤0.05$) across rows.

In canola residue, Hawken +P+K had the highest stand count in the fall, while the remaining Hawken fertility treatments were significantly higher than Jerry (Table 18). In the fallow residue, Hawken and Hawken +P+K fertility treatments had significantly better stands than Jerry. Despite very high levels of P and K present in the soil (17 and 560 mg

kg^{-1} in the upper 15 cm, respectively), the addition of both P and K to Hawken had a mostly positive impact on stand establishment in the fall of 2010, which was likely due to the immediate availability of P and K to the developing seedling.

There was no significant difference in stand count or spike count across planting date (Table 19). As expected, winter wheat planted early had better survival than the late planting; however, both planting dates had very good survival (105.8 and 94.3%, respectively) due to above-normal snowfall and the accompanying moderate soil temperature. Vigor showed a similar trend to survival, with the early planting showcasing better spring vigor than the late planting (7.9 vs. 6.6, on a 0-10 scale, with 10 being the best). This mirrored trend is thought to be common; however, no information is available linking winter survival and spring vigor. A reduction in thousand-kernel weight and yield also occurred with the late planting. This finding aligns with Blue et al. (1990) who reported reductions in yield and kernel weight as planting date was delayed.

Table 19. Planting date effect on stand count, survival, vigor, spike count, thousand-kernel weight and yield at Fargo, ND in 2011.

Date	Stand count	Survival	Vigor	Spike count	TKW†	Yield
	plants m^{-2}	%	0-10‡	spikes m^{-2}	g	kg ha^{-1}
Early	166a§	105.8a	7.9a	748a	27.0a	3935a
Late	150a	94.3 b	6.6 b	713a	25.6 b	3520 b

† TKW = thousand-kernel weight.

‡ Based on a visual score, with 10 being the best.

§ Means followed by the same letter in the same column are not significantly different ($p \leq 0.05$) using a paired t-test.

The planting date x fertility treatment interaction was significant for test weight and protein at Fargo in 2011 (Table 20). Across planting date, Jerry maintained a constant test weight while the Hawken treatments had a significant reduction in test weight for the late planting. Knapp and Knapp (1978) and Pittman and Andrews (1961) also reported a decrease in test weight of winter wheat as planting date is delayed. For protein, the untreated checks of Jerry and Hawken maintained similar protein across planting date, while Hawken plus seed-placed fertilizer had additional protein in the late planting. Past research by Kelley (2001) suggests a similar trend for increased protein in some years.

Table 20. Planting date x fertility treatment interaction for test weight and protein at Fargo, ND in 2011.

	Test weight		Protein	
Treatment	Early	Late	Early	Late
	-------------kg m^{-3}------------		-------------%------------	
Jerry	675.3a	670.2a	14.8 c	14.7 b
Hawken	657.5 c	628.5 b *	15.4a	15.7a
Hawken +P	660.6 bc	633.0 b *	15.2ab	15.6a *
Hawken +K	663.9abc	634.5 b *	15.2ab	15.7a *
Hawken +P+K	671.4ab	632.3 b *	15.0 bc	15.8a *
Mean	665.7	639.7 *	15.1	15.5 *

†Means followed by the same letter in the same column are not significantly different ($p \leq 0.05$) using a paired t-test.

*Denotes significance ($p \leq 0.05$) across rows by variable.

Test weight responded differently to fertility treatment in the two planting dates (Table 20). In the early planted Hawken treatments, Hawken without a treatment had lower test weight, compared with Hawken +P+K. In the late planting, Jerry had the highest test weight, with no difference between the Hawken treatments. This suggests that P and K placed with the seed in the early planting was beneficial to test weight despite very high levels already present in the soil (560 mg kg^{-1} in the upper 15 cm), while neither P nor K provided any benefit to test weight in the late planting.

In the early planting comparing across fertility treatments, Jerry had lower protein than Hawken, while Hawken had higher protein than Hawken +P+K (Table 20). In the late planting, all Hawken treatments had additional protein compared to Jerry. Averaged across planting date, Jerry out-yielded some of the Hawken treatments, so it is not surprising that Hawken produced additional protein for both planting dates (Table 21).

Despite high levels of P available in the soil, treatments involving Hawken +P and +P+K produced similar yields as the winter hardy cultivar Jerry (Table 21). This finding suggests applying P with the seed can increase seed yield to a level similar to the winter-hardy cultivar Jerry even when high levels of P are available in the soil. Others have also reported that fall applied P increased grain yield (Lutcher et al., 2010; Blue et al., 1990).

Table 21. Fertility treatment effect on yield at Fargo, ND in 2011.

Treatment	Yield
	kg ha^{-1}
Jerry	3961a
Hawken	3646 b
Hawken +P	3715ab
Hawken +K	3595 b
Hawken +P+K	3720ab

†Means followed by the same letter in the same column are not significantly different ($p \leq 0.05$) using a paired t-test.

Lisbon and Prosper 2011

Eight agronomic characteristics of winter wheat were measured when winter wheat was grown on wheat and soybean residue at Lisbon and Prosper, ND in 2011. Stand counts in the fall were similar at Prosper for both residues, while in wheat residue, significantly more plants were derived at Lisbon (Table 22). This was due to a residue x planting date interaction at at Lisbon (Table 23). Winter wheat planted late on the soybean residue had a significantly lower plant stand in the fall compared to wheat residue. This was likely due to dry soil conditions for the late planting. Dry soil conditions were likely intensified by the removal of the soybean residue prior to planting. Lisbon only received an estimated 28.4 mm of rainfall in October (NDAWN, 2012). Despite significant stand differences in the fall, harvest yields were not affected as plots noted as having poor stands in the fall had visibly more plants when re-examined in the spring.

Winter survival was very good for winter wheat during the winter of 2010-11, as indicated by the high survival values at both Lisbon and Prosper (Table 22). Additionally, there was a significant residue x cultivar x planting date interaction at both locations (Table 24). At Lisbon, Hawken planted late in soybean residue had greater survival than the same planting date in wheat residue. At Prosper, a similar trend occurred with Jerry and Hawken planted early. At both locations where survival was greater on the soybean residue, the survival values exceeded 100%. A late emergence of plants after stand counts were taken in the fall likely explains some of the differences in survival; however, seedling disease developing from growing wheat after wheat cannot be ruled out. While no disease symptoms were noted during fall counts, it's possible that plants were lost to disease post-fall counts or a disease infection did not kill the plant in the fall but caused it to be less winter hardy. Either way, the trend still suggests that if adequate snowfall is received during the winter, winter wheat planted in soybean residue can survive the winter (as also reported by Wiersma et al., 2006) as well or even better than winter wheat planted into wheat residue.

Table 22. Residue effect for combined and individual analysis of stand count, survival, vigor, spike count, test weight, protein, thousand-kernel weight and yield at Lisbon and Prosper, ND in 2011.

	Stand count		Survival		Vigor		Spike count	
Residue	Lisbon	Prosper	Lisbon	Prosper	Lisbon	Prosper	Lisbon	Prosper
	-------plants m^{-2}-------		-----------%---------		------0-10†------		----spikes m^{-2}----	
Wheat	208a‡	187a	94.3 b	74.9 b	6.8a	6.3 b	529 b	556 b
Soybean	144 b	193a	106.8a	102.8a	5.4 b	7.2a	599a	651a
Combined	ns§		ns		ns		ns	

Table 22 (Continued).

	Test weight		Protein		TKW¶		Yield	
Residue	Lisbon	Prosper	Lisbon	Prosper	Lisbon	Prosper	Lisbon	Prosper
	----------kg m^{-3}--------		---------%---------		----------g----------		------kg ha^{-1}------	
Wheat	675.6a	655.1a	15.5a	14.4a	23.9a	24.4a	2405a	1713a
Soybean	663.2a	647.3a	15.5a	15.0a	23.5a	24.6a	2342a	2102a
Combined	ns		ns		ns		ns	

† Based on a visual score, with 10 being the best.

‡ Means followed by the same letter in the same column are not significantly different (*p*≤0.05) using a paired t-test.

§ ns = non-significant.

¶ TKW = Thousand-kernel weight.

End of Table 22.

Table 23. Residue x planting date interaction for fall stand count at Lisbon, ND in 2011.

Residue	Early	Late	
	---------------plants m^{-2}--------------		
Wheat	110a†	97a	
Soybean	97a	46 b	*
Mean	104	72	

† Means followed by the same letter in the same column are not significantly different ($p \leq 0.05$) using a paired t-test.
* Denotes significance ($p \leq 0.05$) across rows.

Table 24. Residue x cultivar x planting date interaction for survival at Lisbon and Prosper, ND in 2011.

	Lisbon				Prosper			
	Jerry		Hawken		Jerry		Hawken	
Residue	E†	L†	E	L	E	L	E	L
	---				%---			
Wheat	104.9a‡	83.9a	110.8a	77.5 b	69.3 b	79.7a	74.9 b	75.6a
Soybean	123.5a	65.0a	130.2a	108.5a	126.8a	79.0a	116.2a	89.4a

† E = Early planted, L = Late planted.
‡ Means followed by the same letter in the same column are not significantly different ($p \leq 0.05$) using a paired t-test.

As anticipated, spring vigor was better in the wheat residue at Lisbon, with a significant residue x planting date interaction also indicating a higher vigor rating in wheat residue at both planting dates (Table 25). Spring vigor was greater, however, on the soybean residue at Prosper (Table 22). Better vigor on soybean residue at Prosper was not expected, as the soybean residue provided little stubble for trapping snow during the winter. At Prosper, a slightly warmer minimum temperature was recorded on soybean compared to wheat residue (-3.0 vs. -3.6°C, respectively), yet probably not enough to account for the difference. Conversely, at Lisbon winter wheat on wheat residue recorded a colder minimum temperature than soybean residue (-6.0 vs. -4.7°C, respectively) yet had better spring vigor. This suggests that minimum soil temperatures may not always correctly predict spring vigor of winter wheat or that the minimum threshold for injury was not met.

Spike counts at both locations were higher in soybean compared to wheat residue (Table 22). At Lisbon, there was a significant residue x planting date interaction that was caused by a greater number of spikes that developed in the soybean residue at the early planting date relative to the late planting date (Table 25). This is likely due to the lower fall stands reported in the soybean residue compared to wheat residue (72 vs. 104 plants m^{-2}). Additionally, protein was higher for winter wheat grown at Lisbon on soybean residue at both dates. This may be due to the nitrogen credit offered by the previous leguminous crop, but because all above ground residue was removed the previous crop credit would be limited to root contributions. The lower fall stands might also explain some of the differences, as the non-significant differences in yield are not enough to explain greater than 1% difference in protein.

Table 25. Residue x planting date interaction for vigor, spike count, protein and yield at Lisbon, ND in 2011.

	Vigor		Spike count		Protein		Yield	
Residue	Early	Late	Early	Late	Early	Late	Early	Late
	---------0-10†--------		-----spikes m^{-2}-----		-----------%----------		-------kg ha^{-1}-------	
Wheat	7.4a‡	6.1a *	520 b†	538a	15.0 b	14.6 b *	2618a	2193a *
Soybean	6.8 b	4.1 b *	658a	540a *	16.0a	16.4a *	2917a	1766a *

† Based on a visual score, with 10 being the best.

‡ Means followed by the same letter in the same column are not significantly different ($p \leq 0.05$) using a paired t-test.

* Denotes significance ($p \leq 0.05$) across rows by variable.

At Lisbon, both the early planting dates on wheat and soybean residue had higher spring vigor (Table 25). This was expected as early planting dates are thought to have better spring vigor due to additional time to for roots to develop and increase stored energy reserves. Additionally, spike numbers were also significant for the same interaction, with winter wheat planted late on soybean residue producing fewer spikes m^{-2} than the early planting (540 vs. 658 spikes m^{-2}). This is not surprising as vigor in the late planting was reduced (5.4 vs. 6.8, respectively, on a 0-10 scale, with 10 being the best) and it would be expected that stressed plants would produce fewer tillers.

With the wheat residue treatment at Lisbon, the late planting date had lower protein than the early planting, while the inverse was true in the soybean residue (Table 25). For yield, the late planting in both the soybean and wheat residue yielded significantly less. As the yield decreased for the late planting in wheat, protein did not respond as was expected as it was reduced. The inverse protein and yield response held true in the soybean residue, but protein did not increase as much as would be expected for the large decrease in yield. No explanation can be offered as to why protein and yield responded as they did in Lisbon and Prosper.

The residue x cultivar interaction was significant for spike count, protein and yield (Table 26). Spike counts were significantly higher in the soybean residue for both cultivars. While more spikes were produced in the soybean residue, it did not translate into a grain yield advantage, as there was no difference in yield based on residue for each of the cultivars. Instead, the plants in the soybean residue tillered to compensate for the lower fall stands. Despite similar yields for Hawken, a significant protein advantage occurred on wheat residue. This protein advantage on wheat residue is likely due to the lower number of spikes m^{-2}, which conserved N for use during grain filling.

Table 26. Residue x cultivar interaction for spike count, protein and yield at Lisbon, ND in 2011.

	Spike count		Protein		Yield	
Residue	Jerry	Hawken	Jerry	Hawken	Jerry	Hawken
	----------spikes m^{-2}---------		-------------%-------------		---------kg ha^{-1}---------	
Wheat	545.3 b†	512.0 b	15.3a	15.7a *	2509a	2314a *
Soybean	595.9a	601.3a	15.4a	15.5 b	2302a	2366a

† Means followed by the same letter in the same column are not significantly different ($p \leq 0.05$) using a paired t-test.
* Denotes significance ($p \leq 0.05$) across rows by variable.

Protein and yield differed significantly for residue at Lisbon (Table 26). As expected, protein and yield followed an inverse relationship between Jerry and Hawken in the wheat residue. Jerry out-yielded Hawken (2509 vs. 2314 kg ha^{-1}, respectively) but had lower protein (15.3 vs. 15.7%, respectively).

At both Lisbon and Prosper, vigor was significantly better at the early planting date; however, the greater spring vigor at Prosper did not translate into a positive yield advantage (Table 27). Stand counts differed significantly for the date x cultivar x fertility treatment interaction at both Lisbon and Prosper (Table 28). At Lisbon, fall stands in Jerry with the reduced rate of +75% K and the combination + P+K were unaffected by a late planting, while other treatment stands were reduced at the late planting. Additionally, the stands for Hawken without a fertilizer treatment, the reduced rate of +75% P, and the combination +P+K were lower at the late planting. These reductions in stands at Lisbon at the late planting are likely due to the lower amounts of precipitation received around the late planting date, which suggests placing fertilizer with the seed when soil moisture is low can be detrimental to stand establishment. Olson and Drier (1956) reported reduced germination at low levels of available moisture with moderate levels of N and P placed close to wheat and oat (*Avena sativa*) seeds.

Table 27. Planting date effect for combined and individual analysis of stand count, survival, vigor, spike count, test weight, protein, thousand-kernel weight and yield at Lisbon and Prosper, ND in 2011.

	Stand Count		Survival		Vigor		Spike Count	
Date	Lisbon	Prosper	Lisbon	Prosper	Lisbon	Prosper	Lisbon	Prosper
	-------plants m^{-2}---------		-----------%---------		------0-10†------		----spikes m^{-2}-----	
Early	208a‡	176 b	117.4a	96.8a	7.1a	7.3a	588a	630.5a
Late	144 b	203a	83.7 b	80.9 b	5.1 b	6.2 b	539a	577.2a
Combined	ns§		ns		ns		*	

Table 27 (Continued).

	Test Weight		Protein		TKW¶		Yield	
Date	Lisbon	Prosper	Lisbon	Prosper	Lisbon	Prosper	Lisbon	Prosper
	----------kg m^{-3}--------		---------%---------		----------g----------		------kg ha^{-1}------	
Early	686.3a	653.3a	14.8 b	14.6a	24.6a	24.7a	2768a	1976a
Late	652.5 b	649.1a	16.2a	14.8a	22.7 b	24.4a	1980 b	1839a
Combined	ns		ns		ns		ns	

† Based on a visual score, with 10 being the best.
‡ Means followed by the same letter in the same column are not significantly different ($p \leq 0.05$) using a paired t-test.
§ ns = nonsignificant
* Denotes significance at ($p \leq 0.05$).
¶ TKW = thousand-kernel weight

End of Table 27.

Table 28. Planting date x cultivar x fertility treatment interaction for stand count at Lisbon and Prosper, ND in 2011.

	Lisbon				Prosper			
	Jerry		Hawken		Jerry		Hawken	
Residue	Early	Late	Early	Late	Early	Late	Early	Late
	---plants m^{-2}---							
Check	182a†	126a *	252a	130 c *	144ab	182ab	206a	210ab
+P	208a	118a *	194 b	184a	186a	166 b	200a	238a
+K	194a	108a *	224ab	176ab	140 b	176 b	190a	230ab
+P+K	180a	144a	230ab	132 bc *	160ab	184ab	216a	194 b
+75% P	202a	114a *	232ab	174abc *	126 b	200ab *	192a	222ab
+75% K	168a	134a	224ab	176ab	146ab	224a *	212a	214ab

† Means followed by the same letter in the same column are not significantly different ($p \leq 0.05$) using a paired t-test.
* Denotes significance ($p \leq 0.05$) for cultivar across planting date.

At Lisbon for the planting date x cultivar x fertility treatment interaction, there was no significant difference when fertilizer treatments were applied to Jerry at either planting date (Table 28). With Hawken at the early planting, +P applied at the full rate significantly reduced stand in the fall, compared with the check

At Prosper, Jerry with the reduced rate of +75% P and +75% K positively influenced the stand in the late planting compared to the early, while there were no differences in the fall stands compared across planting date for Hawken (Table 28). The positive influence on plant stands with Jerry at the late planting with reduced rates of +75% P and +75% K is puzzling because it would be expected that the full rates of each would have also produced a similar response or a negative toxic response. At Lisbon and Prosper, the results for the fertilizer treatment are mixed and no clear trend is present to suggest that they consistently helped or harmed stand establishment.

The same three-way interaction at Prosper showed inconsistent results with seed-placed fertilizer by date across fertility treatment (Table 28). The full rate of +K and reduced rate of +75% P had lower fall stands in the early planting of Jerry compared with the full rate of +P. While the +P and +K treatments had significantly reduced stands for the late seeding date of Jerry compared with the +75% K rate. Stands were similar when applying fertilizer at the early planting date for Hawken, while the +P+K treatment caused a significant stand reduction for the late planting date compared with the +P treatment. The fertilizer treatments at Lisbon and Prosper indicate no consistent trend for seed-placed fertilizer, and are likely due to the excellent winter survival that occurred at both locations.

Jerry remained a consistent-performing cultivar across planting date for spike count, test weight, protein and thousand-kernel weight (Table 29). It was expected that Jerry would have minor reductions in these factors for the late planting date, but instead the trend suggests minor increases for the late planting. Conversely, Hawken responded as would be expected in a late planting situation, with a decrease in spike count, test weight and thousand-kernel weight while protein was increased.

Table 29. Planting date x cultivar interaction for spike count, test weight, protein and thousand-kernel weight at Prosper, ND in 2011.

	Spike count		Test weight		Protein		TKW†	
Date	Jerry	Hawken	Jerry	Hawken	Jerry	Hawken	Jerry	Hawken
	---------spikes m^{-2}-------		---------kg m^{-3}-------		---------%---------		----------g----------	
Early	575a‡	686a *	658a	649a *	14.4a	14.8 b *	25.8a	23.5a *
Late	581a	573 b	663a	634 b *	14.4a	15.2a *	26.1a	22.7 b *

†TKW = thousand-kernel weight.

‡Means followed by the same letter in the same column are not significantly different ($p \leq 0.05$) using a paired t-test.

* Denotes significance at ($p \leq 0.05$) across variable.

Spike count, test weight, protein and thousand-kernel weight were significantly different for planting date across cultivar for all variables except spike counts for the late planting at Prosper (Table 29). Compared to Jerry, Hawken responded as expected in both planting dates for test weight, protein and thousand-kernel weight. Test weight and thousand-kernel weight were reduced in Hawken, while protein was increased. However, for the early planting date, Hawken produced significantly more spikes m^{-2} than Jerry (686 vs. 575 spikes m^{-2}, respectively). This was likely due to a higher stand count recorded in the fall for Hawken; however, the additional spikes did not result in higher grain yield. Thus, the number of spikes m^{-2} at heading did not accurately predict grain yield.

Vigor was significantly better for Hawken at Lisbon and Prosper (Table 30). Survival was very good at both locations (greater than 88%), and doesn't explain a one-percent higher vigor rating for Hawken. Since variety testing in North Dakota has shown that Jerry is less prone to winter injury than Hawken, and since winter survival and vigor are often discussed in tandem, it was assumed that Jerry would out-perform Hawken in spring vigor (NDSU Extension, 2009). Visual observations in the late spring indicated that Jerry tends to grow and tiller in a horizontal direction prior to jointing (Haun stage 8.0), so it is possible the growth characteristics of Jerry accounts for the differences in the visual vigor scores. The data also suggests that while Hawken typically has a lower capacity for winter survival, when winter conditions aren't challenging for the crop's winter survival, Hawken can perform as well or better than Jerry.

Table 30. Cultivar effect for combined and individual analysis of stand count, survival, vigor, spike count, test weight, protein, thousand-kernel weight and yield at Lisbon and Prosper, ND in 2011.

	Stand Count		Survival		Vigor		Spike count	
Cultivar	Lisbon	Prosper	Lisbon	Prosper	Lisbon	Prosper	Lisbon	Prosper
	-------plants m^{-2}--------		-----------%---------		------0-10†------		----spikes m^{-2}-----	
Jerry	156 b‡	170 b	94.3 b	88.7a	5.5 b	6.2 b	571a	578 b
Hawken	194a	210a	106.7a	89.0a	6.6a	7.2a	557a	630a
Combined	*		ns¶		*		ns	

Table 30 (Continued).

	Test weight		Protein		TKW#		Yield	
Cultivar	Lisbon	Prosper	Lisbon	Prosper	Lisbon	Prosper	Lisbon	Prosper
	----------kg m^{-3}--------		---------%---------		----------g----------		------kg ha^{-1}------	
Jerry	679.7a	660.6a	15.4 b	14.4 b	24.9a	26.0a	2412a	1946a
Hawken	659.1 b	641.8 b	15.6a	15.0a	22.5 b	23.1 b	2335a	1870a
Combined	*		ns¶		ns		ns	

† Based on a visual score, with 10 being the best.

‡ Means followed by the same letter in the same column are not significantly different ($p \le 0.05$) using a paired t-test.

* Denotes significance at ($p \le 0.05$).

¶ ns = nonsignificant.

TKW = Thousand-kernel weight.

End of Table 30.

The full rate of +K with the seed was the only treatment that produced a significant response between Jerry and Hawken for the cultivar x fertility treatment interaction at

Lisbon (Table 31). Potassium placed with the seed for Jerry increased the number of spikes m^{-2} by over 100 (632 vs. 523 spikes m^{-2}), which was the highest number when compared to other fertility treatments for Jerry. These differences between cultivars are unusual and might suggest that the benefits of K placed with the seed could be cultivar dependent.

Spikes m^{-2} were significantly different for the cultivar Jerry at Lisbon (Table 31). The treatment involving no fertilizer and +P produced significantly fewer spikes than the +K treatment. This suggests the full rate of P had no positive impact on tiller production for Jerry. Contrary to this finding, Knapp and Knapp (1978) reported banding 20 kg P ha^{-1} during fall planting of winter wheat increased spikes m^{-2}.

Table 31. Cultivar x fertility treatment interaction for spike count at Lisbon, ND in 2011.

Treatment	Jerry	Hawken	
	--------------spikes m^{-2}------------		
Check	536 b†	561a	
+P	533 b	582a	
+K	632a	523a	*
+P+K	575ab	594a	
+75% P	562ab	559a	
+75% K	585ab	520a	

†Means followed by the same letter in the same column are not significantly different ($p \leq 0.05$) using a paired t-test.
* Denotes significance at ($p \leq 0.05$).

Survival, vigor, spike count and thousand-kernel weight were significantly different for fertility treatment at Prosper (Table 32). The most notable difference in treatment for these factors is the consistent trend for a reduction with the reduced rate of +P. For all variables, the reduced rate of +75% P produced the lowest or one of the lowest ratings. For some unknown reason, the reduced rate of P placed with the seed did not promote seedling development, with the effects lasting throughout the season. It is not clear why the reduced rate of +P produced a negative response while +P at the full rate was always one of the highest.

For winter survival at Prosper, no fertilizer treatment, +P, +P+K and the reduced rate of +75% K offered the highest winter survival (Table 32). Due to the low levels of winter injury during the winter months, there is no clear trend for how seed-placed fertilizer affected survival since the check plot had over 90% survival. Despite the small differences in winter survival between the full rates of +P, +K and +P+K treatments, they tend to positively increase spring vigor.

No clear trend was observed to indicate that a full or reduced rate of seed-placed fertilizer impacted the ability of the plant to tiller and produce spikes (Table 32). The full rate of +P, +P+K and the reduced rate of +K all produced a similar number of spikes m^{-2}, while the full rate of +K, +P+K and the reduced rate of +P all produced a similar number of spikes m^{-2} as the untreated check. This indicates that the fertilizer treatments did little to increase tillering in a year with high snowfall.

Table 32. Fertility treatment effect on survival, vigor, spike count and thousand-kernel weight at Prosper, ND in 2011.

Treatment	Survival	Vigor	Spike count	TKW†
	%	(0-10)	spikes m^{-2}	g
Check	91.9ab‡	6.6 bc	590.8 bc	24.6a
+P	94.3ab	7.0ab	631.8ab	25.0a
+K	82.1 b	6.7ab	581.7 bc	24.5a
+P+K	95.7a	6.9ab	611.9abc	24.9a
+75% P	68.2 c	6.2 c	551.0 c	23.7 b
+75% K	101.0a	7.1a	655.9a	24.5a

†TKW = thousand-kernel weight

‡Means followed by the same letter in the same column are not significantly different ($p \leq 0.05$) using a paired t-test.

Williston and Hettinger 2011

At Williston, there was no significant difference in planting date for stand count and survival, while at Hettinger there was no difference in stand and spike counts (Table 33). Main effects of vigor, protein and yield at Williston and protein, thousand-kernel weight and yield at Hettinger were all significantly diffrent and responded as expected. Survival and vigor was highest for the early planting at Hettinger, with survival and vigor being significantly lower when planting was delayed (56.8 and 99.7% survival and 3.8 vs. 5.8 vigor on a 0-10 scale, respectively). Protein increased with the late planting, thousand-kernel weight was reduced as planting was delayed, and yield was best when planted early at both locations.

At Williston, test weight and thousand-kernel weight differed significantly for the planting date x cultivar interaction (Table 34). Similar to the results recorded at Prosper, Jerry maintained a similar test weight across planting date, while thousand-kernel weight was reduced for the later planting instead of remaining consistent as at Prosper. Across planting dates, Hawken had a lower test weight and thousand-kernel weight when planted late. While Jerry was not able to maintain a consistent thousand-kernel weight across planting dates, a reduction in thousand-kernel weight was still not unusual.

Table 33. Planting date effect for combined and individual analysis of stand count, survival, vigor, spike count, test weight, protein, thousand-kernel weight and yield at Williston and Hettinger, ND in 2011.

	Stand Count		Survival		Vigor		Spike count	
Date	W†	H†	W	H	W	H	W	H
	--------plants m^{-2}--------		-----------%---------		------0-10‡------		----spikes m^{-2}-----	
Early	228a§	260a	112.4a	99.7a	7.8a	5.8a	691a	554a
Late	196a	266a	93.6a	56.8 b	4.6 b	3.8 b	423 b	480a
Combined	ns¶		ns		ns		ns	

Table 33 (Continued).

	Test Weight		Protein		TKW#		Yield	
Date	W	H	W	H	W	H	W	H
	----------kg m^{-3}----------		---------%---------		----------g----------		------kg ha^{-1}------	
Early	784a§	702a	10.9 b	14.0 b	32.7a	28.4a	3590a	3166a
Late	770a	682 b	12.4a	14.7a	30.3 b	26.5 b	2125 b	2439 b
Combined	ns		ns		ns		ns	

† W = Williston, H = Hettinger.
‡ Based on a visual score, with 10 being the best.
§ Means followed by the same letter in the same column are not significantly different ($p \leq 0.05$) using a paired t-test.
¶ ns = non-significant.
# TKW = Thousand-kernel weight.

End of Table 33.

Table 34. Planting date x cultivar interaction for test weight and thousand-kernel weight at Williston, ND in 2011.

	Test weight		TKW†	
Date	Jerry	Hawken	Jerry	Hawken
	-----------kg m^{-3}----------		--------------g--------------	
Early	770a‡	798a *	32.8a	32.6a
Late	764a	776 b *	31.7 b	29.0 b *

† TKW = thousand-kernel weight.

‡ Means followed by the same letter in the same column are not significantly different ($p \leq 0.05$) using a paired t-test.

* Denotes significance at ($p \leq 0.05$) across row by variable.

Hawken was found to have higher test weight than Jerry at both planting dates (Table 34). Another winter wheat variety trial conducted at Williston the same year supports this finding (Ransom, et al., 2011). Thousand-kernel weight was similar for Jerry and Hawken at the early planting, while it was reduced for Hawken at the late planting.

Stand count, survival, vigor and test weight interacted significantly at Hettinger for the planting date x cultivar interaction (Table 35). Jerry had a higher fall stand count for the early planting while an unusually higher stand count occurred for the late planting of Hawken. No explanation can be given as to why the reversal in stand count for Hawken, as Hettinger received a small 4 mm rain event within a few days of the late planting, but a much larger 30 mm rainfall occurred two days after the early planting (NDAWN, 2012). As expected, survival and vigor were both better for the early planting, with large differences between the early and late planting dates for both variables. In fact, Hawken had the poorest winter survival of any location at Hettinger due to receiving the least amount of snowfall during the winter and the soil temperature declining to -14.9°C. Test weight also responded accordingly to planting date, with reduced weights observed for the late planting.

Across planting dates, Hawken had better establishment in the fall than Jerry for the late planting, but survival and vigor ratings for Hawken at both planting dates were significantly reduced (Table 35). It is not clear why Hawken established better at the late planting date, but it was expected that Hawken would have reduced survival and vigor relative to Jerry due to lower snowfall and cold soil temperatures. For the early planting date, test weight was similar for Jerry and Hawken. Similar to the finding at Prosper, the test weight of Hawken was reduced when the planting date was delayed.

Table 35. Planting date x cultivar interaction for stand count, survival, vigor and test weight at Hettinger, ND in 2011.

	Stand count		Survival		Vigor		Test weight	
Date	Jerry	Hawken	Jerry	Hawken	Jerry	Hawken	Jerry	Hawken
	-------plants m^{-2}-------		-----------%----------		--------0-10‡------		--------kg m^{-3}-------	
Early	126a†	135 b	132.3a	67.1a *	6.7a	4.8a *	703.4a	700.9a
Late	112 b	155a *	73.4 b	40.1 b *	4.2 b	3.4 b *	691.2 b	673.0 b *

† Means followed by the same letter in the same column are not significantly different ($p \leq 0.05$) using a paired t-test.
‡ Based on a visual score, with 10 being the best.
* Denotes significance at ($p \leq 0.05$) across row by variable.

A significant cultivar interaction was observed for all variables at Williston. Fall stand counts were higher for Hawken, while Jerry had better survival, vigor and produced more spikes m^{-2} during the growing season (Table 36). The higher stand count for Hawken is likely due to plants emerging later for Jerry, as indicated by a survival rating greater than 100%. Contrary to the usual inverse relationship between yield and protein, Jerry had higher protein and yield than Hawken. While it was surprising that Jerry would produce additional protein and yield compared to Hawken, it is not usual since Jerry had a trend for higher protein in two locations in ND winter wheat variety trial testing in 2011 (Ransom et al., 2011).

Jerry produced an additional 224 spikes m^{-2} in Hettinger, which was the result of nearly 50% winter kill for Hawken (Table 36). Hawken yielded significantly less than Jerry (2282 vs. 3323 kg ha^{-1}, respectively) due to high winter kill, but resulted in a 1% protein increase due to the reduced yield. As expected, thousand-kernel weight was also lower for Hawken.

The cultivar x fertility treatment interaction was significant for winter wheat survival at Hettinger (Table 37). The treatment with the full rate of +K was the only treatment that was not significantly different across cultivars. This interaction with cultivar is interesting because for Hawken this treatment had one of the highest survival rates, while for Jerry it was significantly lower than the other treatments. No explanation can be offered for why the +K fertility treatment showed different treatment responses between Jerry and Hawken since very high amounts of K were already present in the soil (610 mg kg^{-1} in the upper 15 cm).

Table 36. Cultivar effect for combined and individual analysis of stand count, survival, vigor, spike count, test weight, protein, thousand-kernel weight and yield at Williston and Hettinger, ND in 2011.

	Stand Count		Survival		Vigor		Spike count	
Cultivar	W†	H†	W	H	W	H	W	H
	--------plants m^{-2}-------		-----------%---------		-------0-10‡------		----spikes m^{-2}-----	
Jerry	97 b§	119 b	110.3a	102.8a	6.4a	5.5a	617a	629a
Hawken	115a	145a	95.8 b	53.6 b	6.0 b	4.1 b	497 b	405 b
Combined	ns¶		ns		ns		ns	

Table 36 (Continued).

	Test weight		Protein		TKW#		Yield	
Cultivar	W	H	W	H	W	H	W	H
	----------kg m^{-3}--------		---------%---------		----------g----------		------kg ha^{-1}------	
Jerry	766.7 b‡	697.3a	11.9a	13.9 b	32.3a	28.5a	2975a	3323a
Hawken	786.7a	687.0 b	11.5 b	14.9a	30.8 b	26.4 b	2741 b	2282 b
Combined	ns		ns		ns		ns	

† W = Williston, H = Hettinger.

‡ Based on a visual score, with 10 being the best.

§ Means followed by the same letter in the same column are not significantly different ($p \leq 0.05$) using a paired t-test.

¶ ns = non-significant.

TKW = Thousand-kernel weight

End of Table 36.

Across fertility treatments, Jerry without seed-placed fertilizer and the reduced rate of +75% P had better survival than the +K treatment. For Hawken, +K had significantly better winter survival than the untreated check and +P treatment. The soil at Hettinger is inherently very high in P and K (32 and 610 mg kg^{-1}, respectively, in the upper 15 cm), yet Hawken did respond positively to some of the treatments.

Table 37. Cultivar x fertility treatment interaction for survival at Hettinger in 2011.

Treatment	Jerry	Hawken	
	------------------%	------------------	
Check	116.8a†	26.8 c	*
+P	105.9ab	42.3 bc	*
+K	81.8 b	72.0a	
+P+K	101.1ab	54.3abc	*
+75% P	111.3a	56.9ab	*
+75% K	100.3ab	69.5ab	*

†Means followed by the same letter in the same column are not significantly different ($p \leq 0.05$) using a paired t-test.

* Denotes significance at ($p \leq 0.05$).

CONCLUSIONS

Subsurface drainage positively influenced winter wheat survival at Fargo in 2010 but had no effect on winter survival in 2011. Yield advantages were non-significant both years, with subsurface drainage indicating a slightly positive trend in yield the first year and a negative response the second year.

Snow-depth measurements during the winter of 2009-10 and soil temperature monitoring during 2010-11 did detect small differences between previous crop stubble; however, due to adequate snowfall in all locations except Hettinger, very little winter injury was detected regardless of previous crop residue. At all locations where residue was evaluated, the no-residue treatment provided similar or better winter survival compared to the presence of previous crop residue. Due to the large amount of snowfall received in eastern ND during the winter of 2010-11, the soybean residue was able to provide better winter survival at Lisbon and Prosper than the wheat residue. In all cases, previous residue did not provide a significant yield response. Note that differences in winter survival may have been associated with better fall growth and establishment. The better establishment that sometimes occurred in soybean residue or fallow likely resulted in a stronger fall plant.

Planting date was the primary factor that influenced winter wheat survival and yield. Planting at the recommended planting date for the region almost always produced the highest level of winter survival. Under no condition was winter survival reduced relative to the late planting when planted at the appropriate time. While the early planting didn't always produce a significant yield difference, there was always a trend for higher yield at the recommended date. Additionally, grain quality characteristics were usually better at the optimal planting date.

Contrary to what was expected, Hawken had better winter survival than Jerry at Lisbon, while survival was similar at Prosper. At both locations, Jerry had a trend for higher yield than Hawken. At Williston and Hettinger, Jerry provided superior winter survival and yield compared to Hawken. Hettinger was the only location where soil temperatures reached a threshold where high levels of winter injury would be expected, and nearly 50% winter injury was reported for Hawken. Therefore, if soil temperatures remain at or near freezing throughout the winter, Hawken can provide similar winter survival as Jerry.

The recommendation of applying P or K with the seed to increase winter survival of winter wheat cannot be made based primarily on this research, as the winters during this research were not conducive to high levels of winter injury. Additionally, fertility treatments with the seed did not return consistent results across locations. Hettinger was the only locations where winter soil temperatures approached the minimum for winter survival and, yet, P and K treatments were inconsistent for winter survival primarily because P and K levels were already high in the soil. Higher winter survival was reported with K applied to Hawken, while an opposite trend occurred for Jerry. Therefore, additional research is needed in more environments and under controlled conditions to determine if applying P or K at planting can increase winter hardiness.

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APPENDIX

Table A1. Mean squares for the ANOVA for agronomic traits measured at Fargo, ND in 2010.

		Mean Square					
SOV†	df†	Survival	Vigor	TW†	TKW†	Protein	Yield
Replicates	3	9.15	7.83	431	1.97	2.89	696821
A [drainage]	1	0.42	9.45*	10383	23.91	3.59*	8037006
Error (a)	3	2.69	0.43	4437	4.06	0.30	5025701
B [residue]	1	1.17	25.76*	1409	4.97	14.09**	315880
A x B	1	0.98	0.33	34	4.41	0.03	101329
Error (b)	6	0.63	2.77	1143	2.82	0.68	308353
C [date]	1	50.32***	203.12***	13977*	55.92**	8.80	6462918
A x C	1	11.68**	0.64	2617	1.57	10.26	5040881
B x C	1	0.82	4.63	2203	2.83	0.01	13565
A x B x C	1	1.67	1.05	189	0.60	1.75	1067558
Error (c)	11	1.33	2.89	2198	5.91	3.26	1967812
D [treatment]	4	0.84	0.45	4520***	106.34***	0.40	2957125***
A x D	4	0.22	0.45	650*	3.25	0.42	256936
B x D	4	0.25	0.38	229	0.80	0.25	469519*
C x D	4	1.25*	1.75**	1130***	5.11	0.84	113562
A x B x D	4	0.63	0.18	12	1.46	0.13	156109
A x C x D	4	0.36	0.24	400	3.33	0.20	40075
B x C x D	4	0.78	0.48	156	8.37*	0.43	288893
A x B x C x D	4	0.46	0.08	100	2.13	0.83	188063
Error (d)	91	0.39	0.39	186	2.91	0.37	146744

† SOV = source of variation, df = degrees of freedom, TW = test weight, TKW = thousand-kernel weight.
* ** *** Significant at ($p \leq 0.05$), ($p \leq 0.01$), and ($p \leq 0.001$), respectively.